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THE WORKLOAD IMPLICATIONS OF HAPTIC DISPLAYS IN MULTI–DISPLAY ENVIRONMENTS SUCH AS THE COCKPIT: DUAL–TASK INTERFERENCE OF WITHIN–SENSE HAPTIC INPUTS (TACTILE/ PROPRIOCEPTIVE) AND BETWEEN–SENSE INPUTS (TACTILE/ PROPRIOCEPTIVE/ AUDITORY/ VISUAL)

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Supervisors: Dr D Harris & Prof J Hetherington

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ABSTRACT

CASTLE, HEIDI. The Workload Implications of Haptic Displays in Multi–Display Environments such as the Cockpit: Dual–Task Interference of Within–Sense Haptic Inputs (Tactile/ Proprioceptive) and Between–Sense Inputs (Tactile/ Proprioceptive/ Auditory/ Visual). (Under the direction of D Harris & J Hetherington).

Visual workload demand within the cockpit is reaching saturation, whereas the haptic sense (proprioceptive and tactile sensation) is relatively untapped, despite studies suggesting the benefits of haptic displays.

MRT suggests that inputs from haptic displays will not interfere with inputs from visual or auditory displays. MRT is based on the premise that multisensory integration occurs only after unisensory processing. However, recent neuroscientific findings suggest that the distinction between unisensory versus multisensory processing is much more blurred than previously thought.

This programme of work had the following two research objectives:
1. To examine whether multiple haptic inputs can be processed at the same time without performance decrement — Study One
2. To examine whether haptic inputs can be processed at the same time as visual or auditory inputs without performance decrement — Study Two

In Study One participants performed dual–tasks, consisting of same–sense tasks (tactile or proprioceptive) or different–sense tasks (tactile and proprioceptive). These tasks also varied in terms of processing code, in line with MRT. The results found significantly more performance decrement for the same–sense dual–tasks than for the different–sense dual–tasks, in accordance with MRT, suggesting that performance will suffer if two haptic displays of the same type are used concurrently. An adjustment to the MRT model is suggested to incorporate these results.

In Study Two, participants performed different–sense dual–tasks, consisting of auditory or visual tasks with tactile or proprioceptive tasks. The tasks also varied in terms of processing code. Contrary to MRT, the results found that when processing code was *different*, there was significant performance decrement for all of the dual–tasks, but not when processing code was the *same*. These results reveal an exception to two key MRT rules, the sensory resource rule and the processing code rule. It is suggested that MRT may be oversimplistic and other factors highlighted by recent neuroscientific research should be taken into account in theories of dual–task performance.

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I: INTRODUCTION

Visual and auditory workload demands within the cockpit are reaching saturation, whereas the haptic sense (force and tactile sensation) is relatively untapped, despite an increasing amount of studies demonstrating the benefits of haptic displays. However, recently there has been a surge of interest in and enthusiasm for these haptic displays and their potential for de–saturating the other senses (particularly the visual sense) within the cockpit.

The principles behind Wickens's (1980) Multiple Resource Theory model (the predominant workload model used by human factors and engineering practitioners) suggest that haptic displays will not interfere with processing inputs from visual or auditory displays. However, in reality little is known about the nature and capacity of haptic workload, and whether haptic workload processes are shared with visual or auditory processes.

The principles behind MRT (i.e. separate resources), can be traced to the traditional hierarchical and modular view of information processing. This is the view that information is processed in increasingly more complex centres, and that sensory inputs are processed in unisensory brain areas before converging at multisensory brain areas towards the end of the process. However, recent neuroscientific findings suggest that multisensory processing can influence processing in 'unisensory' areas of the brain (e.g. Schroeder & Foxe, 2004) and that, whereas multisensory processing often leads to better performance, sometimes it leads to poorer performance (for example, when the inputs are spatially or temporally incongruous) (e.g. Stein et al., 2004). Therefore, one cannot assume that by spreading tasks across different senses to reduce workload, this will in itself always lead to better performance. As such, it is possible that current theories of dual–task performance are oversimplistic.

Nevertheless, virtually no studies have addressed concurrent performance of two haptic (tactile or proprioceptive) tasks, which has left the issue of haptic workload capacity and the impact of haptic displays on visual and auditory workload open to speculation. In addition, because haptic tasks have been almost completely left out of research into dual–task performance, theories (including MRT) have been based solely on visual and auditory dual–task findings. However, the haptic sense is a major contributor to information processing and therefore must be considered in the development of any theory of dual–task performance. This research aims to address this gap in knowledge.

If the point of introducing haptic displays into environments such as the cockpit is to off–load other senses, then it is important to know that:

(a) The haptic sense will not itself become overloaded.

(b) The haptic sense does not share workload processes with the other senses.

This programme of work addresses these concerns through the following two research objectives:

1. To examine whether multiple haptic inputs can be processed at the same time without performance decrement — Study One

2. To examine whether haptic inputs can be processed at the same time as visual or auditory inputs without performance decrement — Study Two

The results will contribute to our understanding of the haptic sense and to our understanding of multi–input processing in general, as well as being of interest to human factors and engineering practitioners.

II: LITERATURE REVIEW

Overview of the Literature Review

The literature review provides an overview of previous work relevant to this thesis. It is presented in six parts, which include: (1) a description of the haptic sense; (2) the rationale for studying haptic workload (3) workload and theories of dual–task performance; (4) neuroscientific findings regarding multi–input processing; (5) workload measurement; and (6) summary and proposed studies.

Part one of the Literature Review describes what the haptic sense is and how it is defined in terms of its sub–senses and in relation to the other senses.

Part two of the Literature Review provides the rationale for studying haptic workload. It introduces the problems surrounding the current display situation and the potential benefit that haptic displays might offer. It will then introduce the reasons why there is a need for a better understanding of haptic workload capacity.

Part three of the Literature Review will introduce current theories of workload and multi–input processing from the perspective of cognitive psychology. It will provide the argument for Multiple Resource Theory (MRT), the predominant theory of multi–input processing, and Wickens's (1980) MRT model, which has become a popular workload 'tool' within the human factors and engineering community and is the primary basis from which the assumption has been made that haptic displays will help to off–load the visual and auditory senses.

Part four of the Literature Review will outline neuroscientific findings relating to multi–input processing and the notion that performance enhancement as well as decrement can occur during multi–input processing. It also introduces factors relating to performance enhancement and decrement that Wickens's (1980) MRT model does not accommodate.

Part five of the Literature Review will look at approaches to workload measurement and provides the argument for the dual–task performance technique. It also describes the Performance Operating Characteristic (POC), which is a useful graphical expression of dual–task performance.

Finally part six provides a summary of the entire literature review and briefly outlines the studies that were proposed.

1 The Haptic Sense

1.1 General Description

The haptic sense is popularly known as the sense of touch but in neuroscience is referred to as the somatic sense or somatosense. The word haptic is thought to derive from the Greek words haptesthai and haptikos, both referring to 'touch' and more specifically 'to come into contact with'. The haptic sense is one of the four major senses relied upon in flight; the other three being the visual sense, the auditory sense and the vestibular sense in our inner ear.

It is generally agreed that the haptic sense comprises the following four sub–senses:

- **Proprioception** (kinaesthetic sensation)
- Tangoreception (**tactile sensation**)
- **Thermoreception** (thermal sensation)
- **Nociception** (pain sensation)

Proprioception is basically the sensation of bodily position (known as posture) and motion (or kinaesthesia) in relation to the self and to the surroundings. Proprioceptive receptors are sensitive to force–feedback i.e. pressure and displacement.

Tangoreception is more commonly referred to as **tactile sensation** and is the sensation of surface texture, including our own surface. Tactile receptors are mainly sensitive to vibrations (hence the fact that tactile feedback is sometimes called vibrotactile stimulation).

Thermoreception includes the sense of cold and the sense of warmth (sometimes considered separate sub–senses of thermoreception). Thermoreceptors respond to *changes* in temperature and our perception of temperature is relative rather than absolute.

Nociception is the sensation of pain, which can be brought about chemically (usually by chemicals produced by the body) or mechanically (e.g. pressure above a certain level).

Therefore, the haptic sense covers a wide variety of different sensations, all linked by the fact that they cause a person to 'feel' something. The view that the haptic sense refers to 'feeling' can be traced back to Aristotle, who distinguished five major senses: vision, audition, smell, taste and feeling (subsequently known as touch). Researchers prefer to use the word haptic rather than touch to 'acknowledge the importance of (proprioceptive) movement as well as (tactile) contact' (Milgram, 2003) in the experience of information gathering through feeling.

Categorisation of the haptic sub–senses can potentially be quite confusing because proprioception is also informed by the vestibular apparatus (another internal sense, which is important in maintaining balance and controlling head and eye coordination). However, normally in the literature, proprioception refers to 'general' (haptic) proprioception not 'special' (vestibular) proprioception. From now on in this report proprioception refers to that performed by the haptic receptors unless stated otherwise.

The haptic sub–modalities are summarised in
Figure 1, which also shows how other haptic sensations such as tickle, itch, wetness etc. are thought to come about through combinations of different types of haptic feedback. For example, the sensation of wetness is thought to come about as a result of cold (thermoreception) and smoothness (tactile sensation).

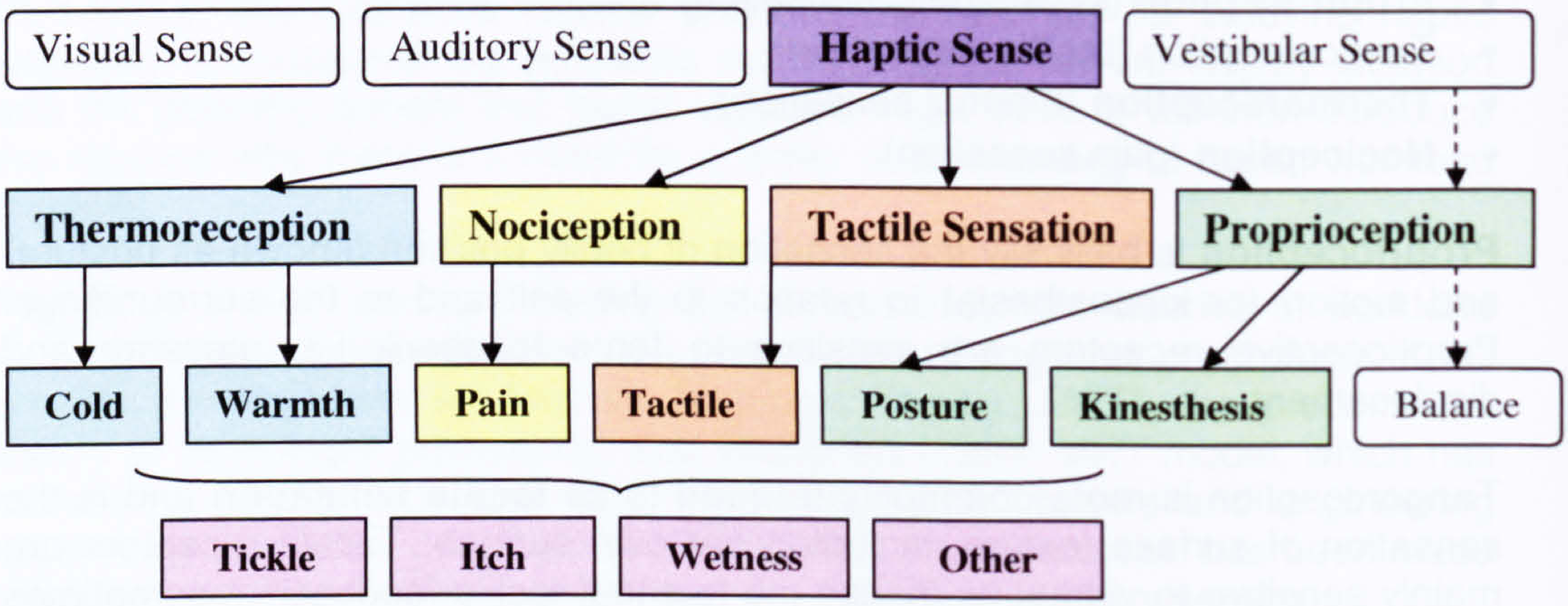

Figure 1: The haptic sub–senses (thermoreception, nociception, tactile sensation, and proprioception) in context

These sub–modalities were first identified at the end of the nineteenth century. Finger (1994) describes how on separate occasions, Magnus Blix, Alfred Goldscheider and Henry Donaldson discovered that the skin had 'sensory spots'; areas that are selectively responsive to certain types of stimuli, e.g. warmth, vibration or force. Sensory spot maps have been drawn using probe devices such as the von Frey hair, which is a small hair that stimulates tiny areas using varying levels of force to determine minimum force thresholds of the force sensing receptors. Hot or cold probes can be used in the same way as the von Frey hair but for assessing temperature thresholds. Electrical probes can be used to stimulate all receptors and the participants report the type and degree of sensation that they experience.

The existence of these four sub–modalities is supported from research suggesting that they have 'functionally distinct receptors and separate neural pathways' (Milgram, 2003). In fact, there is apparent neurological separation of these four haptic sub–senses into two groups within the spinal cord and subsequently entering the brain; these two groups are proprioception/ tactile and thermoreception/ nociception (Bear et al., 2001). Indeed, where damage to peripheral nerves causes loss of proprioception this loss is often accompanied by loss of tactile sensation even though thermoreception and nociception are left intact (for example see Azar, 1998; Cole, 1995). This is not necessarily to say that these groupings are maintained throughout the brain.

However, not surprisingly therefore, temperature is often implicated in pain sensation (Milgram, 2003), and coupled with the fact that temperature perception appears to be relative rather than absolute (Bear et al., 2001; Milgram, 2003), using temperature, as an interface for communicating information to a user, could be potentially complicated. Using nociception as a means of imparting information is undesirable for obvious reasons.

Therefore, it is not surprising that haptic devices are almost exclusively proprioceptive or tactile in nature, and this is likely to be the case for the foreseeable future. As a result, this thesis limits itself to these two types of haptic stimuli: **proprioception** and **tactile sensation**.

1.2 Haptic Receptors

The haptic sense is a general sense in that it is not localised to a particular site on the body. Unlike the eyes, which house the visual apparatus, and the ears, which house the auditory and vestibular apparatus, the entire body is covered in the haptic apparatus from top to toe and from the inside (deep tissues, muscles and tendons), through our layers of skin, to the outside (hairs).

The body contains a variety of haptic receptors that are either slowly adapting (**SA**) or rapidly adapting (**RA**). Slowly adapting receptors do not respond immediately on stimulation but once they respond they continue to do so for the duration of stimulation. Rapidly adapting receptors respond immediately to stimulation but quickly cease responding, only to respond again on stimulus offset. One could say that the RA receptors are the body's alerting receptors, whereas SA receptors are the body's 'reminder' receptors. For example, whereas an immediate RA pain response on touching one's finger on something sharp indicates avoidance action is necessary, any subsequent ongoing pain is due to the SA pain receptors indicating that tissue damage has occurred and protective action is required.

The haptic sense receives its inputs via many types of specialized receptors, which include Pacinian corpuscles; Ruffini corpuscles; Krause end bulbs; Meissner corpuscles; Merkel's disks; free nerve endings; Basket endings; Muscle spindle organs; Golgi tendon organs; and other proprioceptors. Some of these receptors are sensitive to vibrations, some to movement, some to forces and others to warmth, cold and pain. There is some debate about whether haptic sensations can be defined by receptors alone. There are two major theories about the way that haptic sensations associated with the four sub–

modalities come about: Labelled–line (or Specificity) Theory and Pattern Theory.

The Labelled–line Theory of sensory spots on the skin was initiated by von Frey's proposal that each sub–modality could be attributed to a receptor type. This is in line with anatomical studies revealing the existence of the receptors listed above. The Labelled–line Theory also suggests that different sensations have different pathways to the brain beginning with a specific receptor and this is also supported by anatomical research findings (see Liebman, 1991 for an overview of sensory pathways).

However, one inconsistency is that thermal spots do not remain constant and can fluctuate throughout the day (Milgram, 2003). Pattern Theory attempts to explain this through the notion of 'temporal coding', where 'differences in sensations arise because of differences in the spatio–temporal pattern of input carried to the brain' (Milgram, 2003). Essentially, thermoreceptors are believed to be receptive to temperature change and so sensations are relative rather than absolute. Therefore, the inconsistency mentioned above may be an associated characteristic of the thermoreceptor and does not necessarily 'disprove' Labelled–line Theory.

Nevertheless, Pattern Theory was also supported by pain research findings that show how force receptors produce the sensation of pain when stimulated by very intense force. Similarly, pain is also experienced when thermal receptors are stimulated to an intense level (Milgram, 2003). However, subsequent research suggests that chemicals released in damaged tissue (e.g. through intense pressure or temperature) stimulate pain receptors in that area (Arinello, 2004). Therefore the pain sensations might be more indicative of tissue damage than of receptor type 'plasticity'.

All the same a phenomenon called the 'thermal grill illusion', where combining non–painful warm and non–painful cold stimulation produces pain (Milgram, 2003) is yet another 'peculiarity' of the relationship between temperature and pain. One possible explanation is the fact that temperature and pain receptors share anatomically similar neural pathways to the brain, suggesting a relationship between the two sensations in the way that they are processed.

Ultimately, Pattern Theory cannot explain the existence of the specific receptors listed above or their selective responses to the associated stimulation. It is probable that a combination of Labelled–line Theory and Pattern Theory is the likely explanation for haptic sensations but at the moment, Labelled–line Theory appears the stronger of the two. Therefore, understanding haptic receptor characteristics is at the core of psychophysical investigation and haptic display & control design.

It is estimated that more than 360 billion haptic receptors cover our bodies and some areas of the body are more sensitive to haptic stimulation that others. The hands, lips, face, neck, tongue, fingertips and feet are the most sensitive to touch and this is a reflection of the greater concentration of receptors in those areas.

Areas of the body with the greatest number of receptors are represented in the brain accordingly. It is believed that haptic receptors send information to both the somatosensory cortex and the motor cortex but other brain areas are also implicated in haptic sensation and exploration. Due to their increased concentration of receptors, certain areas of the body are better suited to receiving haptic feedback than other areas (for example, the hands, lips, face, neck, tongue, fingertips and feet are very sensitive as mentioned above). Therefore, localisation of haptic displays according to receptor concentration is an important factor in their efficacy.

1.3 Categorisation of the Haptic Sub–Senses in Relation to Each Other and the Other Senses

If one accepts Labelled–Line Theory, that sensations are brought about as a result of stimulation of different receptor types, then one has to question whether the brain:

(a) Unifies the inputs from these different receptor types to create one sense (the haptic sense) or into sub–senses (e.g. tactile and proprioceptive sub–senses)

AND

(b) Separates these inputs from those from other receptor types to distinguish them from the visual, auditory, vestibular, olfactory and gustatory senses.

OR

(c) This apparent unification and separation is just an illusion brought about by either (i) 'later' classification of inputs by other factors such as spatio–temporal factors, object–/ event–related factors, or derived meaning etc. or (ii) the motivation to understand and classify inputs in the same way as we desire to understand and classify everything we encounter.

Traditionally, the view has been that inputs from receptors of a particular type travel up a specific pathway that takes the inputs to a specific uni–sensory brain area, where the input is analysed for its basic physical features, before it travels to 'later' multi–sensory brain areas where sensory cohesion occurs on the basis of other factors such as spatio–temporal factors.

This view was supported by anatomical evidence of uni–sensory pathways and the situation of apparently uni–sensory areas of cortex along these pathways and the merging of different pathways within the 'later' multi–sensory areas of cortex.

However, more recent neuroscientific findings (see Section Four) suggest that (a) uni–sensory brain areas are not totally uni–sensory and (b) activity in multi–sensory brain areas often influences activity in 'uni–sensory' areas within a timeframe that suggests processing in the multi–sensory area may have occurred prior to that in the uni–sensory area. The point is that ambiguity exists regarding the level of separation between the different senses and the point at which this separation occurs. Therefore, the degree to which different sensory displays are dealt with as separate versus overlapping entities by the brain is uncertain.

This is a particular grey area for the haptic sense and its sub–senses and this is reflected by the variations within the literature as to how the proprioceptive and tactile senses should be classified i.e. as one sense, as separate sub–senses (or channels) within the haptic sense, or as distinctly separate senses in their own rights. Note, however, that the distinction between different channels versus different senses is yet another ambiguity.

1.3.1 Categorisation and Receptor Type

As Labelled–Line Theory implies, the senses can be classified in terms of the type of stimulus to which the sense's receptors are attuned. Tactile and proprioceptive receptors are classed as mechanoreceptors i.e. sensitive to mechanical stimuli rather than light or chemicals. As mentioned in the previous section, mechanical receptors are responsive to pressure, vibrations, bending and other distortions. However, to complicate things, these haptic sub–senses are only *part* of this mechanical receptor 'family'.

The sense of hearing is a mechanical sense as well. It is generally accepted that a long time ago, the ability to hear probably evolved when the vibration (tactile) receptors of our 'earless' remote ancestors evolved to respond to airborne vibrations (sound) (Kalat, 1992, p. 204). For example, fish have no ears; they have a row of tactile receptors on each side of the body (called lateral lines), which provide the equivalent of a sense of hearing underwater. As fish evolved into early land vertebrates, they left the water but their tactile receptors would have been unable to process air–borne vibrations. It is believed that some specific tactile receptors at the sides of the head adapted to pick up sounds and this ability is what we call hearing (Kalat, 1992, p. 204). This adaptation is so great though that generally hearing is not treated as part of the mechanical senses, even though strictly speaking it should be.

Another mechanical sense is the vestibular sense. The vestibular system detects the position and acceleration of the head through mechanical displacements of hairs inside the inner ear, and cues adjustments to head position and eye movements based on that information.

Categorising inputs based on receptor type e.g. mechanoreceptors versus light receptors (photoreceptors) or chemical receptors (chemoreceptors) would lead to the following general sensory groupings:

- Mechanoreceptors — tactile sensation, haptic proprioception, vestibular proprioception, audition and some nociception
- Photoreceptors — vision
- Chemoreceptors — gestation (taste), olfaction (smell), nociception (pain)
- Thermoreceptors — thermoreception and some nociception
- Polymodal receptors (those that respond to mechanical stimulation, chemical stimulation and thermal stimulation) — some nociception

This categorisation produces overlap between apparently different senses (e.g. tactile sensation and audition) as well as separation between sub–senses commonly associated with a single sense (i.e. the haptic sense). It is possible that this is reflected in how the brain classifies the associated inputs. Note, however, that some nociceptors respond to mechanical stimulation, some respond to chemicals and some respond to extreme temperatures, whilst other nociceptors are polymodal. However, this variability is unique to the sense of pain and it stands to reason that the sense of pain would respond to different types of inputs (for example, increases in pressure, high temperature and chemicals associated with tissue invasion or damage), it does suggest that classification of senses simply based upon receptor type is unlikely. Indeed, natural separation between different senses occurs through their differing pathways to the brain and the subsequent areas of the cortex to which the inputs travel. The pathways associated with the haptic sub–senses are described in the next section.

1.3.2 Categorisation and Haptic Pathways

In the case of the haptic sense, the primary afferent axons (nerves that bring inputs from the receptors to the brain), include the slow–conducting C and Aα fibres (conducting at a speed of 0.5–2 m/sec and 5–30 m/sec respectively) for thermoreception and nociception, the faster Aα fibres (35–75 m/sec) for tactile sensation and the very fast Aα fibres (80–120 m/sec) for proprioception. These axons follow specific pathways up the spinal cord to the brain; the tactile and proprioceptive axons follow the dorsal column–medial lemniscal pathway whereas the thermoreceptive and nociceptive axons follow the spinothalamic pathway. As the two sets of axons travel from the spinal cord through the brain stem, they eventually run alongside each other but still remain separate. Another difference between the two sets of inputs is that the tactile and proprioceptive axons ascend ipsilaterally (and do not cross until they reach the medulla on entering the brainstem), whereas the thermoreceptive and nociceptive axons immediately cross on entering their pathway and ascend contralaterally. For more see Bear et al., 2001).

All of the haptic inputs synapse at the thalamus (a brain stem structure located deep within the brain) before travelling on to their primary sensory areas of cortex (Bear et al., 2001). A certain amount of transformation of input occurs within the thalamus, for example enhancement of tactile inputs through inhibition of inputs from adjacent receptors, and the strength of neuronal activity within the thalamus changes based on their recent activity (Bear et al., 2001). Thalamic neurons are 'also controlled by input from the cerebral cortex. Accordingly, the output of the cortex can influence the input (to)... the cortex!' (Bear et al., 2001). Tactile and proprioceptive inputs then travel to the primary somatosensory cortex (Kolb & Whishaw, 2003), whereas thermoreceptive and nociceptive inputs are taken to many different areas of the cortex (Bear et al., 2001).

This description of the pathways that haptic inputs take from their receptors to the cortex emphasises the separation between tactile/proprioceptive versus thermoreceptive/nociceptive inputs. However, as most haptic displays will be tactile and proprioceptive in nature, this description suggests that sharing of processes and brain areas may exist between these two types of inputs and therefore, these types of displays may tap overlapping information processing 'resources'. The concept of resources and the implications of resource sharing are discussed in more detail in Section Three.

Finally, however, there appears to be a degree of tactile/ proprioception separation in terms of their representation in the somatosensory cortex.

1.3.3 Categorisation and Neurological Evidence for Separate Haptic Sub–Senses

Support for the existence of separate haptic sub–senses can be found when neurological damage causes part(s) of the haptic sense to be lost (Sacks, 1970; Cole, 1995).

One individual, called Christina (see Sacks, 1970), lost her proprioceptive ability but retained light touch (tactile sensation), as well as the other haptic abilities, thermal sensation and pain sensation. This suggests that haptic proprioception is separable from the other three haptic sub–senses.

Another individual, Ian Waterman (see Azar, 1998; Cole, 1995) lost proprioception and tactile sensation but not the other components of the haptic sense, namely, thermal and pain sensation. This suggests that tactile sensation is separable from the thermoreception and nociception (as well as from proprioception as implied by Christina's case mentioned above).

It is also possible to lose nociception whilst thermoreception (and all the other senses) remain intact, suggesting some separation between nociception and thermoreception (as well as the other sub–senses) (Bear et al., 2001).

Loss of proprioception is effectively paralysing and invariably means the ability to speak properly is also lost. Both Christina and Ian Waterman taught themselves to move and speak again, but using only visual and auditory cues, which means their movement and speech (particularly in Christina's case) seems unnatural and 'robotic'. It takes huge effort to just stand as great concentration is required to keep the back upright, legs straight and to maintain balance. Facially, they can appear flat and expressionless, although less so in Ian Waterman's case as his loss was mainly from the neck down.

Relying on vision and hearing has disadvantages. For example, if the lights go out Ian slumps to the floor and has to lie there until the lights come on again; consequently he has to sleep with the lights on or he would not be able to get up in the middle of the night for anything.

However, amazingly, although Ian cannot pick up a glass without vision, he can smoothly produce gestures whilst he is speaking without visual feedback (see Cole et al., 1998; McNeill, 1992). It could be that this is because gestures require the haptic equivalent of verbal processing[*] whereas movement in space is obviously spatial and that these may constitute different forms of haptic sensory processing.

Because it is possible to lose only one of the haptic sub–senses as a result of injury or illness, there is obviously some separation between them. Needless to say, life without one of the haptic sub–senses is severely debilitating (particularly loss of proprioception) and dangerous (particularly loss of nociception) and cannot be compensated for by the other sub–senses. Loss of proprioception can be aided by vision but it involves constant effort and almost full concentration to perform seemingly basic tasks. It is indisputable therefore, that each of the haptic sub–senses plays a unique role in information processing; and are arguably as individual from each other as vision is from audition.

1.3.4 Categorisation and Function

Tactile and proprioceptive receptors are very similar to each other in that they respond to mechanical stimuli, share the same pathway and are processed in the somatosensory area of the cortex (albeit within different areas of the somatosensory cortex).

However, within the literature tactile sensation and proprioception are invariably discussed separately. They are separated on what appears to be their *functional* independence more than anything else.

In fact the tactile sense is more similar to hearing than proprioception on a functional level. Both tactile sensation and hearing can detect vibrations travelling through a medium that originates outside of our bodies and they can both transform these vibrations into information that is potentially highly meaningful.

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[*] See Section 6.2 for explanation of the haptic equivalent of verbal processing

On the other hand, proprioception and the vestibular sense often work in conjunction with each other to process and regulate the position and movement of our body. As mentioned previously, in some of the literature, the vestibular sense is classed as part of proprioception, presumably due to their similar functionality (e.g. Burdea, 1996; Wyburn et al., 1964). For example: '... even without vision we are still aware of movement and the new position taken up by the body or part of the body as a result of the movement. The information necessary for this awareness is provided by mechanoreceptors grouped as the special and general proprioceptors. The special proprioceptors are the sense organs for the vestibular mechanism and are situated within the skull. The general proprioceptors are the receptor organs for "kinesthesis" or the sense of joint movement and position'. (Wyburn et al, 1964).

This description suggests a clear functional distinction between tactile sensation and proprioception despite the shared pathway and area of cortex. This would be an important distinction at the level of perceiving what event or object the inputs are referring to. This level of information processing (where sensory information is combined to create a perception of what something is) is believed to occur within the (multi–sensory) association areas of cortex, which are situated 'later' (in structural terms) in the brain. As mentioned previously, recent neuroscientific findings suggest that these 'later' brain structures may influence processing within 'earlier' brain structures such as the thalamus and the primary sensory areas of cortex (see Section IV for more). This stands to reason, as feedback from the association areas would be crucial for filtering the vast quantity of sensory inputs that, without this direction, the brain would otherwise process within the earlier brain structures, and enable focusing of attention towards inputs that are relevant and pertinent. Feedback from the association areas would also enable improved focusing and coordination of attention based upon the combined multi–sensory inputs associated with a particular event, location or object. (see Section IV).

The point is that where there is functional or 'task–related' differences between sensory inputs then it is likely that they will be treated by the brain as being relevant to different processes or events and therefore distinguished as separate There is no doubt that the control of actions involved in tactile exploration will rely upon varying levels of proprioceptive and visual feedback, and vice versa in some circumstances. The involvement of different senses in certain tasks will depend upon the task at hand and this relies upon feedback from the association areas of the brain; areas that are believed to be multi–sensory in nature. Therefore, whether tactile and proprioceptive inputs are part of the same sense or are separate senses may be less relevant to the brain than whether they relate to the same event or not.

1.4 Summary

The first part of this section gave a general description of the haptic sense and its four sub–senses (tactile sensation, proprioception, thermoreception and nociception) and explained that the focus of this thesis is tactile and proprioceptive inputs because haptic displays are almost exclusively tactile and proprioceptive in nature and are likely to be so for the foreseeable future. This was followed by a section describing haptic receptors in more detail and the relevance of localising haptic displays to areas of the body with the greatest concentrations of haptic receptors. This section also introduced Labelled–Line Theory, which argues that sensations are determined by receptor type.

The next four sections focussed upon whether tactile and proprioceptive inputs are treated as those from separate senses by the brain. The first of the three described how the senses could be classified based on receptor type, which would group tactile and proprioceptive inputs clearly together (along with audition, vestibular sensation and part of nociception). However, it was argued that this was unlikely as nociception involved many different types of receptors and that natural separation existed between different groups of receptors through specific pathways to specific brain areas. The next section described the pathways associated with the haptic sense and highlighted the separation between tactile/ proprioceptive inputs versus thermoreceptive/ nociceptive inputs in terms of pathways and subsequent processing areas within the cortex. Again, this emphasised similarities between tactile and proprioceptive information processing. Nevertheless, it was then described how each of the haptic sub–senses could be selectively lost through injury and how this loss could not be compensated for by other haptic inputs, emphasising the unique role that each haptic sub–sense had in information processing. The final section talked about roles a little further and described the difference between tactile and proprioceptive functions. This section argued that inputs may be treated as overlapping or independent based upon their relevancy to particular events or tasks rather than simply based on sense (this notion is picked up again in Section IV).

Whether tactile and proprioceptive inputs should be treated as one sense or two senses and whether they are independent of other senses or not is the primary focus of Study One and Study Two, respectively. It is relevant to display designers who may base their choice of displays on the notion popularised by Wickens's (1980) MRT model, that displays utilising different senses are easier to use in parallel than displays utilising the same sense. The argument for this assumption is discussed in Section II of this thesis and the counter–argument is discussed in Section IV.

2 The Rationale for Studying Haptic Workload Capacity

2.1 The Rationale for Introducing Haptic Displays into Environments such as the Cockpit

2.1.1 Visual Overload and 'Automation Surprises'

It was in 1968 that Clement et al. suggested condensing many visual displays into one to reduce workload by minimising eye movements and this approach was adopted, to great effect.

However, it could be argued that this has now been taken to an extreme. To take aircraft as an example, the visual sense is currently still the primary sense used in flight but the technical and performance capabilities of modern aircraft have increased the amount of information that must be available to pilots and the limited cockpit space means this information must be presented using multiple display *modes* rather than resorting to introducing more displays for the pilot to scan. Thus, significant pressure is placed upon a pilot's ability to extract and interpret now relatively huge amounts of information from the available visual displays and their associated display modes.

It is paramount that the pilot is kept constantly 'in the loop' but in doing so, in this fashion, there is a growing risk that they may experience information overload of the visual sense and that vital information may be missed or misinterpreted without the pilot realising (i.e. loss of situation awareness). A survey by the German Pilot Association revealed that 67% of the pilots questioned experienced visual overload, whilst 80% reported feeling 'out of the loop', or not knowing what was happening (Burgner, 1997).

Without doubt, high workload is associated with increased errors (and therefore decreased safety), decreased overall productivity (Moray, 1988) and stress, with its related health risks (Sharit et al., 1982; Sharit & Salvendy, 1982a, b; Bachman & Udris, 1982).

Automation is not necessarily the answer, as although it is meant to decrease workload (and indeed can cause periods of 'underload', which is in itself a problem (Young & Stanton, 2002)), it also does the opposite, i.e. it can increase workload (Wiener & Curry, 1980; Harris et al., 1982). Moray (1988) distinguishes between 'perceptual–motor workload' and 'cognitive workload', and suggests that whereas non–automation increases perceptual–motor workload, automation on the other hand increases cognitive workload. This is because automation focuses on relieving the pilot of the perceptual–motor tasks (i.e. constantly scanning displays and flying the aircraft), but leaves the pilot in the role of 'goal–orientated planner and decision maker', which places great emphasis on memorizing, interpreting, translating and calculating what is going on and why things have changed on the displays or display modes. This role still places emphasis on the pilot processing mainly visual information in order to remain ‘in the loop’.

Nikolic and Sarter (2000) point out that, although automated systems can initiate actions on their own they do not have the ability to properly notify the user about those actions so that the user can be kept in the loop. A significant cause of this situation is the constant emphasis on displays that cannot be scanned effectively, because they are hidden (the pilot must flick between display modes) and because they provide foveal vision feedback; system scanning is more efficient using peripheral vision rather than foveal vision (Sarter & Woods, 1997; Sarter, 2000; Nikolic & Sarter, 2000).

Sarter and Woods (1995) called this problem “strong and silent” automation, which is characterized by the risk that unexpected changes may be missed (Sarter & Woods, 1994, 1997, Sarter, Woods, & Billings, 1997; Theeuwes, 1991; Yantis & Jonides, 1990). Unexpected mode transitions in themselves may lead to a loss of mode awareness (e.g., Sarter & Woods, 1994, 1995, 1997; Vakil, Hansman, Midkiff, & Vaneck, 1995; Wiener, 1989) and ultimately a breakdown in situation awareness.

Sarter and Woods (1994) suggest that these ‘automation surprises’ have already led to numerous aviation incidents and accidents. For example, on April 26, 1994, an Airbus A300–600 operated by China Airlines crashed at Nagoya, Japan, killing 264 passengers and flightcrew members. It was concluded that ‘conflicting actions taken by the flightcrew and the airplane’s autopilot’ contributed to this accident and that it was an example of ‘how a breakdown in the flightcrew/automation interface can affect flight safety’ (FAA Human Factors Team, 1996).

The same conclusion was drawn after the crash of a Boeing 757 operated by American Airlines near Cali, Columbia on December 20, 1995, and a November 12, 1995 incident ‘(very nearly a fatal accident) in which a American Airlines Douglas MD–80 descended below the minimum descent altitude on approach to Bradley International Airport, CT, clipped the tops of trees, and landed short of the runway’ (FAA Human Factors Team, 1996).

As a result of these accidents and incidents the Federal Aviation Administration (FAA) launched an investigation to assess flightcrew/ flight deck automation interfaces. The term ‘automation surprises’ kept recurring and it became apparent that there was a ‘need to improve situational awareness through the management of automation including mode awareness and airplane energy awareness... position awareness... proximity awareness... and detection of potential causes (of accidents) while under autopilot control’ (FAA Human Factors Team, 1996).

The investigation concluded that these incidents represented a much more widespread problem with automation and situation awareness, regardless of aircraft type, manufacturer or operator. It is also likely that the equivalent loss of situation awareness due to automation is having an equally devastating effect in other domains such as medicine (see Cook et al., 1992; Sparaco, 1994).

Nikolic and Sarter (2000) conclude that 'new forms of feedback are needed that enable the automation to play a more active role in human–machine communication'. They also suggest 'the introduction of effective peripheral visual cues and the distribution of tasks and information across sensory channels'. In theory this would help to reduce the risk of automation–related problems and reduce the risk of visual (especially foveal visual) overload.

Therefore it is necessary to rethink the display of information to users so that workload is kept at an optimal level and to avoid the problems associated with increased automation (paradoxically, those of both underload and overload). One potential solution, as was mentioned above, is to convey important information via other senses and interest is growing into the potential use of haptic devices to convey information normally presented visually.

2.1.2 Loss of Situation Awareness & 'Controlled Flight into Terrain'

As mentioned, the visual sense is the dominant sense inside the cockpit but as with all the senses, it is a limited 'resource' (see Section Three for more on this). Modern aircraft place increasing emphasis upon multiple visual displays and visual display modes; this places pressure upon the visual sense and there is a risk of overload and compromised situation awareness.

The implications are grave. When loss of situation awareness occurs, an overloaded pilot may not even notice visual and auditory warnings. An example of this happened relatively recently, when an A–10 pilot failed to notice a 32–degree nose down attitude until roughly 400ft, when it was too late (Anon. (a), 2004). This collision occurred despite the presence of warnings via a system called GCAS (Ground Collision Avoidance System), which provides visual and auditory alerts to the pilot regarding possible collision, including the auditory message 'Pull Up! Pull Up!', which should have been alarming. However, because the pilot was fully concentrating on another task (a navigational task, to be specific) the visual and auditory warnings seemed to occur unnoticed.

This type of accident falls into the category of accidents called controlled flight into terrain (CFIT), where an aircraft is unintentionally flown into terrain. CFIT accidents account for 40% of all aircraft accidents (Moroze & Snow, 1999), and they are the *primary* cause of fatalities in aviation across the board (Matthews, 1997), accounting for up to 80% of fatalities in commercial aircraft accidents (Anon. (b), 2004). About 70% of CFIT accidents occur during the descent, approach and landing phase of flight (Moroze & Snow, 1999). In about 85% of CFIT accidents, Instrument Meteorological Conditions are an implicating factor (Moroze & Snow, 1999), i.e. outside visuals are impaired and the pilot(s) need to rely heavily upon their (visual) instruments.

When it comes to military CFIT accidents, the losses are still staggering. Smith (1997) calculated that the USAF suffered $2 billion in cost, 200 fatalities, and 100 aircraft lost over the 10–year period leading up to the report. However, roughly 75% of military CFIT accidents occur during daylight and during visual meteorological conditions (i.e. outside visuals are adequate or good) (Krause, 1994). This reflects the typical training pattern of military aircrew but suggests that weather cannot be the causal factor in all CFIT accidents.

Moroze and Snow (1999) reviewed the data from Krause (1994) and found that loss of spatial awareness due to non–weather factors accounted for a high percentage of CFIT accidents (75%). Out of a total of 254 CFIT accidents, the data were categorized by Moroze and Snow (1999) into the following types of situation awareness loss:

- Spatial Disorientation (53 cases; 21%)
- Channeled attention (94 cases; 37%)
- Task saturation (overload) (12 cases; 5%)
- Visual illusion (31 cases; 12%)

Statistics suggest that between 5 to 10% of *all* aviation accidents can be attributed to spatial disorientation, 90% of which are fatal (Antunano, 2004). Collins and Dollar (1996) looked up all reports of spatial disorientation accidents from 1976–92 and their search yielded 1,022 reports of spatial disorientation accidents that resulted in 2,355 fatalities. Over 70% of these accidents were associated with poor outside visibility, where the pilot(s) must rely (sometimes exclusively) on their instruments to fly the aircraft.

The proportion of fatal general aviation accidents associated with spatial disorientation has reduced as the number of pilots holding an instrument rating has increased (Collins & Dollar, 1996) but it is quite apparent that an instrument rating is not sufficient to avoid spatial disorientation occurring in some cases. On the other hand, trials by the US Navy into tactile feedback have demonstrated it is virtually impossible to disorientate a blindfolded pilot who receives continuous orientation feedback through a tactile device called TSAS, which is described in Section 2.2.1 below (see: McGrath et al., 1998; McTrusty & Walter, 1997; Raj et al., 1998; 2000; Rochlis & Newman, 2000; Rupert, 1999; 2000; 2001; Rupert et al., 1999; 1994; 1990).

As mentioned above, channelled attention is another major factor in CFIT accidents. Channelled attention effectively means that the pilot's attention is so consumed by a particular task that overall situation awareness may be compromised. Current terrain avoidance warning devices are not sufficient protection against this, as demonstrated by the A–10 CFIT described earlier. Before ground proximity warning systems (GPWS) were mandated in the mid 1970s for commercial aircraft by the FAA, pilots relied on piloting skills to determine if the terrain encroached on the flight path. The GPWS mandate reduced CFIT accidents from about nine per year in the seven years immediately preceding the mandate to about four per year afterwards (Gurevich, 1991). This rate has remained fairly constant but demonstrates that these warnings are not penetrating channeled attention in roughly half of these cases.

It is easy to understand how visual display warnings can be missed when visual attention is channeled elsewhere, but why would auditory warnings also be missed? Aircraft auditory displays produce sound levels up to 125 decibels. Average human speech is about 60 decibels, so 125 decibels should be easily heard. However, the noise in a military cockpit is on average 125 decibels during climb and cruise and 130 decibels during takeoff and landing (Bjorn & Wilt, 2004). Therefore, it is clear that auditory warnings could be missed due to background noise, for example the air incident reported by Bjorn and Wilt (2004), where the pilot's missing an auditory warning was put down to background noise interference. Therefore, auditory warnings have to compete for attention against loud background noise. Haptic alerts on the other hand would not need to compete against this background noise (although there may be other *haptic* background vibrations or forces to consider).

When auditory warnings are transient in nature (Wheatley & Hurwitz, 2001), they are more vulnerable to being missed than visual alerts. However, increases in auditory alert length and repetition are associated with stress (Ahlstrom, 2003), and can be annoying (Belz, 1997), especially when individuals need to communicate verbally to one another in an already noisy environment. There is also evidence to suggest that auditory alert repetition can disrupt thought processes in general (Wolfman et al., 1996). Increases in stress and disruption to thought processes are undesirable under normal circumstances but especially so in an emergency, when an individual must think and react as quickly and as accurately as possible. It is possible that haptic alerts may be less stressful and less disruptive although this needs to be confirmed.

Human information processing capacity is limited (Allport, 1993b; Kahneman, 1973; Posner & Boies, 1971; Schneider & Shiffrin, 1977; Wickens, 1980). This is discussed in more detail in Section Three. An individual operating in an environment such as the cockpit is bombarded by an array of perceptual inputs simultaneously and, in order to function effectively, must make selections as to what to attend to immediately and what can wait or be ignored. Some of these selections may be made consciously but most will be sub–conscious. This is called selective attention (Allport, 1993b; Posner, 1991) and is obviously a defining factor of channeled attention.

Overload is said to occur when the environmental demands exceed attentional capabilities. Poorly designed systems may deplete the pilot's pool of attentional resources to the extent that he/ she may be more likely to become involved in an accident (Wierwille, 1995). According to Wickens (1980, 1992), poorly designed systems include those that place too much emphasis on one sense, see Section Three for more on this view. Conveying information through multiple senses (e.g. visual, auditory and haptic) may be an effective way of enabling a pilot, heavily loaded in one sense, to assimilate information through an alternative sense (Hancock & Caird, 1992; Pachiaudi & Blanchet, 1990).

The aim of this section was to emphasize the serious consequences of loss of situation awareness and how current visual and auditory displays do not adequately prevent this loss but may in fact be part of the problem in some circumstances. Tests conducted on the haptic display called TSAS (see Section 2.2.1) indicate that spatial disorientation could be eliminated through the use of this or similar haptic display. Furthermore, the problems associated with auditory alerts (missed alerts, stress etc.) may in theory be avoided by using haptic alerts to either supplement or replace auditory alerts. Finally, the introduction of haptic displays in general may help to prevent overload by off–loading the visual sense.

2.2 Examples of Haptic Displays and What They Can Offer

As mentioned, visual displays dominate the cockpit, and although auditory displays are increasingly being used as well, haptic displays are virtually absent in cockpits (Veen & Erp, 2001).

Examples of haptic devices that a pilot might already have come into contact with are:

- Force–feedback control sticks, which aim to convey aircraft handling quality cues to the pilot. These sticks are still something of a novelty in aircraft and their full potential has yet to be realised.
- G seats, which are mainly employed to emulate the changes in gravitational and acceleratory forces, normally felt by the pilot during actual flight through their physical contact with the aircraft i.e. the seat. These cues (as well as those received through the vestibular sense) support spatial orientation. G seats are designed for use in simulators but are exploited relatively infrequently.

Any device that stimulates the skin, hairs, muscles, tendons, joints and/ or deep tissues is providing haptic cues to the brain. This stimulation informs us of our surroundings in the same way as the visual sense does. The haptic sense is a sense that is often taken for granted. Shutting one's eyes gives an impression of what it might be like without sight. However, it is more difficult to imagine what it might be like without our haptic sense. For example, we would have no sense of any surfaces (including our own surface), no sense of the floor beneath our feet, of the position and movement of our body, we would feel no pain and no heat or cold — in effect we would be rendered paralysed and numbed.

2.2.1 Tactile Displays

Most tactile feedback is presented in the form of vibrations, using tactors (or vibrotactors). Tactors vary in size but are usually about the size of a standard bottle top. They are normally round and flat like a coin, and produce vibrations that can vary in frequency and rhythm. To be effective they must be placed either directly on the skin or next to the skin through clothing, adjusting their frequency and amplitude according to the clothing thickness to obtain the necessary baselines. Basic tactile alerts are fairly common in pagers and mobile phones. However, tactile cues can be used to communicate temporal and spatial information as well as to convey texture.

While most vibrotactile displays are designed to stimulate the skin of the fingertip, vibrotactile devices exist that stimulate places of the body including the back, the arm, and the feet (Brooks & Frost, 1986; Kaczmarek et al., 1992; Tan & Pentland, 1997; Rovan & Hayward, 2000).

Other tactile displays often employ miniature transducer arrays to cause tactile sensation via skin indentation and other methods. Typical stimulation mechanisms involve arrays of moveable pins or inflatable miniature bladders to either indent the skin or vibrate it locally (Caldwell et al., 1999; Moy et al., 2000; Summers & Chanter, 2002).

Actuation techniques can include electromechanical actuators, piezoceramics, servomotors, shape memory alloys, fluids, and others (Ikei et al., 1997; Taylor et al., 1997; Wagner et al., 2002). Other systems generate friction electrostatically when a user slides a finger over the display (Ostrom et al., 1999). Some devices avoid direct solid contact with the skin by using air jets (Asamura et al., 1998). Many devices are based on electrostimulation (e.g. Bach–y–Rita et al., 1998; Inoue et al., 2003). Electrostimulation provides controlled localised stimulation of specific haptic receptors and this technique is mainly being applied in the fields of prosthetics and rehabilitation. Devices that use electrogel bristles brushing against the skin have been introduced (Konyo et al., 2000). Yet others require miniature magnets to be glued to the skin for electromagnetic activation (Shinoda et al., 1998). For more details of tactile feedback techniques refer to Pasquero (2003).

Veen and Erp (2001) suggest the following categories of information present in cockpits that are suitable for tactile–feedback devices:

- Warnings
- Geometric information: Directions in 3D space (see also Rupert, 2001; Erp, 2000); Reference frames e.g. an artificial horizon (see also Rupert, 1999); Borders in the sky.
- Coded information, e.g. altitude, fuel supply or radar signals.
- Communication between crewmembers and members of a formation, which might be particularly useful for covert operations.

Tactile Display Example (a): iDrive Controller (BMW and Immersion Technologies)

A simple example of how haptic feedback can replace visual feedback is in the car, whilst driving. Instead of looking down at the gear stick every time one wants to change gear, our haptic feedback on the location, position and movement of the gear stick frees the visual system to watch the road ahead. Buttons and switches provide haptic feedback and even simple changes to these basic devices can have a positive affect upon safety, such as making them different shapes and textures so that they are easier to discriminate without having to look at them.

When control function can be felt, the eyes are freed and the controller does not necessarily need to be positioned within the immediate visual field. For example, the iDrive controller by BMW and Immersion Technologies uses familiar tactile sensations to represent all the car's secondary systems on one controller. This controller is highlighted in Figure 2 and the sensations (or tactile 'icons') are delivered to the fingers when they are in contact with the device.

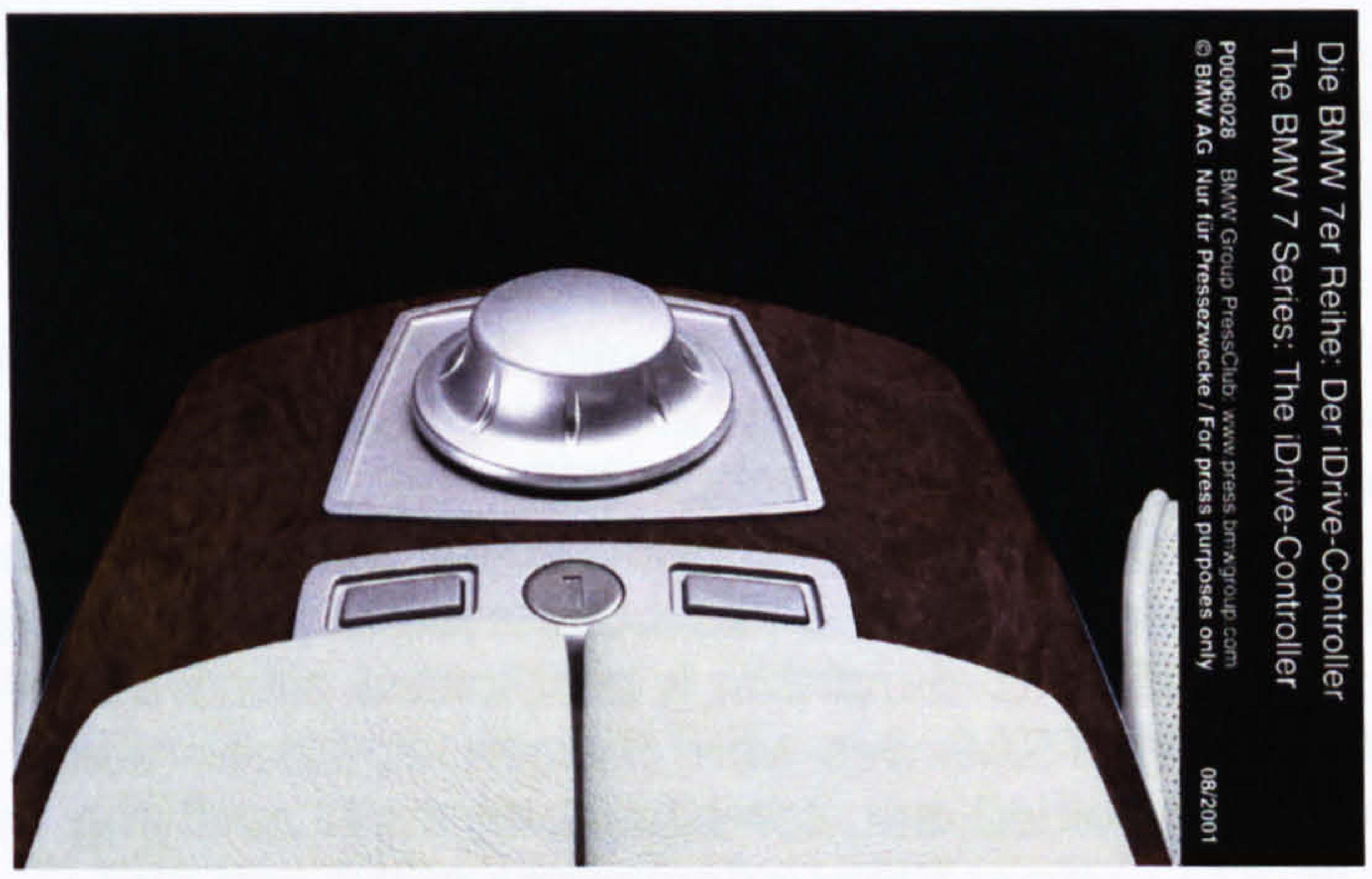

Figure 2: The iDrive Controller (Reproduced by permission of Frank Wienstroth at BMW Group, 2008)

Tactile Display Example (b): Tactile Situation Awareness System (TSAS), US Naval Aerospace Medical Research Laboratory

However, haptic devices can also replace more complex visual tasks. An interesting example is the Tactile Situation Awareness System (TSAS), developed by the US Naval Aerospace Medical Research Laboratory (NAMRL) to provide both spatial cues (for orientation or navigation) and target cues (for target detection, discrimination & tracking). It comprises a vest (worn beneath the flying suit for example), lined with vertical rows of 'tactors' (vibrating pads). These tactors vibrate to indicate directional drift as well as target type and target direction, see Figure 3. NAMRL found that pilots were able to perform flying manoeuvres blindfolded when TSAS was worn (Rupert, 2000).

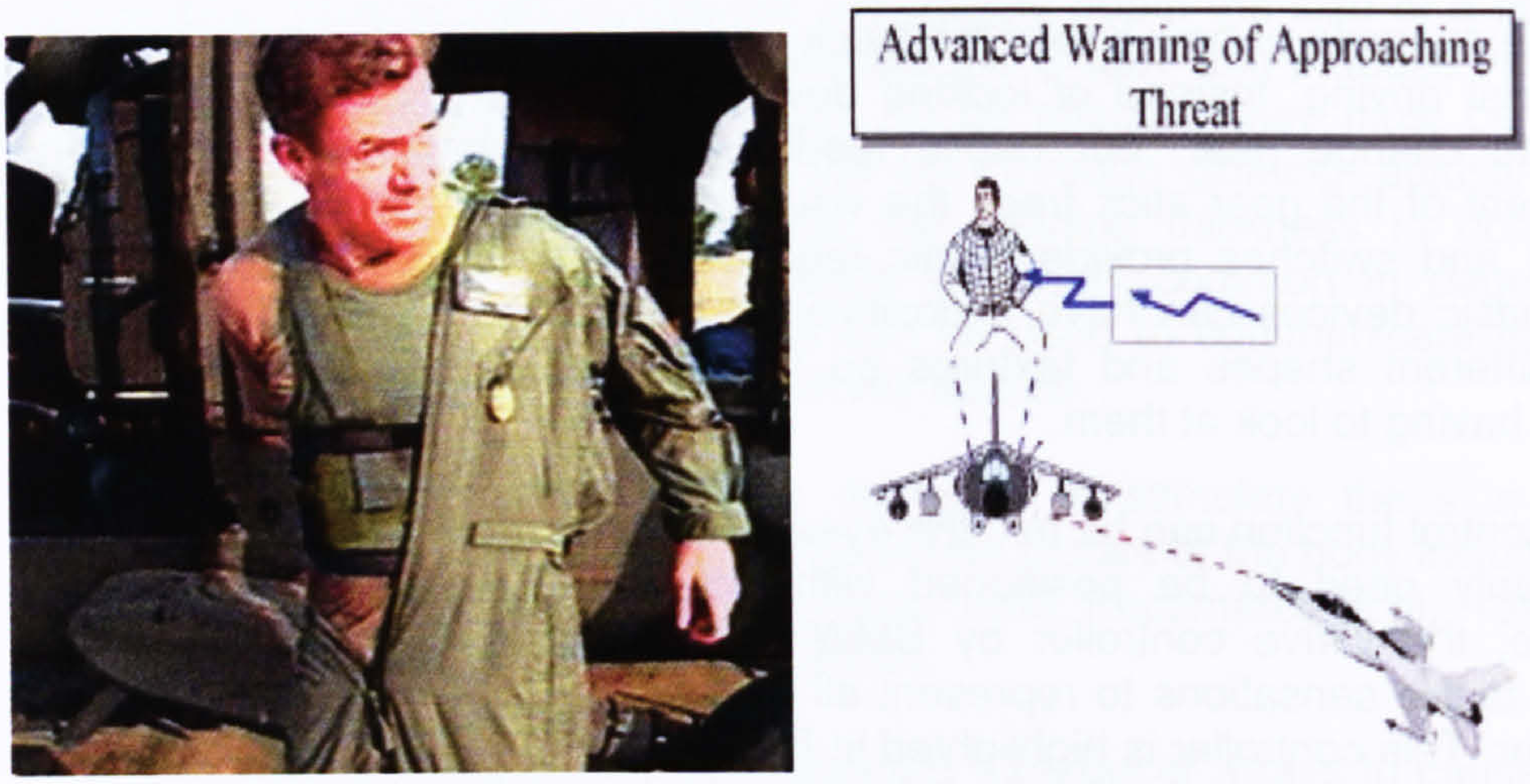

Figure 3: Tactile Situation Awareness System (TSAS), developed by the US Naval Aerospace Medical Research Laboratory (NAMRL) (with permission from Angus Rupert, 2008)

Apart from unloading the visual sense, haptic devices can also provide an extra layer of redundancy in the system. For example, TSAS has an important role to play in preventing spatial disorientation (SD), by providing orientation cues when outside visuals become diminished. Without visuals, the primary cause of SD during flight is the inability of the vestibular system to keep the pilot informed of constant motion. NAMRL found that a blindfolded pilot was able to maintain spatial orientation when TSAS was worn (Rupert, 2000). In reality, a pilot would obviously not be blindfolded but, for situations such as flying through cloud, TSAS may be able to prevent SD ever occurring in the first place.

TSAS (and presumably similar haptic devices) could be a significant step towards not only de–saturating the visual system, but towards reducing the incidence of SD by providing crucial feedback at times of increased visual workload or when outside visual cues are unavailable.

See also the navigational back display being developed by Tan et al. (Tan et al, 2003, 2000; Ertan et al., 1998).

2.2.2 Proprioceptive Displays

Proprioceptive feedback is presented in the form of displacement and/ or force feedback. Displacement devices provide positional information to the user and these vary in complexity. For example, displacement sticks in the cockpit can be linked or unlinked to the control surfaces and where they are linked, the pilot can receive flying handling cues. Anecdotal evidence suggests that linked control sticks improve situation awareness in multi–crew aircraft.

Patterson (2000) argues that Airbus replaced the conventional control sticks (situated centrally to each pilot) with sidesticks because it was perceived that the former obstructed the pilot's view of the flight instrument panel. However, as Patterson (2000) explains, because the replacement sidesticks are no longer mechanically linked to the control surfaces of the aircraft (i.e. they operate using 'fly by wire', where the only links between the controls and the control surfaces are computer cables), the pilots can no longer receive aircraft handling feedback via the controls; nor can they feel what the other pilot is doing with the controls. In theory, the pilots could be moving their sidesticks in the opposite senses without knowing. Patterson (2000) goes on to explain that this lack of haptic feedback was a factor in an incident that occurred on an Ansett A320 on 12 Aug 1991 at Sydney Airport. The aircraft passed within metres of each other and in the subsequent investigation it was discovered that the first officer was resting his hand on the sidestick and was accidentally instructing the aircraft to descend whilst the captain was instructing the aircraft to climb. As a result of these conflicting instructions, the aircraft did nothing. Because of lack of sidestick feedback, each pilot was unaware of the problem. These sidesticks also provide no feedback to pilots regarding what the autopilot computers are doing. Burgner (1997) states that in a survey by the German Pilot Association, 65% of pilots flying the Airbus A320/321, A330/340 requested improvements to sidestick feedback.

Force–feedback devices are control sticks that use mechanical actuators to actively apply specifically computed opposing and resistive forces to the user. Force–feedback has been reported to improve the performance of manual tasks (Dennerlein et al., 2000; Dennerlein & Yang, 2001; Hannaford et al., 1991; Huang et al., 2002; Repperger et al., 1995; and see Kitagawa et al., 2002 for a discussion). In addition, force–feedback was shown to improve cognitive task performance in a study by Brooks et al. (1990). Finally, force–feedback has been shown to improve the sense of realism and immersion within the virtual environment (Huang et al., 2002) and in teleoperation (Childress, 1986).

Proprioceptive Display Example (a): Turbulence Control Stick (US Air Force Research Laboratory, Wright Patterson Air Force Base)

Force–feedback control sticks can enhance situation awareness through providing flying handling cues to the pilot but they can also be used to aid pilot control in more challenging situations. A good example is the turbulence control stick system developed by the US Air Force Research Laboratory at Wright Patterson Air Force Base, which significantly reduces pilot–induced oscillations (albeit within the simulator) (Repperger, 2000).

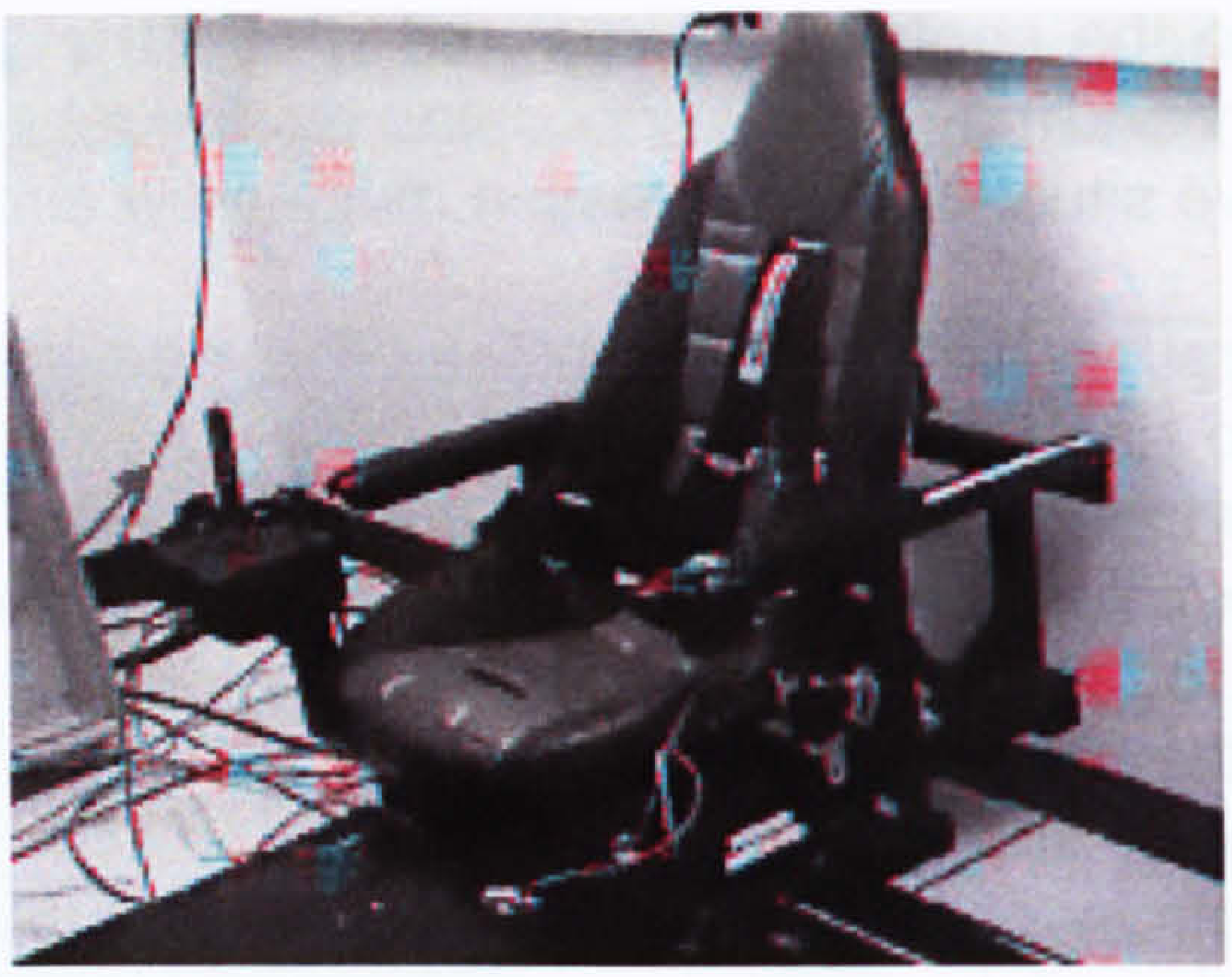

Figure 4: Turbulence Control Stick System (Reproduced by permission of Dr. D. Repperger, US Air Force Research Laboratory, Wright Patterson Air Force Base)

The same system was used to track a user's state and detect imminent loss of control of an aircraft (Haas & Repperger, 1998; Repperger & Haas, 1998; Repperger et al, 1998; Repperger, 2000). This system is able to detect imminent loss of control a few seconds before it occurs and before any warning has been issued.

Proprioceptive Display Example (b): CyberGlove, CyberGrasp and CyberForce (Immersion Technologies)

Figure 5: CyberForce attached to the CyberGlove and CyberGrasp system (Reproduced by permission of Immersion Corporation, Copyright © 2008 Immersion Corporation. All rights reserved)

CyberGlove by Immersion Technologies tracks hand and finger movements and when combined with CyberGrasp (the glove 'exoskeleton', again by Immersion Technologies) the user is able to experience realistic force feedback. This sort of technology was originally commissioned by the US Navy for teleoperation, which is the remote control of vehicles and robots, and is important because certain dangerous tasks, currently performed by humans, could be performed from the comfort of a simulator or control room. Astronauts, deep–sea divers and military aircrew will be amongst those who will eventually benefit.

CyberForce (Immersion Technologies) can be attached to the CyberGlove and CyberGrasp system to provide whole arm inertia and weight (see Figure 5). Whole arm force feedback can be used during the simulation of manual tasks such as driving, flying and picking up objects during teleoperation.

2.2.3 Other Types of Haptic Displays

Despite the fact that thermoreceptive feedback is being investigated (e.g. Jones & Berris, 2002), this evaluation focuses on the more readily available tactile and proprioceptive displays. It is possible that in the future, other haptic sensations such as pain, tickle or itch will be exploited for their alerting potential but whether that is desirable is a matter of opinion.

2.3 Further Arguments for Haptic Displays

The haptic sense is not as well understood as the visual or auditory senses. There are only a few groups who have current research programmes in this area (Veen & Erp, 2001). However further arguments for haptic devices in the cockpit can be summarised as follows.

2.3.1 Improved Responses with Tactile Alerts

As with TSAS, most haptic displays are used mainly to support continuous tasks such as spatial orientation and navigational guidance (Christensen, O'Donnell, Shingledecker, Kraft, & Williamson, 1986; Gilliland & Schlegel, 1994; Malcolm, 1984; Weinstein & Wickens, 1992; Zlotnik, 1988). However, little is known about the effectiveness of haptic feedback for supporting data–driven attention allocation in case of unexpected discrete changes and events (Sarter, 1995).

Sklar and Sarter (1999) make a start in this area by comparing performance using visual feedback to tactile feedback, as well as to visual and tactile feedback together, on the same task. The task was to monitor and respond to 'mode transitions', whilst concurrently performing normal flight procedures in the simulator. Mode transitions were indicated using visual–only alerts, tactile–only alerts, or a combination of visual and tactile alerts. In the tactile–only condition, accuracy was 100% and reaction time was faster than in the visual–only condition, where accuracy was only 83%. When tactile and visual feedback was given at the same time, accuracy was 100% and reaction time as fast as in the tactile–only condition.

These results indicate that this tactile feedback was not only a valuable *alternative* to visual feedback but that it was a valuable *addition* to visual feedback as well. The results also suggest that no interference occurred when participants were asked to process the tactile and visual feedback at the same time — on the contrary; performance was raised to the level of the better single feedback condition out of the two.

With regards to performance accuracy during surgery, the benefits of haptic feedback have been quantified using medical simulators. For example, in the absence of haptic feedback the number of errors that damage tissue increases by a factor of three (Wagner, et al., 2003).

2.2.2 Omni–Directional Feedback

The huge amount of information that is presented to the pilot is predominantly offered using visual displays. The structural limitations of the visual sense provide a design constraint in the development of new cockpits. For example, like the auditory sense, the haptic sense is omnidirectional, which means it can process information from any direction (like having eyes in the back of the head, elbows, soles of the feet etc.; inside and out). Whereas the visual sense has 200–degree peripheral coverage and two–three degree movable cone of focus, assuming there is sufficient light and the eyes are open! This makes both the auditory and haptic senses useful for picking up information from any direction, for example warnings and any spatial information. However, the auditory sense is not very reliable when it comes to discriminating the spatial origin of a sound (Williams, 2002), giving the haptic sense a distinct advantage on this front.

2.2.3 Enhanced Operation of Controls

Pilots must wear gloves during flight and anecdotal evidence suggests that the loss of tactile feedback through the gloves makes it more difficult to operate the increasing number of buttons and switches on the control stick. A simple use of tactile feedback is shape encoding of manual controls, such as those standardized in aircraft to control landing flaps, landing gear and the throttle, (Chapanis & Kinkade, 1972).

Shape encoding is particularly important if the operator's eyes cannot leave a primary focus point or when operators must work in the dark. However, sometimes shape encoding is not possible. In particular, anecdotal evidence suggests that the gloves hinder control of the 'mouse' toggle button, a more recent addition to the control stick in modern aircraft.

Haptic gloves that increase tactile feedback to the user could solve this problem. There is evidence that the addition of tactile information reduces response times in interactive systems (Nelson, McCandlish, & Douglas, 1990). When tracing the shape of an object with the fingertip, for example, the addition of tactile information leads to increased velocity in finger movements, and, implicitly, reduces the visual load in completing tasks (Akamatsu, 1991; Akamatsu et al., 1995). The cumulative benefits of tactile feedback may be quite substantial.

2.2.4 Haptic Feedback Is Less Likely to be Missed

The haptic sense cannot be 'switched off', unlike the eyes that can be shut and the ears that can be shielded. For example, even by wearing thick gloves, we might prevent haptic feedback from the outside to the hands, but the hands would still be receiving constant haptic feedback — from the gloves and from the outside *through* the gloves. This factor makes the haptic sense particularly useful for providing warnings, for example, as they are less likely to be missed. The caveat of course is that any haptic feedback must be tailored so that it can be transmitted through any clothing such as gloves.

Haptic memory is comparable to visual and auditory memory in that the memory of haptic stimuli fades after exposure to the stimuli (Gilson & Baddeley, 1969). Haptic memory decay generally begins to fade after fifteen seconds (Gilson & Baddeley, 1969) or longer (Kiphart et al., 1992). This can be contrasted to visual memory, which begins to fade after between one and two seconds, and to auditory memory, which begins to fade after roughly four seconds (Pritchard, 2000). These findings suggest that haptic memory is relatively extended and provide another reason why haptic feedback is less likely to be missed than auditory and visual feedback.

2.2.5 Input Distractibility and Input Secrecy

The auditory sense has an intrinsic attention grabbing quality. This and the fact that it is omnidirectional (one does not have to be looking in a particular direction to pick up auditory inputs) make it far more suited for warning systems than the visual sense. However, the attention grabbing nature of the auditory sense means that discrete information delivered through this sense tends to be more distracting than the same discrete information presented visually — even when the task at hand is a visual one (Wickens & Liu, 1988; Latorella, 1998; Helleberg & Wickens, 2002). It is possible that discrete information delivered through the haptic sense might be less distracting to the primary task than auditory alerts and this would be beneficial because the haptic sense is also omnidirectional as mentioned previously. However, this has yet to be confirmed.

Haptic alerts are more covert than visual and auditory alerts. They have potential in situations when light and noise are either unavailable or undesirable. Haptic displays can be hidden beneath clothing and in theory do not require an individual to alter their gaze or interrupt their conversation/ listening in order to monitor them. Again, the covert potential of haptic displays needs formal investigation.

2.2.6 Tolerance to High G–Loads

High positive or negative G–loads, such as those experienced by fighter pilots and astronauts, can degrade visual perception, as normal blood circulation is interrupted. For example, while some pilots can tolerate up to nine positive G–loads, loss of peripheral vision is not uncommon at sustained three–five positive G–loads (Shwartz, 2002). If the situation is not corrected, loss of colour vision will follow and finally the whole visual scene will turn white then black (Post et al, 2000). This is an indication that loss of consciousness is highly likely, but with the degraded visual perception, situation awareness is compromised, just at a point when effective corrective action is most critical.

However, Veen and Erp (2001) found that the perception of tactile feedback is 'not substantially impaired during high G–load conditions, at least up to six positive G–loads', with and without 'a pressure suit and extended straining' (Veen and Erp, 2001). This has implications for providing the pilot with the information he/ she needs to remain 'in the loop' during high G–loads, when visual perception is degraded and there is imminent risk of loss of consciousness.

Incidentally, negative G–loads also affect visual perception due to burst blood vessels in the eye, causing vision to turn red, and this is not uncommon during sustained two–three negative G–loads (Brothers, 2004). Note, however, that no research has been conducted into tactile perception under high negative G–loads.

2.2.7 Three–Dimensional Representation of Spatial Information

The visual view of the outside world from inside the cockpit is limited. Camera–monitor systems have their own restricted field of view and also present a new set of challenges. Haptic displays, such as TSAS, could provide uninterrupted representation of three–dimensional space.

Visual information can be difficult to interpret, for example, when representing spatial information (which is three–dimensional) on a two–dimensional visual display. Presenting such information to the skin might reduce those interpretation problems. The surface of the skin is a two–dimensional surface but it is also a 'closed manifold embedded in a 3D space (sphere topology)' (Veen & Erp, 2001). The skin may therefore be used to represent three–dimensional spatial relations, for example direction, in a far more intuitive way. Note that the haptic sense is an internal as well as external sense (effectively three–dimensional) and that haptic stimulation of any part of the body is felt 'through' the body towards the opposite side. Despite this haptic localisation is reliable even on the body's least sensitive regions, such as the back (Tan et al., 2003) and is superior to auditory localisation as mentioned earlier.

2.4 Haptic Workload Capacity is Unknown

The temptation may be to put as much information through the haptic sense as possible. For example, NAMRL have expressed interest in using TSAS to present both target and navigation information at the same time (Rupert, 2001). This would be possible by using variations in vibration rhythms to convey target–related information, while providing navigation– or orientation–related information through varying vibration frequencies and positions on the device. However, this would constitute two concurrent haptic tasks and it is feasible that this device would be used in conjunction with another haptic device, such as a force–feedback stick, which would constitute three concurrent haptic tasks.

The makers of TSAS claim that the tactile cues employed are so intuitive they do not require any workload capacity (Rupert, 2001). However, this seems unlikely to be the case, as even automatic information processing has been found to take up some level of capacity (Moray, 1988). In fact the findings relating to the influence that TSAS has upon workload are inconclusive: Raj et al. (1999) found that Pilots reported reduced workload when using TSAS, whereas, Cheung et al. (2004) found no significant reduction in Pilots' perceived workload when using TSAS.

It is important to emphasise that the workload capacity of the haptic sense is unclear as virtually all research into workload and sensory–related information processing limitations has been conducted using visual and auditory inputs. Furthermore, as mentioned above, the ears and eyes can be covered but there is no way of switching the haptic sense off and, due to this there is probably no way of fully limiting what is received by the haptic sense. Little is known about the mechanisms governing haptic selectivity and focus. Therefore it may be even more vulnerable to overload than the visual sense, which can be easily focused and its inputs limited. Even if the haptic devices employed do provide inputs that remain within haptic workload limits, the addition of extraneous cues that cannot be controlled or switched off may cause an overload. Extraneous cues include turbulence, gravitational and acceleratory forces, background vibration etc. Finally, an inability to selectively focus on one information source means that other haptic cues (such as extraneous cues) may divert the user's attention and affect haptic workload and haptic–related situation awareness.

Because it is not clear whether tactile and proprioceptive displays utilise the same sense or different senses, and whether this matters or not (see Sections Three and Five for more on this issue) it is not possible to make sensible decisions about what and how many haptic displays to expose the user to. In addition, it is also not certain what impact (if any) haptic displays will have upon visual and auditory information processing.

As such there is a real need to address the workload implications of introducing haptic devices into the cockpit.

2.5 Summary

Modern aircraft place great emphasis on the ability of the pilot to extract visual information from multiple visual displays and visual display modes. There is a growing concern that this situation leads to visual overload. Automation is not the ideal solution as this is associated with a kind of overload called cognitive overload, where the pilot must interpret what is going on from changes happening automatically out of their control. This can lead to 'automation surprises' where something apparently unexpected occurs and the pilot temporarily loses situation awareness.

Loss of situation awareness can have serious consequences, including 'controlled flight into terrain' (CFIT) accidents, which occur when pilots inadvertently fly their aircraft into terrain. In the commercial aviation world they are associated with instrument meteorological conditions (Taneja, 2002). However, despite technological advances related to forecasting and displaying of weather hazards and increases in the number of pilots who are instrument rated, CFIT accidents continue to be the primary cause of aviation fatalities. CFIT accidents in military aircraft tend to occur in visual meteorological conditions and this suggests that poor outside visibility cannot be the primary cause of these types of accidents. Analyses by Moroze and Snow (1999) support this notion and suggest that 75% of CFIT accidents are associated with factors relating to loss of situation awareness, despite the presence of visual and auditory terrain avoidance warnings.

Missed auditory warnings, spatial disorientation, channeled attention and overload of the visual sense were highlighted as issues directly related to loss of situation awareness. Haptic displays already exist that provide continuous situation feedback to the pilot, to prevent spatial disorientation and to free up the visual system (see: McGrath et al., 1998; McTrusty & Walter, 1997; Raj et al., 1998; 2000; Rochlis & Newman, 2000; Rupert, 2000; Rupert et al., 1999; 1994; 1990). It could therefore be expected that installing such a device into the cockpit would reduce the occurrence of CFIT accidents.

There are essentially two types of haptic display, tactile and proprioceptive displays. Tactile displays provide feedback in the form of vibrations and proprioceptive displays provide feedback in the form of force–feedback. For pilots, tactile devices such as TSAS (NAMRL) can offer real solutions to the challenges of overload, spatial disorientation and ensuring situation awareness at all times. TSAS is uncomplicated, easy to learn to use and pilots comment that they feel safer with the tactile cues than without them (McGrath et al., 1998; McTrusty & Walter, 1997; Raj et al., 1998; 2000; Rochlis & Newman, 2000; Rupert, 1999; 2000; 2001; Rupert et al., 1999; 1994; 1990). On the other hand, proprioceptive displays have been shown to improve control accuracy (for example, the turbulence control stick developed at AFRL, WPAFB) during extreme weather conditions. A simple form of proprioceptive feedback that could be re–introduced into cockpits is linked controls, which provide aircraft handling cues to the pilot and inform pilots of control actions taken by each pilot and by the autopilot system. Linked controls move in synchrony with the associated aircraft control surfaces and incidents have occurred in which unlinked controls were implicated as a causal factor.

The haptic sense can provide 360 degree, 3–dimensional, continuous coverage and haptic cues can be coded to supply complex as well as simple information. Because haptic displays do not require light or sound they are more discrete and could help move towards the windowless cockpit. They can be worn on the torso and this frees up the eyes and hands. Protective clothing that normally dulls sensation could hypothetically be modified to contain tactile 'tactors', so that feedback is regained. Plus, haptic perception is not as impaired by high G as vision is (Veen & Erp, 2001).

However, because we cannot switch the haptic sense off, it is not easy to selectively limit or focus haptic attention. This may be a problem, considering haptic information processing capacity is unknown; no matter how intuitive a device is, it is still likely to require some level of processing capacity. In addition, the characteristics and capacity of haptic workload capability is relatively unknown compared with the visual and auditory senses.

With these concerns in mind, it is important to choose haptic displays where benefits have been demonstrated and human factors issues fully explored. Conversely it is equally important that the potential benefits of haptic devices are not ignored simply because there is much work to be done in the process of confirming their effectiveness and safety. This is especially important in light of research findings into the primary causes of aviation fatalities, and the potential preventative benefits of haptic displays and multi–sensory information presentation.

The focus of this thesis is (a) to try to establish whether tactile and proprioceptive tasks share information processing 'resources' and (b) whether they share information processing resources with the visual and auditory senses. This is important so that sensible decisions can be made regarding what and how many haptic displays can be presented to the user at the same time and what effect these haptic displays may have (if any) upon visual and auditory information processing.

The next section discusses cognitive psychology theories of workload and the factors that determine overload, including the role of shared versus independent sensory information processing 'resources'.

3 Workload & Theories of Dual–Task Performance

3.1 The Concept of Workload

Excessive workload is of ongoing concern in human–computer interaction research and development. 'In order to evaluate [existing and] alternative solutions in system design, it is often deemed necessary to measure not only system performance, but also human operator workload' (Johannsen, 1979).

Jahns (1973) argued that workload has three defining elements:

- Task input characteristics, quantity and level of difficulty
- Operator effort and allocation of effort between tasks
- Task performance (the actual outcome)

This understanding of workload is also proposed by Rohmert (1971 & 1973), Rohmert and Laurig (1972), and Rolfe and Lindsay (1973).

Using this definition of workload it becomes obvious that the only element a display designer has any direct control over is task input. Operator effort can be affected by task input but is to a great extent under the control of the operator. Task performance is the result of both input and effort. Therefore it is crucial that designers aim to minimise aspects of task input that may increase workload as much as possible to maximise task performance.

One obvious way of assessing the effect of input on workload is in terms of performance. However, as mentioned above, task performance is a result of both input load and effort. For example, the same operator can perform equally well on two separate tasks even though one task may be more difficult than the other, simply by increasing effort on the more difficult task. Therefore, when using a performance measure to assess the effect of input on workload, it is crucial for designers to control operator effort.

Workload utilises cognitive and behavioural resources and these resources are made available to the user largely through the mechanisms governing information processing in the brain. Research in relation to information processing and workload requires an understanding of the area of attention and some notes on this area are provided in the Section 3.1.1.

When it comes to assessing workload using performance, it is common to ask the user to perform two tasks at the same time. When it is possible to perform one dual–task combination but not another dual–task combination, inferences are made about information processing limitations based upon how the dual–task combinations differed from each other. For example, perhaps one of the dual–task combinations featured same sense inputs whereas the other combination featured different sense inputs; the inference might be made that performance suffered due to sense input characteristics.

Over the years various theories have been developed based upon this methodology that try to explain why some tasks and task combinations are more difficult to perform than others, thereby determining workload. These theories are discussed in Section 3.2.

3.1.1 Attention

William James (1890), stated:

'Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others...'

It is generally agreed that attention is fundamentally involved in information processing and it is also generally agreed that attention has a limited capacity at any one time. Since the 1950s attention has been likened to the 'searchlight' (for example, see Broadbent, 1958) and, based on this paradigm, most research has focussed on either investigating the characteristics of the associated information processing limitations or the 'location' of these limitations within the information processing 'architecture' (Allport, 1993a). It is the former that is the concern of this thesis.

Research into the characteristics of attentional information processing limitations tends to fall into four separate but related areas:

- Selective Attention (the selection, for further processing, of sensory inputs and central processing 'events' over other inputs and events e.g. the selection of congruent over incongruent inputs and events; the 'selecting out' of stimuli that predict nothing of any relevance i.e. habituation (Balkenius, 2000).
- Focused Attention (the ignoring of certain inputs and events in order to focus on inputs and events associated with the chosen task).
- Divided Attention (the concurrent monitoring and processing of inputs and events associated with two or more tasks).
- Sustained Attention (the process of attending to relevant inputs and events for a sustained period of time).

Because, this thesis is concerned with attentional capacity (specifically, how many and what tasks can be performed at the same time), it falls into the area of divided attention. Not surprisingly, the technique commonly used to explore divided attentional limitations is the dual-task technique, and an overview of the relevant dual-task theories is provided in Section 3.2.

It is common within the literature to identify two main types of attentional information processing, bottom-up and top-down. Bottom-up processing suggests feedforward transfer of information from receptor to initial cortical sites and then to later cortical sites and traditionally, these initial cortical sites have been seen as uni-sensory sites, whilst the later sites have been seen as the multi-sensory sites. Top-down processing suggests feedback transfer of information from later cortical sites to earlier cortical sites or direct from the later cortical sites to output production. Most theories and models of attentional limitations assume bottom-up processing to be the predominant 'direction' of information transfer and this is coupled with the assumption that the first stage of information processing is conducted in a unisensory manner. However, this relatively limited view of information transfer has been questioned by recent research and this is the focus of Section Four.

Finally, a note on controlled versus automatic attention. Controlled processing is believed to be serial in nature, slow and limited by short term memory; it 'requires subject effort, permits a large degree of subject control, but needs little training to develop' (Schneider et al., 1982). On the other hand, automatic processing, or automatisation, is believed to involve parallel processing and is fast and not limited by short term memory; it 'uses little subject effort, permits little direct subject control, but requires extensive and consistent training to develop' (Schneider et al., 1982). Most research and theory of attentional limitations assume that controlled attention is taking place and practice effects are controlled as much as possible to prevent automatisation occurring. This applies in this thesis and, although dual-task comparisons involve repetition of individual tasks within different dual-task combinations, there is little evidence to suggest that practice effects are transferable between dual–task combinations.

3.2 Theories of Dual–Task Performance

As mentioned, theories of dual–task performance attempt to explain why workload may be exceeded under certain circumstances but not under others by examining what tasks we can and cannot perform within the same time period. What is common to all theories of dual–tasking is that the performance difficulties that can arise during a dual–task are a result of limited information processing processes or resources.

3.2.1 Single–Channel Theories

The single–channel theories (Craik, 1947; 1948; Hick, 1948; Vince, 1949; Welford, 1952) suggest that there is only one information processing 'channel' or 'resource' but that this channel can be time–shared between tasks. This view implies that information processing is serial in nature, even though it is possible that neither task needs to use 100% of the available channel at any single point of time (Heuer, 1996). According to these theories, dual–task performance depends upon timing and sequencing and it may not be possible to perform the respective tasks in the time available.

This theory was devised based on the Psychological Refractory Period (PRP) phenomenon (Telford, 1931), which suggests that when two inputs occur in close succession, the first will interfere with the second due to its basic processing requirements. This is closely related to the attentional blink phenomenon, where each input requires a certain time frame to itself before the next input can be processed; if the second input is presented before the first has been processed then the second input is not processed fully or at all (Duncan et al., 1994). This is discussed further in Section 3.2.4. Often the PRP does not cause the second target to be lost altogether and Welford (1952) suggested that inputs not attended to immediately are held in a temporary 'store'.

Welford went on to suggest that separate functions could be performed in parallel, such as input processing, choosing a response, and control of the chosen response, while processing within each of these functions was performed in a serial manner. This did not change the basic premise that two task inputs could not be processed at the same time, causing dual–task interference.

However, it is important to note that dual-task performance decrements may not always be due to limited information processing resources. Norman and Bobrow (1975) suggested the term 'resource-limited' to describe tasks that improve with increased allocation of resources and the term 'data-limited' to describe tasks that do not improve with increased allocation of resources because information quantity or quality is insufficient. The 'most thorough way of investigating resource usage in dual-task performance is by constructing a Performance Operating Characteristic' (Wells & Matthews, 1994, p. 25), which is described in more detail in Section Five. Participants 'perform a pair of tasks, under a variety of instructional priority conditions. If the tasks share a common resource, prioritisation of one task can only be achieved by diverting resources from the other' (Wells & Matthews, 1994, p. 25). Thus, there will be a performance trade-off between the two tasks. However, if the tasks are data-limited and resources are not shared, then performance improvement or decrement in one task will not be accompanied by performance decrement or improvement (respectively) in the other task.

In fact, task performance decrement suggestive of resource limitations appear to be related to task similarity. For example, dual–task findings suggest that it is possible to perform two tasks at the same time if the tasks do not share input sense or output modality:

- Allport et al. (1972) showed that pianists could sight–read music (visual input plus manual output) at the same time as shadowing (verbally repeating) dictated text (auditory input plus vocal output).

- Hirst et al. (1980) showed that reading aloud written text (visual input plus vocal output) and writing dictated text (auditory input plus manual output) could be done at the same time.
- Trumbo and Milone (1971) showed that manual tracking of visual inputs could be performed at the same time as vocal responses of auditory inputs but not so well with manual responses to the same auditory inputs.
- McLeod (1977) showed that a manual tracking task could be performed relatively easily with a vocal reaction time (RT) task but not so easily with a manual RT task.

Heuer (1996) suggests that the most plausible explanation is a model that accepts 'the existence of structural interference' related to the 'functional specialisation of the cerebral hemispheres' (Heuer, 1996). This is a view shared by Springer and Deutsch (1981) based on the premise that the left hemisphere is associated with verbal processing and the right hemisphere is associated with more manual processing. See Friedman and Polson (1981) for more on this view. However, it is not really possible to explain the visual versus auditory input effect using this theory.

In support of these findings, Duncan et al. (1997) showed that the attentional blink phenomenon (described in Section 3.2.4) occurs when inputs are of the same sense (i.e. all visual or all auditory) but does not exist when inputs consist of different sense inputs (i.e. one visual and one auditory). This implies that parallel processing is possible when the stimuli require separate sensory processes or structures.

Therefore, dual-task findings are not particularly supportive of Single-Channel Theories.

3.2.2 Multi-Channel Theories

Multiprocessor theory (Allport et al., 1972) attempts to explain the importance of task similarity to dual-task interference through 'a set of independent channels (or processors)... that work in parallel' (Heuer, 1996). It suggests that dual-task interference occurs when the tasks in question use the same processors because these tasks will need to be time-shared. This theory is able to account for the dual-task findings mentioned above by suggesting that different sense inputs require different processors and therefore can be processed in parallel but same sense inputs require the same processor and must be processed serially (time-shared), which can result in performance decrements. The same applies to output modalities.

However, the dual-task facilitation effect (Heuer, 1996, 1990; Duncan, 1979; Chernikoff et al., 1960; Chernikoff & Lemay, 1963; Fracker & Wickens, 1989) cannot be easily explained by multiprocessor theory. Heuer (1996) explains that this less common effect occurs when tasks of a similar type (e.g. they are both visual) seem to benefit when they are 'in some way supported by identical or coordinated rather than competing processes.' See Section Four for the neuroscientific findings and theories surrounding this effect.

Multiple–resource theory (MRT) explains the fore–mentioned input sense and output modality effects in terms of resources. MRT suggests that each input sense has its own resource, each output modality has its own resource and therefore different inputs or outputs can be processed in parallel without any difficulty. See Section 3.2.3 for other MRT 'rules'. Performance suffers when the same resource must be utilised by more than one task at a time and the *capacity* of this resource to process the multiple *parallel* inputs is exceeded. Dual–task interference is taken as indication of shared resources, whilst little or no interference is taken as indication of independent resources.

In this light, Navon and Gopher (1979) suggest that the dual–task facilitation effect can be explained by distinguishing between 'fixed proportion and variable–proportion functions, where the former refers to fixed capacity for each resource and the latter to 'borrowing' of capacity between resources where required' (Heuer, 1996). However, it is unclear how this is explicable in neuroscientific terms.

The most prominent multiple–resource theory is Wickens's Multiple Resource Theory (MRT) model (Wickens, 1980, 1984), which is described in more detail in the next section.

3.2.3 Wickens's Multiple Resource Theory (MRT) Model

According to Multiple Resource Theories (MRT) a workload resource is a hypothetical entity that is necessary for task performance. When performing two tasks at the same time (e.g. walking and map–reading), it might be assumed that trying harder (using more of that hypothetical workload resource) improves overall performance. However, this is not always the case and proponents of MRT argue that this is because the workload resource has limited capacity (see for example, Allport, 1980; Kantowitz & Knight, 1976; Kinsbourne & Hicks, 1978; McLeod, 1977, Navon & Gopher, 1979; Wickens, 1980). Thus, allocating more effort to task one may mean less of that resource is available to allocate towards task two, and therefore performance on task two is likely to suffer. Similarly, more effort on task two may mean that performance on task one suffers.

Generally, manipulations of task effort are achieved through varying task difficulty. However, it is sometimes the case that increases in task one difficulty (thereby necessitating increased effort on that task) do not affect task two performance (and vice versa). MRT advocates, such as Wickens (1980) suggest that this is due to there being multiple workload resources as opposed to a single workload resource. He explains that when changes in dual–task effort affect performance, this is because the tasks share the same workload resource(s).

Conversely, Wickens (1980) suggests that when these changes in task effort do not affect performance, this is because they do not share the same workload resource(s).

These notions are supported by further dual–task studies that find:

- Often there is virtually no dual–task interference (i.e. each task performs as well in the dual–task condition as in their respective single task conditions).
- When dual–task interference occurs, altering dual–task input sense, without altering difficulty, often results in reduced interference.

Wickens's MRT model (Wickens, 1980, 1984, represents these multiple resources in terms of the following dimensions (see Figure 6):

1. **Stage** of processing (**perceptual & central** versus **response**)
2. **Sense** of input (**visual** versus **auditory**)
3. **Code** of processing (**verbal** vs. **spatial**)
4. **Response** modality (**manual** versus **vocal**)

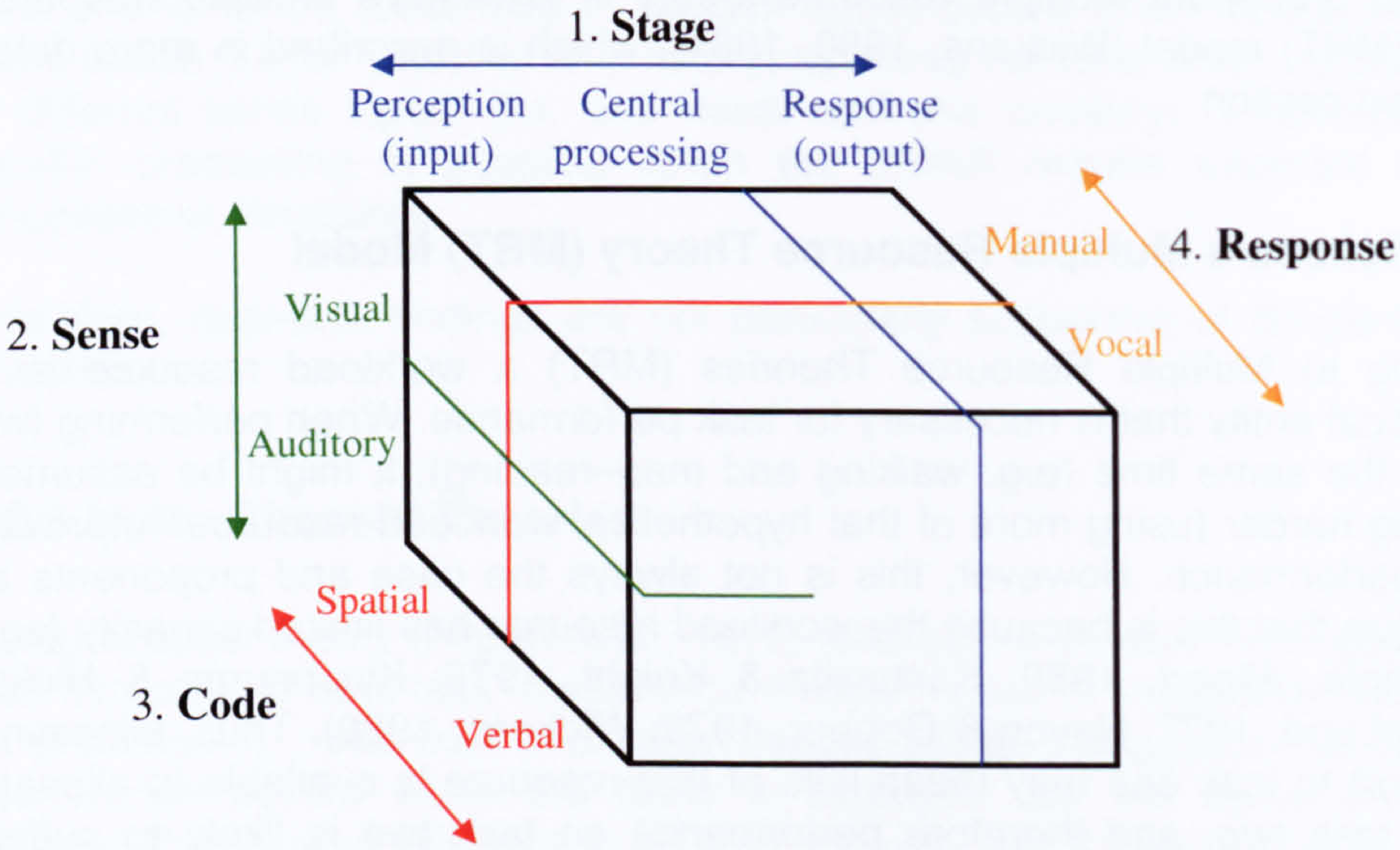

Figure 6: The Multiple Resource Theory (MRT) Model (Wickens, 1980, 1984)

Wickens (1980, 1984) suggests that:

- When resource demands overlap then increasing the difficulty on one task will cause performance on the other task to deteriorate.
- When resource demands are different then increasing difficulty on one task will *not* cause performance on the other task to deteriorate.

- When resource demands partially overlap (e.g. tasks require the same sensory resources but not the same code or response resources), then increasing difficulty on one task will cause performance on the other task to *partially* deteriorate.

Partial deterioration simply means that some deterioration has occurred but not as much as the deterioration associated with total overlap of resources. It is obviously a relative rather than an absolute concept and is easier to explain when dual–task performance is represented on a performance operating characteristic (POC) curve (see Section Five for more on this).

Studies on stage–defined resources support the notion that perceptual and central processes rely on one resource and response production on another resource. For example, it is found that response difficulty can be manipulated in one task, with no affect on the other task when the latter is a perceptual/ central processing task (Isreal et al., 1980 (a, b)). However, it has been found that when perceptual/ central processing difficulty is manipulated, this has an affect upon performance of a second task when the latter task is also a perceptual/ central processing task (Isreal et al., 1980 (a, b)). Therefore, increasing workload at the response stage should not affect workload at the perceptual & central processing stage and vice versa. More support for stage–defined resources comes from Shallice et al. (1985).

Perceptual/ central processing tasks are defined by input sense and processing code.

The following is evidence of support for sense–defined resources:

- It has been repeatedly shown that we can perform dual–tasks where one task is visual and the other is auditory, but have great difficulty when both of the two tasks are either visual or auditory (e.g. Allport et al., 1972).
- Numerous studies have shown that multi–sensory dual–tasks are easier to perform than same–sense dual–tasks (e.g. Parkes & Coleman, 1990)

However, regardless of this, one also has to be aware of possible interference, through scanning–related delays if the two tasks are too far apart, and through the effects of masking if the two tasks are too close together (Wickens & Liu, 1988).

Evidence of code–specific resources shows that when a visual task and an auditory task share processing code resources (i.e. they are both spatial or both verbal (verbal equivalent in the case of visual tasks e.g. text)), partial deterioration of performance occurs (see Wickens, 1992; Polson & Friedman, 1988 for more on this).

Kinsbourne and Hicks (1978) suggest the processing codes relate to the two hemispheres. This can be explained as follows: 'The two types of (processing) codes bear an obvious relation to the two cerebral hemispheres. Processing of verbal material is closely associated with left hemisphere activity, while the right hemisphere seems to have a prominent role in the processing of spatial material' (Heuer, 1996).

A similar argument has been made for the manual and vocal response modalities that define the response stage of Wickens's model (i.e. that manual responses rely upon spatial processing and therefore the right hemisphere, while vocal responses rely upon verbal processing and therefore the left hemisphere). For more on the evidence for manual versus vocal response modalities see Martin (1989); McLeod (1977); Tsang and Wickens (1988); Vidulich (1988); Wickens (1980); Wickens and Liu (1988); Wickens et al. (1983).

Recently, Wickens added another dimension to the model, the notion of visual channels; focal versus ambient (Wickens, 2002); see Figure 7. This accounts for certain situations where it is possible to perform two visual tasks at the same time i.e. a focal and a peripheral (ambient) visual task.

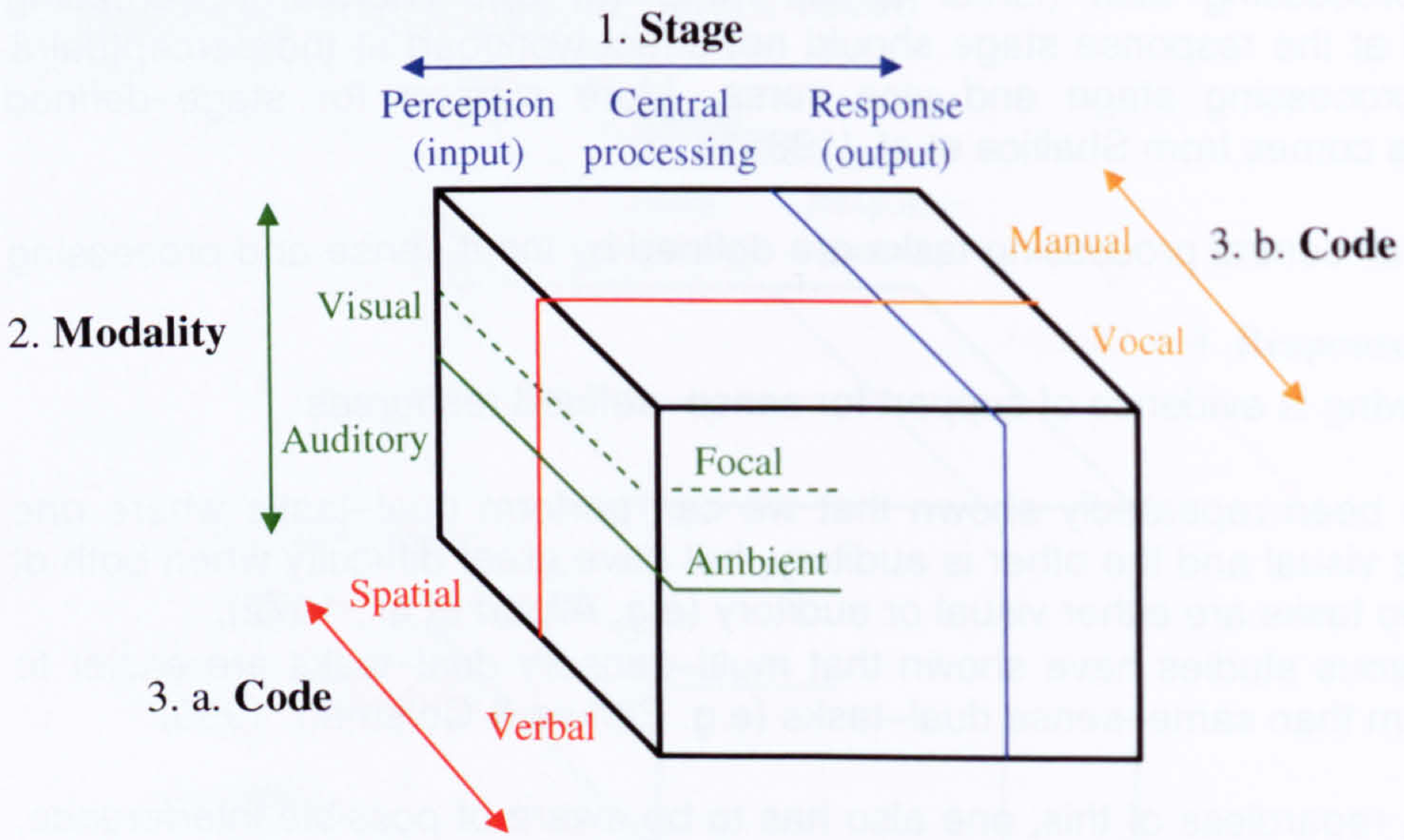

Figure 7: The Multiple Resource Theory (MRT) Model (Wickens, 2002)

Wickens's MRT model is a useful framework from which predictions about dual–task performance interference can be made. These predictions could have significant impact in the area of human–computer interaction in the cockpit because it is an environment in which there are multiple displays (currently mainly visual and auditory displays) that require spatial and verbal type processing and in which the operator must respond using both the manual and vocal modalities.

However, it is worth mentioning that Loftus et al. (1979) found interference occurred between an audio/ verbal task and a visual/ spatial task, despite opposite predictions based on Wickens's MRT model. Assuming methodology was not an issue in this study, these results suggest that other factors were at work, which the MRT model does not at present accommodate for. See Section Four for the neuroscientific perspective on multi–input processing.

It is also notable that Wickens's MRT model does not include haptic inputs and therefore, although it is possible to make inferences about incorporating haptic displays based upon the principles behind the MRT model this still needs investigation. Section One highlighted the uncertainty about whether tactile and proprioceptive haptic sub–senses should be considered separate senses in their own rights. Without knowing whether tactile and proprioceptive inputs can be treated as separate senses or not it is difficult to know for certain whether, within the framework of this model, they will share resources or utilise separate resources.

The next section on the Attentional Blink describes a phenomenon that appears to lend support for Wickens's MRT model, particularly the notion that spreading inputs across the senses will aid information processing and therefore keep workload to an acceptable level.

3.2.4 The Attentional Blink Phenomenon

Alongside the dual–task performance research mentioned so far, psychophysical research into the Attentional Blink phenomenon contributes greatly to the understanding of multi–input processing and therefore a review of these findings is relevant to this thesis.

Any dual–task limitation ultimately has its basis in our neurophysiology. Often it is obvious where these limitations lie; some tasks are physically impractical to perform at the same time. The physical constraints of the body mean that certain nerve fibres have been selected through evolutionary processes over others (Heuer, 1996). The larger the diameter of the nerve fibre the faster the nerve impulse can travel (although myelination of smaller fibres increases this speed to some degree); in parts of the body that are small in size and densely innervated (such as the fingers for example), there is an associated limitation as to how large in diameter the nerve fibres can be and therefore a limitation as to how quickly impulses can travel to the brain from the sensory receptors. Distance from the brain is also a factor; for example, nerve impulses have further to travel from the feet than from the hands and therefore take more time (albeit in terms of milliseconds).

These factors have a direct bearing on our information processing capabilities. For example, Heuer (1996) goes on to state that the control system in the brain is particularly adapted to the temporal constraints of the peripheral nervous system and that, as a result, our effectors (e.g. hands or feet) cannot be driven by high frequency impulses if the resulting action is to be useful. This is supported by studies (Johnston et al., 1970; McLeod, 1973; Trumbo & Milone, 1971) that show how dual–task performance decrements are particularly pronounced when *responses* to tasks must be made at the same time. Wickens's Multiple Resource Theory encapsulates this using the resource metaphor; the theory suggests that output mechanisms require distinct 'resources' that are separate from input and central processing resources. Wickens's labelled these output resources as either 'vocal' or 'manual' and suggested that performance will suffer if two responses requiring the same kind of resource must be realised at the same time (Wickens, 1980, 1984; Wickens et al., 1984).

There are also temporal limitations to the process of attention. Stimulus onset asynchrony (SOA) is the time period between the onset of a first stimulus and the onset of a second stimulus. When SOA is varied, accuracy of responses improves as the SOA between two inputs increases (Eriksen & Collins, 1969). This suggests that a certain degree of time is required to attend to individual items. In addition, time course was found to vary according to attentional control mechanism (stimulus–driven (passive) or goal–directed (active)). For instance Muller and Rabbitt (1989) suggested that mechanisms used by the brain during goal–directed attention were slower but more sustained than those employed during stimulus–driven attention and these differing affects on time course might in turn determine whether interference to subsequent items occurs.

Despite this there have been attempts to estimate time spent per item regardless of the control mechanisms employed, and some researchers have assumed serial processing of items, which is a necessary assumption for estimates of time–course per item to be made. Using the search paradigm (simultaneous presentation of multiple stimuli), Wolf et al. (1989) found that subjects searched at a rate of 50 ms per item, and that the time dwelt on each item (dwell time) depends on the difficulty of discriminating between these items. However, the assumed serial model may be inappropriate. For instance, Palmer and Mclean (1995 (a, b)) suggested that if during search, non–targets were actually examined in parallel by a limited capacity processor, dwell time across discrete items may be much longer. This was supported using the partial report RSVP (rapid serial visual presentation) paradigm (the sequential display of stimuli, normally at a single position), which requires differentiating one or two items from a background of distractor stimuli. For example, Broadbent and Broadbent (1987) found that participants could not report the second of two items that were temporally adjacent even at an SOA of 320 ms, although again, results were affected by discrimination difficulty.

Duncan (1980) suggested that this poor performance on the second item reflected the duration of processing required for the first target. Raymond et al. (1992) explains that during processing of the first target, suppression of attentional mechanisms occurs, as if they 'blink', hence the term 'attentional blink' (AB). Using partial report RSVP, Duncan et al. (1994, 1996) found that for SOAs of several hundred ms it appeared that information processing resources were unavailable for processing of the second target and concluded that this revealed restrictions to dual–task processing.

This restriction was also found *within* the auditory sense (Duncan, 1994) but not *between* the visual and auditory senses (Duncan et al., 1997). In the past it was known that search was less efficient across within-sense targets than across between-sense targets (e.g. Treisman & Davies, 1973). However, as far as the attentional blink phenomenon was concerned, until the Duncan et al. (1997) finding, it had been proposed that any target or stimulus should interfere with the next regardless of modality. Duncan claims that his experiments produce 'exact measurements of the time course of interference produced by one attended target on another, as a function of whether targets are presented within or between modalities' (Duncan et al., 1997). This latter finding provides support for the MRT notion of separate sensory resources (encapsulated in Wickens's (1980) MRT model), which is based on the finding that dual–task limitations appear to exist within but not between the senses.

Moore et al. (1996) suggest that RSVP tasks usually use masked stimuli. He claims that masking makes discrimination more difficult, which has been shown to lengthen dwell time but that this masking is necessarily absent from search tasks, which would explain the difference between the search and RSVP results (approx. 50ms and 500ms respectively). This was confirmed by Bennett & Wolfe (1996) who showed that participants required only 50 ms per item in an RSVP task if, once presented, the item remains in view for the rest of the trial. However, an auditory equivalent of this approach would probably result in increased discrimination difficulty caused by distortion of the item that remained in earshot by subsequent (overlapping) items. The same issue may apply to tactile inputs as well. Therefore this approach is likely to be specific to the visual sense. None the less, this approach still supports the notion that there are temporal limitations (albeit reduced) on within–visual–sense processing and therefore is not a counter–argument to the Duncan et al. 'within but not between sense' findings,, nor, therefore, to Wickens's suggestion of separate sensory resources.

However, Shapiro et al. (1995) found that the attentional blink is not found if there is a brief pause immediately after the first target whereas feature and spatial similarity prolonged the blink. This might tie in with the fact, mentioned above, that discriminability affects the dwell time as this relates to similarity. It would also seem that if items were similar (less discriminable) then the use of faster stimulus–driven processes would be less likely; goal–directed processes would probably be required, and dwell time might be prolonged.

Overall these findings suggest that dual–task attention has limitations related to the temporal processing requirements of our information processing system and that these limitations are apparent within senses but not between senses. Results such as those of Shapiro et al. (1995), mentioned above, suggest that the structure of an event could be the main factor rather than representation in different sensory channels per se and perceived separation of stimuli enhances this separation into structure. However, dividing concurrent inputs across senses would serve to increase perceived separation and would explain the 'within but not between sense' finding of Duncan et al. (1997). As a result it also indirectly lends support to Wickens's notion that dual–tasks using separate senses will cause less interference than those using the same sense (although the rationale for the Shapiro et al. (1995) findings is based on increased input discrimination rather than Wickens's separate attentional resources).

3.3 Summary

Workload can be defined as the effect of task input and operator effort upon performance. Operator effort is mainly under the control of the operator but is affected by the effort requirements of the task(s). Therefore, the factor that has arguably the greatest impact on workload is task input and this also happens to be the factor that the designer has almost complete control over.

In assessing the effect of task input upon workload, it is common to use the dual–task technique. When the effects of different dual–task combinations on performance are compared, inferences can be made about human information processing limitations. Thus, theories of dual–task performance are useful in deciding which combinations of tasks will probably exceed workload capabilities and which combinations can be performed within these capabilities.

Single resource and single capacity theories of dual–task performance propose that information processing is limited by a single processing channel and when more than one input must be processed at the same time, this channel must be time–shared between inputs. However, many studies have shown that when dual–task inputs differ in terms of input sense and response modality, they can be performed at the same time with relative ease and therefore alternative theories of dual–task performance were necessary.

To be specific, dual–task inputs that are both either visual in nature or auditory in nature are associated with performance decrements, whereas when one task is visual and one is auditory within the dual–task combination, performance appears to be unaffected. The same principle applies to response modalities: interference seems to occur only when both tasks require manual responses or both tasks require vocal responses, but does not seem to occur when one task requires a manual response and one task requires a vocal response.

Multi–processor and multiple resource theories of dual–task performance explain these findings by suggesting that each sense and each response modality uses its own processor or resource and that when these differ within a dual–task combination, these inputs can be processed in parallel. Multi–processor theory argues that when inputs are of the same type, the same processor must be time–shared. However, the dual–task facilitation effect (where similar inputs result in improved performance) cannot be easily explained by multi–processor theory. Multiple resource theories (MRT) on the other hand suggest that similar inputs can be processed in parallel within the same resource but that the limit of that resource is likely to be exceeded quicker than when only one input requires that resource. MRT suggests that dual–task facilitation occurs when a proportion of resource capacity is borrowed from another resource. However, it is unclear how this is explicable in neuroscientific terms.

The most prominent MRT model is Wickens's MRT model (1980). Based upon dual–task performance findings, Wickens suggests that the auditory and visual senses use different resources; spatial and verbal processing 'codes' use different resources; and manual and vocal responses use different resources. Based on this model, an example of a dual–task combination that would not cause performance interference would be where one task was a visual spatial task requiring manual responses and the other task was an auditory verbal task requiring vocal responses. In theory, if either task overlaps in terms of sense, processing code or response modality, then performance interference is likely to occur.

The attentional blink phenomenon was also discussed. This phenomenon (where inputs that are presented in close temporal proximity to each other are associated with the apparent inability to process the second of these inputs) is said to reveal temporal processing limitations that help to explain dual–task performance interference. This effect has been found to occur when both inputs are visual or both inputs are auditory, but not when one input is visual and one input is auditory. This provides support for Wickens's MRT model.

However, other attentional blink findings suggest that the phenomenon occurs only when inputs are difficult to discriminate between and that the effect is a function of input discriminability (or structure) rather than input sense. Nevertheless, it could be argued that spreading inputs across the senses increases the perception of input separation and thus serves to increase discriminability. Therefore, this view does indirectly lend support for the principles of Wickens's MRT model even though the rationale behind these principles is somewhat different.

Overall, dual–task findings suggest that spreading inputs across different senses (as well as different processing codes and response modalities) will help to keep workload within acceptable limits. Wickens's MRT model is a useful framework from which predictions about dual–task performance can be made. These predictions are particularly useful for environments such as the cockpit because it is an environment in which there are multiple displays (currently mainly visual and auditory displays) that require spatial and verbal-type[*] processing and in which the operator must respond using both the manual and vocal modalities.

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[*] See Section 6.2 for explanation of 'verbal-type' processing

It is notable however that the model does not include haptic inputs (probably because, historically, dual–task studies are limited to visual and auditory inputs) and therefore, although it is possible to make inferences about incorporating haptic displays based upon the principles behind the MRT model, this still needs formal investigation. Section One highlighted the uncertainty about whether tactile and proprioceptive haptic sub–senses should be considered separate senses in their own rights. Without knowing whether tactile and proprioceptive inputs can be treated as separate senses or not it is difficult to know for certain whether, within the framework of this model, they will share resources or utilise separate resources.

Section Two described why there is a need to examine the potential impact of haptic displays upon workload and Section Three provides a theoretical framework (Wickens's MRT model) against which the results of this research can be discussed. As mentioned throughout this thesis there is a real need to investigate (a) whether tactile and proprioceptive inputs use separate workload 'resources' or not and (b) what impact tactile and proprioceptive inputs have on visual and auditory workload. These investigations are the focus of Study One and Study Two, respectively.

Wickens's MRT model implies that if tactile and proprioceptive inputs use separate resources then they can be performed at the same time without increasing workload (assuming other factors are controlled). However, if they share resources then introducing a scenario within the cockpit where a tactile and proprioceptive task must be performed at the same time would likely result in increased workload. Note, however, that another possibility is that it is possible to perform two tactile tasks at the same time or two proprioceptive tasks at the same time without increasing workload, perhaps because they do not require workload capacity or because they can be broken down into further 'channels'.

Based on the assumption that the tactile and proprioceptive sense(s) are different from the visual and auditory senses, Wickens's model would also imply that haptic inputs will require different resources from visual and auditory inputs and thus will not be associated with increases in workload, should a tactile or proprioceptive task be performed at the same time as a visual or auditory task.

The next section (Section Four) describes neuroscientific findings relating to multi–input processing and offers a different perspective on the mechanisms governing dual–task interference versus dual–task facilitation.

4 The Neuroscientific Perspective on Multisensory Processing

4.1 The Traditional Hierarchical & Modular Theory of Information Processing & Late Multisensory Integration

Most of the research on information processing has been conducted on a 'sense–by–sense' basis (Calvert et al., 2004 p. xi). The dual–task theories outlined in Section Three make the assumption that each sense should be treated separately and this culminated in the notion of separate sensory resources (Wickens's MRT model (1980), also described in Section Three). Because dual–task interference tends not to occur when each task utilises a different sense, this has been interpreted as indication that each sense uses a separate resource as opposed to the notion that spreading inputs across the senses increases the perception of input separation, which may aid input discrimination (a factor in multi–input interference characterised by the attentional blink effect (Shapiro et al. (1995)). Refer to Section Three for more on MRT and the attentional blink.

This assumption of sensory independence has its roots in the traditional hierarchical and modular theory of information processing, in which multi–input and multisensory integration is believed to occur quite late in information processing terms and thus given relatively little attention by those interested in control mechanisms governing the allocation and division of attention, and perception.

The traditional view of information processing argues that inputs are processed by increasingly higher structures and processes within the nervous system (Wickens, 1992). Essentially, the view is that sensory inputs are first processed by separate uni–sensory brain structures before being integrated within 'association' brain structures that are specialised for specific types of processing such as spatial processing, verbal processing, decision–making, and response formation etc.

In Section One, the tactile and proprioceptive pathways were described but the general principle is the same for all the senses. Sensory inputs are received by receptors and impulses are sent to the brain. On entering the brain, it is believed that they synapse at the thalamus, before travelling on to their respective primary sensory areas of cortex. These primary sensory areas have always been treated as uni–sensory areas and Jones and Powell (1970), for example, proposed that primary sensory brain areas are connected only to other areas of the same sense. It is believed that the inputs travel from the primary sensory areas to secondary sensory areas (which, again, are usually treated as uni–sensory) and the traditional view is that it is only after leaving these areas that sensory integration begins to occur. Note therefore that it is believed that only feed–forward processes take place from the receptor to the point that multisensory integration begins. Feed–forward refers to the direction of travel, from receptor to increasingly 'higher' and 'later' brain structures. Feedback on the other hand would refer to the opposite direction (from 'later' brain structures towards 'earlier' brain structures) and lateral would refer to travel between structures at the same 'level'. The traditional view is that feedback and lateral processes do not occur until later in information processing (for example in decision making and action formation and control).

Fodor (1983) brought the notion of independent sensory processing to the fore in his 'Modularity of Mind', which argues that sensory inputs are separated into parallel processing channels that are not influenced by later 'central processes'. Fodor emphasised the independence of each of the senses and suggested that information processing occurred in a feed–forward fashion (from receptor to unisensory brain area, and then to central processing brain areas). As mentioned this modular view is reflected in Wickens's MRT Model (1980).

However the physiological processes underlying multisensory perception have been understudied until recently. The next section describes recent neuroscientific findings that suggest multisensory integration may occur at much earlier stages in information processing than traditionally believed This brings science a step closer to resolving issues such as the binding problem ('the problem of how the unity of conscious perception is brought about by the distributed activities of the central nervous system' (Revonsuo & Newman, 1999)), but also suggest that the principles behind MRT and Wickens's MRT model may need a re–think.

4.2 Neuroscientific Evidence in Support of Early Multisensory Integration

The brain must process an enormous quantity of multisensory inputs, and it must integrate those inputs that, 'regardless of (sensory) modality, should be related to one another because they are derived from a common event. At the same time, the brain also needs to keep separate the (inputs) ... derived from different perceptual events' (Calvert et al., 2004). Recent neuroscientific evidence suggests that integration of relevant inputs occurs at much earlier stages of information processing than previously believed.

Multisensory integration has been found to occur within the superior colliculus (e.g. Stein & Meredith, 1993) and within areas of the temporal, parietal, and frontal lobes (Schroeder & Foxe, 2004). These sites are within cortical areas known as association areas (as opposed to sensory or motor areas), and are traditionally believed to be used in later, more complex input analyses. As mentioned in the previous section, multisensory integration has been assumed to occur only within these types of brain areas and, crucially, that processing within these association areas occurs only at temporally later stages of information processing. It is worth emphasising again that, in line with this view, sensory inputs were assumed to be processed in isolation from one another starting with their specific receptors, travelling along separate pathways and then analysed within separate unisensory cortical areas before being integrated within the association cortical areas towards the end of the process. Because of this it was logical to explain dual–task effects in terms of separate attentional 'resources' defined mainly by sense, hence Wickens's MRT model.

Therefore, it is significant that more recent findings provide evidence of multisensory integration during the early, allegedly *unisensory* stages of sensory processing (Macaluso et al., 2000; King, 2004; Calvert et al., 1999; Foxe et al., 2000; Giard & Peronet, 1999; Levanen et al., 1998; Molholm et al., 2002; Schroeder & Foxe, 2002; Schroeder et al., 2001; Schroeder & Foxe, 2004). In addition, other findings provide evidence that processing in association areas can influence processing within 'earlier' 'uni–sensory' structures, and because this influence is found within such a short time frame from input onset, it has been suggested that processing in association areas can occur *prior* to that in the 'uni–sensory' areas (Schroeder & Foxe, 2004).

Schroeder & Foxe (2004) suggest the following multisensory integration issues that must be addressed to confirm that multisensory integration is fundamental to information processing:

1. Does multisensory integration occur across all of the senses, particularly vision, audition and somatosensation (the haptic sense)?
2. Does multisensory integration occur within or after the minimum temporal period for 'unisensory' area activation, and therefore early or late (respectively) in information processing? (Schroeder & Foxe, 2004)
3. In what form does multisensory integration exist? Does it take place 'within a single neuron (neuronal convergence) or in adjacent neurons within a single cortical region or interconnected ensemble (areal convergence)'? (Schroeder & Foxe, 2004)
4. Is multisensory integration 'mediated by feed–forward, feedback, or lateral axonal projections'? (Schroeder & Foxe, 2004)

The findings relating to each of these issues are described in the following sub–sections.

4.2.1 Does Early Multisensory Integration Occur Across All of the Senses?

Blindness that begins in infancy can lead to auditory and tactile representations in areas of the visual cortex (Bear et al., 2001; Cohen et al., 1997; Rauschecker, 1995; the latter two cited in King, 2004), whereas, the auditory cortex of deaf humans can respond to visual inputs (Bear et al., 2001; Finney et al., 2001).

However, when it comes to the non–blind and the non–deaf, there is also a bulk of neuroscientific suggesting widespread early interactions between the major sensory systems (visual, auditory and haptic) (Schroeder & Foxe, 2004). Some of these findings are summarised in the following sub–sections.

Further evidence for multisensory integration within 'early' brain sites comes from lesion studies. Ettlinger and Wilson (1990) describe no significant loss of multisensory function after lesions to the 'later' multisensory areas of cortex, which they suggested at the time was due to 'leakage' between the unisensory areas, based on the assumption that no connections exist between these unisensory areas. Foxe and Schroeder (2005), on the other hand, propose that this lack of functional loss is likely to be due to the 'early' multisensory integration that has since been observed.

Finally, research shows that sensory information undergoes a certain amount of transformation in both the dorsal column and thalamic nuclei (Bear et al., 2001), inhibiting or enhancing the inputs passing through. Neurons 'in both the thalamus and the dorsal column nuclei are also controlled by input' from the cortex (Bear et al., 2001).

This section highlighted evidence in support of widespread multisensory integration at anatomically early brain sites. The next section looks at the evidence for early multisensory integration in temporal terms.

4.2.2 Within What Time–Frame Does Multisensory Integration Occur?

Auditory–on–visual effects and visual–on–auditory effects have been found very early in temporal terms and at cortical locations normally associated with early unisensory visual or auditory (respectively) processing (Bental et al., 1968; Calvert & Bullmore, 1997; Calvert et al., 2001; Giard & Peronnet, 1999; Molholm et al., 2002).

Somatosensory–on–auditory effects have also been found very early in temporal terms and at cortical locations normally associated with early unisensory auditory processing (Foxe et al., 2000; 2002; Fu et al., 2003; Leinonen et al., 1980; Levanen et al., 1998; Robinson & Burton, 1980; Schroeder & Foxe, 2002; Schroeder et al., 2001; Schroeder et al., 2003).

Interestingly, Alais and Carlile (2005) found that a time lag between visual and auditory stimuli is required in order for the receiver to perceive distant audiovisual signals as synchronised and therefore relating to the same external event. They also found that this time lag roughly related to the speed of sound. They concluded that the brain's acceptance of considerable time lags 'allows auditory and visual signals to be synchronized to the external event that caused them' (Alais & Carlile, 2005). This implies that (a) visual stimuli inform processing of subsequent auditory stimuli and (b) 'stored knowledge' is required about the temporal synchronicity of stimuli. Whether this stored knowledge is held within multisensory neurons on site or whether it is held within other brain areas is unclear.

4.2.3 In What Form Does Multisensory Integration Occur?

Evidence suggests that multisensory integration frequently occurs at the single–cell level, as individual neurons in many areas of the brain respond to more than one sense at a time (Stein et al, 2004).

The areas of the brain in which single–cell multisensory integration has been found to occur include the association areas of the cortex as well as mid–brain structures such as the superior colliculus (Stein et al., 2004). The individual neurons within these areas receive afferent (incoming) nerve fibres from at least two different senses (Stein et al., 2004). The association areas include:

- The orbitofrontal cortex, where neurons respond to all types of sensory input for what appears to be the purpose of defining 'what' something is (Stein et al., 2004).

- The amygdala, which is involved in expression of emotions and recognition of others' emotions. It responds to all types of sensory input and stimulation of this area results in heightened attention and anxiety (Bear et al., 2001).

- The hippocampus, where representations of visual space are combined with inputs about self motion from the proprioceptive and vestibular senses (Stein et al., 2004).

- The presubiculum, which responds to visual cues in spatial relation to head direction, whilst processing vestibular cues prompted by head direction change (Stein et al., 2004).

- The superior temporal sulcus, which responds to changing stimuli such as the lips of a speaker and sounds produced by the speaker (Stein et al., 2004).

However, the area that has received the most attention is the midbrain structure, the superior colliculus (SC). This area is involved in the 'coordinated orientation of the various sensory organs (e.g. eyes, head, ears, limbs, whiskers, and mouth) that best position an animal to both assess and react to the stimuli of interest' (Stein et al., 2004). Therefore, this area is important in directing attention towards inputs as well as the coordination of responses. Individual neurons within this structure are activated by many different senses. 'All possible convergence patterns (i.e. visual–auditory, visual–somatosensory, auditory–somatosensory, and visual–auditory–somatosensory) have been noted among SC neurons' (Meredith & Stein, 1983; 1986; Stein et al., 1983; Wallace & Stein, 1996; cited in Stein et al., 2004).

More details on multisensory integration within the SC area are given in the next sub–section, which describes the principles that appear to govern this integration.

4.2.4 What are the principles governing multisensory integration at the single cell level?

Multisensory integration is challenging to the brain because of the differences between the senses (Spence & Driver, 2004). It is likely that much of the processing that occurs, as inputs are received by the brain, is dedicated to trying to 'iron out' the physical differences between different sensory inputs, so that congruency and incongruency can be quickly assessed (a) to determine whether the inputs refer to the same event or object; (b) to determine whether the inputs are giving confirmatory or conflicting information about that event or object and (c) to decide which sensory input to 'go with' if conflicting information is received.

In the past decade there has been a significant increase in research into the principles that the brain uses in multisensory integration and how these may help to shape our understanding of selective and divided attention.

In particular, there is now much evidence from research into the SC area to suggest that spatial and temporal factors are important (Spence & Driver, 2004). Key findings include:

- Most multisensory integration seems to involve summation of the inputs (Stein et al., 2004).

- When multisensory inputs are similar in terms of the spatial location and time–frame in which these inputs occur, neural activity seems to involve summation and sometimes enhancement of the inputs (Stein et al., 2004). The brain must assume that spatial and temporal coincidence is associated with inputs from the same event. In practice this results in additive or superadditive (greater than the additive value) neural activity, which is reflected by enhanced detection and localisation ability (Stein et al., 2004). This 'multisensory facilitation of the responses of SC neurons occurs only when each stimulus falls within its excitatory receptive field' (King, 2004).

- If the multisensory inputs do not occur within the same specific time–frame they will stimulate the neurons at different times and the brain appears to assume that these inputs refer to separate events.

- Similarly, when multisensory inputs are dissimilar in terms of the spatial location they will stimulate different neuronal receptive fields (Stein et al., 2004) and the brain appears to assume that these inputs refer to separate events.

- When multisensory inputs are very dissimilar in terms of the spatial location and time–frame in which these inputs occur, neural activity to both inputs can be suppressed or even eliminated (King, 2004). In this instance, the brain must assume that the spatial and temporal discrepancy is representative of unrelated events and therefore, may treat one or both as simply distracting. In practice this results in subadditive (less than the additive value) neural activity and is reflected by decreased ability to orient towards the inputs (Stein et al., 2004)

Multisensory integration is associated with a neural response that is significantly *different* from the neural response to either of the sensory inputs on their own (Stein et al., 2004).

However, when spatial and/ or temporal discrepancies occur between inputs normally associated with the same event, the brain must select which of the inputs is likely to be the most reliable and this can result in illusions (Stein et al., 2004). For example, the visual sense is usually more accurate and reliable for spatial information than the auditory system and therefore visual inputs tend to dominate over auditory inputs (King, 2004) and this can result in illusions such as the 'ventriloquism effect' (Howard & Templeton, 1966, cited by Stein et al., 2004). The ventriloquism effect occurs as a result of incongruous auditory and visual spatial cues and causes the receiver to perceive that the auditory inputs originate from the source of the visual inputs (an example of visual dominance) (Vroomen & Gelder, 2004). This highlights the tendency that the brain has to try to resolve multi–sensory conflicts, in reality creating two illusions: (a) the illusion that the auditory inputs are originating from a different source and (b) the illusion that the visual inputs are compatible with the auditory inputs (despite the fact that the 'dummy's mouth' is not producing any of the lip movements one would normally associate with the heard speech). Dominance of one sense over another would probably require some kind of weighting system, where inputs from different senses are given more or less weight depending upon algorithms regarding which sense is most reliable under various spatiotemporal conditions and degree of incongruency.

Overall, what comes across is the issue of congruency versus incongruency of inputs, in determining whether multisensory integration results in enhancement of responses, depression of responses, or even illusions. In particular, spatial and temporal congruency seems to be a determining factor in multisensory integration.

These multisensory integration findings are obviously specific to the SC area, which is an area involved in the orienting of attention to events as well as responses to those events. Therefore it is not surprising that this area very much relies upon congruency of spatial and temporal inputs. However, there is a strong possibility that the principle of congruency of multisensory inputs may also be fundamental to other brain areas involved in other types of multisensory tasks.

For example, other factors have also been found that determine whether multi–sensory inputs are perceived as discrepant or non–discrepant. Variations in visual brightness in relation to variations in auditory pitch and loudness produce perceptions of discrepant versus non–discrepant inputs (Marks, et al., 1987; Marks, 1974; 1989). There is also a linguistic relationship between visual and auditory congruency perceptions i.e. sounds are referred to as high–pitched or low–pitched and the higher–pitched the sound the higher it is placed spatially on the musical stave and vice versa. For more on the relationship of visual and auditory congruency to linguistic labels, see Marks et al. (1997) and Marks (1982, a. & b.).

Many of the visual–auditory factors that determine discrepancy or non–discrepancy are quite abstract and do not have a 'common acoustic or optical referent' (Marks, 2004). In these cases it is the linguistic label that is the linking 'referent' (Marks, 2004), suggesting that associations with linguistic labels may be automatically made in the early stages of information processing when the congruency of basic multi–sensory features is determined. Associations of this kind may be formed from experience that certain multi–sensory features are linked to certain events or objects e.g. darkness (black) is associated with quiet (reduced loudness).

The SC area, along with the other association areas listed earlier, are traditionally associated with higher and 'later' processing of inputs. However, Section 4.2.1 highlighted that multisensory integration appears to cause activation in 'unisensory' areas and in Section 4.2.2 it was suggested that these multisensory influences on 'unisensory' brain areas appear to occur early in temporal terms. The next section looks at how early multisensory integration could be mediated.

4.3.4 How is Multisensory Integration Mediated?

The next question is whether the fore–mentioned activity in 'earlier' cortical areas is a result of processes that are feed–forward (from 'earlier' structures or direct from the sensory receptors), lateral (between structures at the same 'level'), or feedback (backwards from 'later' to 'earlier structures).

The thalamus could be considered the initial 'junction–box' for the separate sensory inputs entering the brain. Normally, neural fibres from the thalamus project sensory inputs to the specific 'unisensory' cortical area associated with those inputs. This is an example of feedforward mediation (i.e. in the direction of receptor towards cortex). However, the group of neural fibres that take haptic inputs from the thalamus to the somatosensory cortex also includes fibres that project to the auditory cortex (Schroeder & Foxe, 2004). This may be one way that early multisensory integration is mediated, although this would also need to be found for more sensory combinations in order to fully explain the early multisensory influence mentioned previously.

However, the potential for multisensory integration is greater when information can be mediated backwards as well as forwards. Cross–connections have been found between auditory and visual cortices (Falchier et al., 2001; Rockland & Ojima, 2003) that are 'consistent with either feedback or lateral connections' (Schroeder & Foxe, 2004).

In addition, Schroeder and Foxe (2002) found evidence of 'feedback–mediated' visual input to the auditory cortex and this corresponds with another finding that these visual inputs have much longer latency times than auditory inputs into the auditory cortex (Schroeder & Foxe, 2004). Support also exists for feedback–mediated auditory inputs to the visual cortex (Schroeder & Foxe, 2004).

On the other hand, the connection activity of somatosensory input to the auditory cortex, coupled with the very short time period in which this effect occurred, matches that of auditory input to the auditory cortex and suggests feed–forward processes such as those described earlier (Schroeder & Foxe, 2004).

However, evidence of feedback–mediated processes within early structures, including 'unisensory' structures, supports the argument that information processing involves 'collaboration between new sensory input and ongoing cortical processes' (Schroeder & Foxe, 2004) and suggests that multisensory integration permeates throughout rather than being limited to the later stages.

4.3 Summary

Traditionally, multisensory integration has been assumed to occur only within association areas of the brain and, crucially, that processing within these association areas occurs only at temporally later stages of information processing. In line with this view, sensory inputs were assumed to be processed in isolation from one another starting with their specific receptors, travelling along separate pathways and then analysed within separate unisensory cortical areas before being integrated within the association cortical areas towards the end of the process. Because of this it was logical to explain dual–task effects in terms of separate attentional 'resources' defined mainly by sense, hence Wickens's MRT model.

However, multisensory integration is apparent across all the senses and has been found to occur (a) at brain sites normally associated with early unisensory processing (b) within very short time frames from stimulus onset and (c) through a combination of feed–forward, lateral and feedback information relay, which appears to vary with sense. In addition, multisensory integration is not significantly affected by lesions to 'later' multisensory brain areas. These findings suggest that multisensory integration occurs at both anatomically early and temporally early stages within information processing.

The brain area that has received the most attention is the Superior Colliculus (SC) and research highlights the importance of spatial and temporal congruency in multisensory integration within this area. This research reveals that congruent inputs lead to neural activity that is a summation of the individual inputs. Sometimes, this summation is superadditive, resulting in enhanced performance. On the other hand, incongruent inputs can lead to summation that is subadditive and is associated with poorer performance. Despite the fact that these results are specific to the SC area, it is likely that the principle of congruency is important for multisensory integration in other brain areas. However, at this stage it is not possible to generalise with any certainty.

These findings provide evidence for multisensory integration at a variety of information processing levels and suggest that it is feasible that some of this integration takes place at the very earliest anatomical and temporal stages. They directly challenge the notion that multisensory integration occurs only after unisensory processing and at much later stages of information processing. The findings also challenge the view that information processing occurs in a linear hierarchical fashion from basic to more complex analyses.

Finally, these findings strongly suggest that Wickens's Multiple Resource Model requires a re–think because it explains attentional resources in fundamentally unisensory terms. This is not necessarily to say that the visual and auditory performance outcomes predicted by Wickens's model are incorrect — MRT is based on a huge amount of research suggesting that dual–task performance is better overall when the two tasks utilise different senses. This in fact is supported by neuroscientific findings that multisensory inputs are usually summated and therefore significantly different from either input on its own. However, the MRT principle of separate sensory resources may be misleading and oversimplistic.

5 Workload Measurement

5.1 Approaches to Workload Measurement and the Methodological Argument for the Dual–Task Technique

O'Donnell and Eggemeier (1986) suggest the following criteria for Workload Assessment Technique selection:

- Sensitivity — Capability of the technique to discriminate significant variations in the workload imposed by a task.
- Diagnosticity — Capability of the technique to discriminate the amount of workload imposed on different operator capacities or resources (e.g. visual vs. auditory modality or spatial vs. verbal input code).
- Intrusiveness — Tendency for the technique to cause degradations in ongoing primary task performance.
- Implementation — Factors related to the ease of implementing the technique (e.g. instrumentation requirements and participant training).
- Acceptance — Willingness of participants to follow instructions and actually utilize the particular technique (i.e. face validity).

Moray (1988) identifies three approaches to workload measurement: the physiological approach, the subjective approach and the behavioural approach (which includes the dual–task technique mentioned in Section Three). The approach chosen to measure workload in subsequent analyses in this thesis is the dual–task technique (from the behavioural approach). Each approach will now be briefly described and their abilities to satisfy the above criteria summarised. The aim of this section is to provide the methodological argument for adopting the dual–task technique to measure workload in this thesis.

5.1.1 The Physiological Approach

Physiological approaches to workload assessment involve measurement of operator autonomic or central nervous system responses to the task(s) being performed by the operator (Wickens, 1992). These approaches include (a) the evoked brain potential (EP) technique (b) pupil diameter measurement, and (c) heart–rate measurement. Refer to Wickens (1992) for details of these measures.

Needless to say, application of such an approach requires specialised equipment and, although unintrusive in the sense that they do not interfere with task performance, they are potentially physically intrusive because they require either the attachment of electrodes or head restraint (in the case of pupil measurement). Note, however, that heart rate measurement is no longer as intrusive as it once was. These issues will have a bearing on implementation, intrusiveness and operator acceptance. Pupil measurement and heart rate measurement tend to be highly sensitive but relatively undiagnostic, whereas the EP measure tends to be highly diagnostic but not particularly sensitive. Implementation of the pupil measurement technique requires control of ambient light and both this technique and the heart-rate measurement technique are affected by emotional state. These issues are discussed in greater detail in O'Donnell and Eggemeier (1986).

Finally, physiological measures are not direct measures of the effect of workload on performance; one can only infer that physiological indications of workload increase would be accompanied by deterioration in performance (Wickens, 1992).

5.1.2 The Subjective Approach

Much progress has been made with subjective measures and their value should not be ignored especially when it comes to acknowledging and defining individual differences. The NASA-TLX subjective measure (Hart & Staveland, 1988; Hart et al., 1986 (a, b); Vidulich & Tsang, 1985 (a, b)) is an attempt to define the dimensions that account for individual differences in subjective workload assessments. The measure comprises six scales that are closely related to the three dimensions used in another popular subjective measure called SWAT (O'Donnell & Eggemeier, 1986; Nygren, 1982; Reid et al., 1981), which in turn is based on the well-known Cooper-Harper subjective rating scale. The six NASA-TLX scales include: time pressure, physical demand, mental demand, performance, effort and frustration. One concern is whether subjective reporting provides an accurate and reliable reflection of workload. However, in the NASA-TLX, the importance of each scale is weighted by the user and it is claimed that this weighting reduces variance by up to 50% (see O'Donnell & Eggemeier, 1986 for more details).

Subjective measures are inexpensive and easy to implement. They are non-intrusive because they are implemented after task completion and operator acceptance is good.

However, they are an indirect measure of the effect of workload on task performance. In fact Tulga and Sheridan (1980) found that the perception of workload increases as task demands increase, until errors begin occurring, at which point, the perception of workload begins to *decrease.* Moray (1988) suggests that this decrease is due to a change in strategy criterion, whereby initially, speed is maintained whilst avoiding errors, then as the task becomes more challenging this approach becomes more and more taxing, until the only way to maintain speed is through acceptance of errors (resulting in poorer performance but a reduction in perceived workload). This suggests that subjective workload may not be a reliable predictor of task performance and that, ultimately, it is necessary to assess workload in terms of task performance if the goal is to minimise errors.

5.1.3 The Behavioural Approach and the Dual–Task Technique

Behavioural approaches measure task performance and include (a) the primary task technique and (b) the dual–task technique (often referred to as the secondary task technique).

The primary task technique is where a task is performed by itself and the resulting performance is taken to reflect the workload demands of that task. Another task may also be performed by itself and then the performance on both of these tasks may be compared to give an indication of which task was associated with greater workload demand. Level of intrusiveness is low with this technique and operator acceptance is good. Ease of implementation depends upon the ease in which performance data can be gathered and will vary greatly from task to task.

However, the diagnostic capabilities and level of sensitivity of this technique are limited in comparison with the dual–task technique. Problems will arise when task difficulty is insufficient and as a result, performance is perfect; when this is the case for the two tasks being compared, it is impossible to judge which task out of the two demands more workload resource(s). Refer to Wickens (1992) for other criticisms of this technique.

As mentioned in Section Three, the dual–task technique involves performing two tasks at the same time and comparing each task's dual–task score to their single task score (when that task is performed by itself). If task performance is worse during the dual–task condition than it is in the single task condition then dual–task interference is said to have occurred. When many dual–tasks are performed, it is possible to make inferences about the types of dual–tasks that are associated with interference and those that are not. The theory behind why some dual–tasks cause interference and others do not was the subject of Section Three.

This has proven to be a popular technique and associated research findings have shaped the development of cognitive science theories on information processing, workload and multi–input processing, as discussed in Section Three. These theories culminated in the Multiple Resource Theories (MRT) and models of workload such as Wickens's MRT model, also discussed in Section Three. One criticism is that this situation has become circular in that while dual–task findings have led to the formation of MRT, they also tend to be interpreted in terms of MRT because MRT–based assumptions are made in the design of dual–task tests and controls.

With regards to intrusiveness and the dual–task technique, it is not appropriate to impose a secondary task in a real environment where safety may become an issue, because even where workload demand is not increased, the effect of task concurrency causes slight performance decrements in itself (Wickens, 1992). However, many environments of interest to researchers (such as the cockpit), offer plenty of opportunity to measure dual–task performance due to the fact that these environments naturally expose operators to multiple displays and controls. In addition, where the setting is the laboratory, then there is usually no concern over safety.

As for the primary task technique, ease of implementation in the dual–task technique depends upon the ease in which performance data can be gathered.

Direct comparisons between tasks within the dual–task combination can be made possible by standardising results. For example, each task can be performed by itself initially (the single task condition) and the scores from the single task conditions are treated as 100%; scores from the same tasks performed within the dual–task condition are converted to percentages of their single task scores. In the same way, direct comparisons between different dual–task combinations are also made possible.

A battery of dual–tasks can be conducted (Kahneman, 1973), so that the effect of small variations in task difficulty and other factors such as input sense, processing code etc. can be compared. The number of comparisons within a battery of dual–tasks can be limited by controlling factors that are perhaps of less interest such as response modality for example. This approach can make the dual–task technique enormously sensitive and diagnostic but does increase design complexity.

The diagnostic capability of the dual–task technique can be limited by how operators proportionately allocate effort between the two tasks. This is difficult to control just by instructing the operator to allocate, for example, 50% effort to one task and 50% effort to the other task. Traditionally the secondary task technique involves instructing the operator to prioritise one of the tasks (the primary task) over the other task (the secondary task), so that left–over resource(s) from the prioritised primary task can be judged by how well the secondary task is performed. Another approach is to use an embedded secondary task, where one of the tasks has natural priority over the other task, for example, the primary task within a cockpit might be to fly the aircraft and the secondary task might be to listen out for radio inputs (Wickens, 1992).

However, a technique devised by Gopher et al. (1982) aims to objectively control effort allocation to such a degree that many different variations in task priority are possible, and more confidence can be had in the operator's allocation of effort and therefore the diagnostic power of the dual–tasks in question. This technique is the subject of the next section.

5.2 A Method to Control Effort Allocation

Proportional effort allocation is assumed to be 'at least partly under voluntary control' (Heuer, 1996). However, as mentioned in the previous section, unless allocation of effort can be controlled by the researcher, the diagnostic capabilities of the dual–task technique are limited.

A technique using on–screen effort 'indicators' was devised by Gopher et al. (1982) and is a significant step towards objectively controlling effort allocation.

Participants are instructed to perform two tasks (e.g. task one may be a visual verbal-type* task and task two may be a visual spatial task) under dual–task conditions, with graded changes in the relative priorities of each task, whilst difficulty is held constant. Figure 8 shows these two hypothetical tasks presented on a screen. Above the task 'areas' there are task effort allocation indicators (see Figure 8). Each task has its own indicator and, in this example, the task one indicator is on the left and the task two indicator is on the right. These indicators are moving bars that represent real–time effort. The two indicators are separated by a 'priority bar' (this is highlighted in red in Figure 8).

The priority bar is movable but is set by the researcher. For example, the total width of the screen represents 100% allocation of effort and in the single task condition, the priority bar would be positioned all the way to the right for task one (because task one indicators move from left to right) and all the way to the left for task two (because task two indicators move from right to left). Under dual–task conditions, the priority bar is positioned somewhere between these two extremes so that a certain proportion of effort must be allocated to task one and the other proportion to task two. In the example in Figure 8, the priority bar is set to allocate 25% effort to task one and 75% effort to task two.

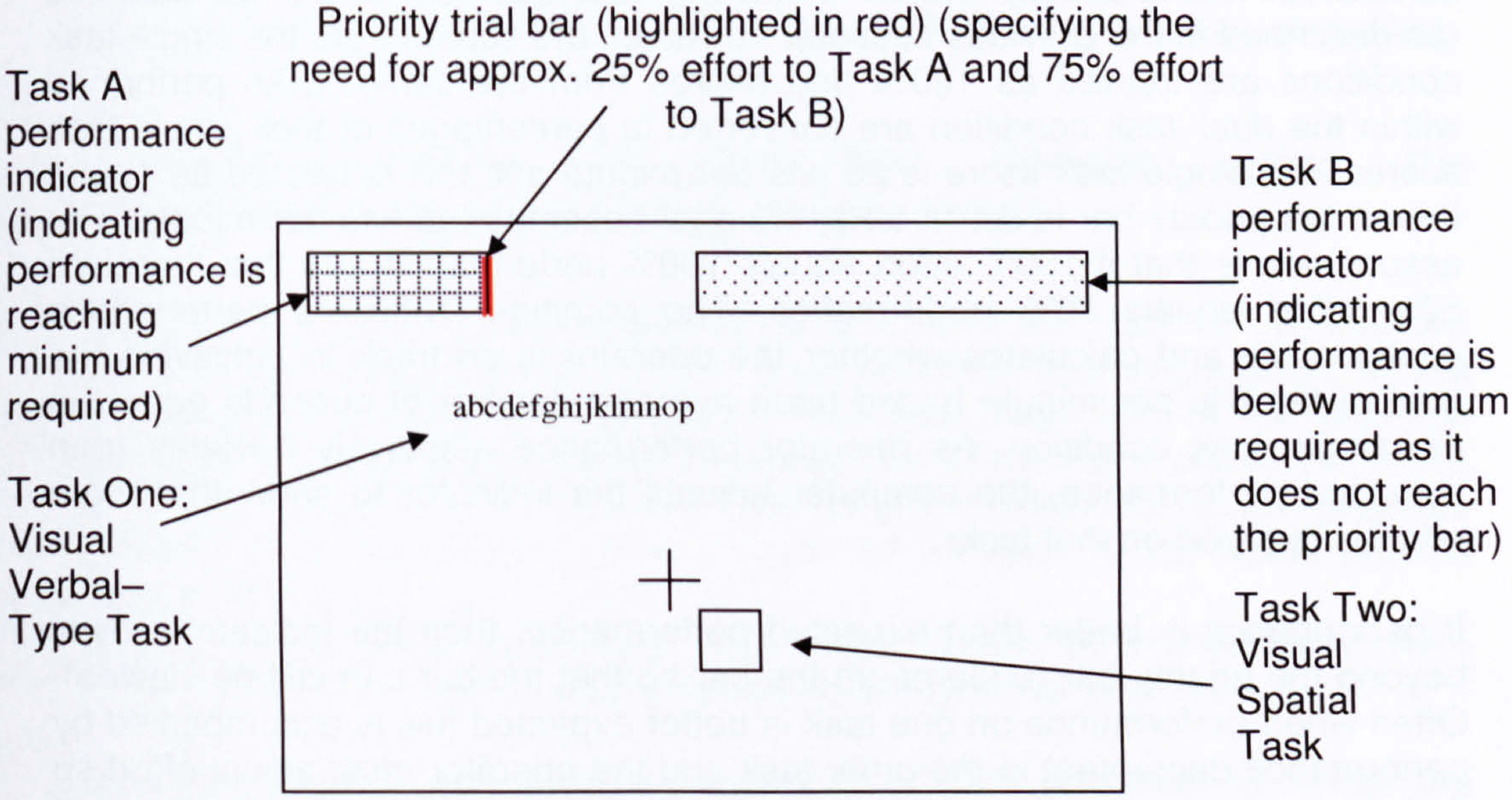

Figure 8: Task priority level indicated using visual feedback. Based upon the resource allocation methodology described in Gopher et al. (1982)

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* See Section 6.2 for explanation of 'verbal-type' processing

In theory, two bars could be used to enable separate limits for each task (for example 35% to task one, 35% to task two and 30% spare capacity) which may be useful if a researcher wanted to judge operator ability to handle unexpected or extraneous inputs.

The same dual–task can be performed many times with the priority bar set at a different pre–determined point each time (e.g. 25%_75%; 50%_50%; 75%_25% where the first figure in each pair refers to effort allocated to task one and the second figure refers to effort allocated to task two). The number of different variations must be balanced against the time that operator will be spending performing the same dual–task over and over again, due to practice and fatigue effects (not to mention the tedium for all involved).

However, when effort allocation is varied in this way, it enables dual–task performance to be represented using the performance operating characteristic (POC) curve which is an effective way of presenting dual–task results and enabling the differences between dual–task techniques to be viewed with ease. The POC curve is described in the next section.

Before going on the POC curves, three more points about this effort allocation method must be made.

The first is a practical point regarding how the real–time effort indicators are calculated. This is directly related to how the dual–task results are standardised (as described in the previous section). To recap, the scores from the single task conditions are treated as 100% and scores from the same tasks performed within the dual–task condition are converted to percentages of their single task scores. If a single task score is 20 hits per minute and this is treated as 100%, then if the priority bar is set to 50%, the goal becomes ten hits per minute. The assumption is that if 100% effort equals 100% performance and that therefore 50% effort equals 50% performance. The computer monitors performance continuously and calculates whether the operator is on track to achieving the goal of ten hits per minute based upon average number of seconds per hit in the single task condition. As operator performance negatively deviates from expected performance, the computer adjusts the indicator to show that more effort is required on that task.

If performance is better than expected performance, then the indicator moves beyond the priority bar (underneath the bar so that the bar can still be viewed). Often when performance on one task is better expected this is accompanied by performance decrement in the other task and the operator must adjust effort so that the correct proportion of effort is allocated to each task. In this thesis, if performance on *both* tasks was better than expected the operator would see both task indicators meeting at the priority bar and the excess would not be indicated to the operator for two reasons:

(a) It was not practical to do so as the overlapping indicators would be confusing to the operator.

(b) Reduction of effort was applicable only when one of the tasks was suffering as a result; when performance on both tasks exceeded expectations this would indicate resource independence and possibly even dual–task facilitation, and neither would be revealed if operators felt they needed to reduce effort on *both* tasks.

The second point is to do with the possible interference caused by the monitoring of on–screen effort indicators (which is essentially a visual spatial monitoring task). However, potential interference can be controlled to a certain extent by presenting the on–screen feedback during the single task conditions so that the single task baseline accommodates for this interference as much as possible. In addition, any interference from the on–screen feedback would not come from the act of allocating and controlling effort, which in itself has not been found to require any resources (De Shon et al., 1996).

Finally, the third point is that although this feedback is presented visually, it may be possible to present it some other way, such as through tactile feedback. For example, vibration on the left hand to represent task one effort and vibration on the right hand to represent task two effort; vibrations may be present only when effort deviates from the goal and the level of vibration intensity may increase as deviation increases, diminishing as deviation diminishes and ceasing when the goal is reached. This is only food for thought but may be useful where it is impractical to use on–screen feedback, for example, within the cockpit simulator, or within environments where light is restricted or must be controlled.

5.3 Representation of Dual–Task Results using the Performance Operating Characteristic (POC)

POC stands for Performance Operating Characteristic (Norman & Bobrow, 1975). A POC curve plots joint levels of performance in a single graph and is made possible by the effort allocation technique described in the previous section as that technique enables the production of the many points that make up the POC curve. For example, the different effort allocation priorities mentioned in the previous section (25_75, 50_50 and 75_25) would provide three points on the curve.
Figure 9 shows a POC curve where the priorities chosen by the researcher were 30_70, 50_50 and 70_30. Single task scores are at either extreme.

Therefore, a POC curve traces the bounds of joint performance, under the different levels of task effort allocation. The subsequent area within the curve indicates the level of resource sharing or independence between the two tasks.

In Figure 9 there are three hypothetical curves (A, B and C), each depicting different levels of resource sharing/ independence. The area within Curve A represents total overlap of resources; within Curve B partial overlap; and within Curve C complete independence.

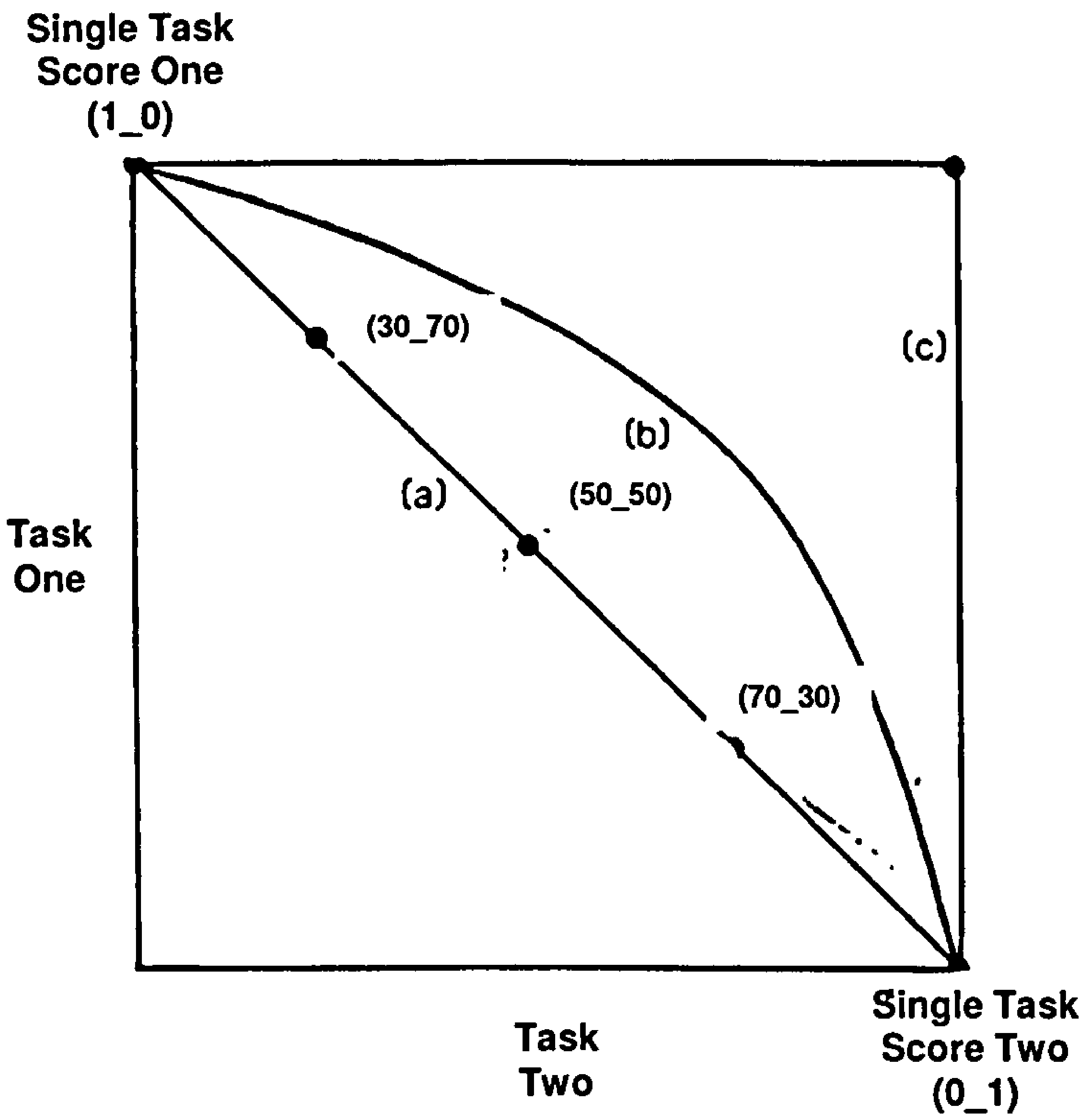

Figure 9: Three hypothetical POC curves. Based on the description in Gopher & Donchin (1986)

If other variables are manipulated as well, such as difficulty, then an additional POC curve has to be constructed for each new difficulty condition, creating a 'family' of POC curves. Because, increases in task difficulty are normally met with increasing effort, it is often not clear from performance decrements alone how much capacity is being used and this is where the value of POC curve 'families' is appreciated, because changes in curve area as a result of changes in difficulty can reveal the difficulty level required to reveal resource sharing. When performance remains perfect despite increases in difficulty then it is inferred that resource independence is being exhibited.

However, POC curve methodology means that a complex experimental design is necessary. It is also more time-consuming in both data collection and in analysis than any of the other techniques for studying workload, which could result in fatigue and practice effects, as mentioned earlier. Practice eventually leads to automatisation and this in turn sometimes reduces dual-task interference (Bahrick & Shelly, 1958; Brown & Poulton, 1961). However, although practice in itself appears to reduce interference (Heuer, 1996, 1984), in some cases, automatisation actually increases dual-task interference, when the automatic strategies are interrupted by the addition of second task (Pew, 1974 (a, b); Trumbo et al., 1968, Noble et al., 1967; McLeod, 1973; Bornemann, 1942 (a, b)). There is little evidence to suggest that practice effects are transferable between dual–task combinations.

With regard to automated skills and workload, Moray (1988) states that 'even very highly skilled pilots whose manual control skills are highly automatic, experience severe load when flying in turbulent air'. This suggests that practising until hit rate reaches a plateau — where there may be an element of automatisation — does not affect the requirement for workload; even automatic tasks require resources it seems. Therefore, recording single and dual–task scores only after sufficient practice has taken place for performance to plateau should control any practice effects. Counterbalancing condition presentation order should also help to counteract practice and fatigue effects.

The richness of the information that can be potentially extracted from POC curves makes the extra effort worthwhile. Fundamentally, the power of the POC curve to represent dual–task performance provides a highly sensitive diagnostic that is not achieved by using any of the other workload measures.

5.4 Summary

The measure which has been chosen to measure workload in subsequent analyses in this thesis is the dual–task technique. The methodological argument for this is based upon the fact that it is a direct measure of performance, it is relatively straight forward to implement, and that it is a highly sensitive and diagnostic technique. Other techniques were described but none of them are able to meet all of these criteria.

As mentioned in Section Three, the dual–task technique involves performing two tasks at the same time and comparing each task's dual–task score to their single task score (when that task is performed by itself). If task performance is worse during the dual–task condition that it is in the single task condition then dual–task interference is said to have occurred. When many dual–tasks are performed, it is possible to make inferences about the types of dual–tasks that are associated with interference and those that are not. The theory behind why some dual–tasks cause interference and others do not was the subject of Section Three.

Dual–task scores can also be standardised by converting them into percentages of the single task scores, which enables direct comparisons to be made between each task within the dual–task and between different dual–task combinations.

However, in order to address the issue of effort allocation in dual–task performance, this measure is coupled with on–screen effort allocation indicators (a method of controlling effort devised by Gopher et al. (1982). This provides feedback to the operator regarding whether they need to increase or decrease effort on either task. Because this feedback may cause interference during the dual–task condition, single task conditions should also be performed with the on–screen feedback so that any interference is controlled as much as possible.

This method of controlling effort enables many different variations in proportional effort and each variation provides a separate data point so that overall dual–task performance can be represented on a curve. This curve is called the Performance Operating Characteristic (POC) curve and the area beneath the curve represents dual–task performance and gives an indication as to whether resources are totally shared, partially shared or totally independent.

When difficulty is manipulated, this results in a 'family' of POC curves and the effect that variations in difficulty has on the area beneath the curve, indicates the difficulty level required to reveal resource sharing.

This approach results in a battery of dual–task tests that greatly enhances the diagnosticity and sensitivity of the dual–task technique, in a way that is unrivalled by any other technique. However, it requires a complex design and its execution can be time–consuming. It was suggested that practice and fatigue effects can be controlled through prior practice until performance plateaus and also through counterbalancing condition presentation order.

6 Summary of Literature Review and Proposed Studies

6.1 Summary of Literature Review

The haptic sense has four sub–senses: tactile sensation; proprioception; thermoreception; and nociception. Natural separation exists within the nervous system between tactile/ proprioceptive processing and thermoreceptive/ nociceptive processing. Tactile sensation and proprioception are processed within the same 'unisensory' area of cortex (the somatosensory cortex), however, it is possible to lose one haptic sub–modality through injury or illness whilst the rest remain intact. It is therefore unclear whether these sub–senses should be treated as separate senses in their own right.

In recent years there has been a surge of interest in tactile and proprioceptive haptic displays for use in multi–display environments such as the cockpit. The main impetus for haptic displays in the cockpit is to off–load the visual sense to prevent overload and the resultant loss of situation awareness, which can have devastating consequences. The rationale is that spreading inputs across multisensory displays will result in reduced workload and therefore improved performance and safety. However, haptic workload capacity is unknown and it is not clear whether tactile and proprioceptive displays utilise the same sensory processes or separate sensory processes.

The rationale that spreading information across the senses will improve performance is derived from a huge amount of dual–task findings that have been performed on the visual and auditory senses. These dual–task findings led to the formation of the workload theory called MRT and the workload model by Wickens (1980) called the MRT model. MRT and the MRT model suggest that each sense has its own workload resource, which has limited capacity and that therefore two same–sense inputs will be associated with performance decrement whereas two different–sense inputs will not. According to dual–task findings, spreading the inputs across the senses is not the whole picture; inputs should also differ in terms of processing code in order for the benefits of multisensory inputs to be realised. For example, it is not enough that one input to be visual and the other auditory if they are both spatial tasks or if that are both verbal tasks; one must be spatial and one must be verbal (or the equivalent of verbal in the case of visual tasks*). Therefore this is an important consideration when designing any evaluation of haptic sense workload.

The rationale described above has its roots in the traditional hierarchical and modular view of information processing. This view argues that different sensory inputs are processed in separate unisensory areas of cortex before travelling on to multisensory areas for 'higher' processing. The MRT suggestion that spatial and verbal processing requires separate resources is also related to this modular view. However, recent neuroscientific findings provide evidence for

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* See Section 6.2 for more on the verbal tasks

early multisensory integration in both temporal and anatomical terms, and some of this early integration is evident in 'unisensory' brain areas. This suggests that (a) it may not be appropriate to think of these brain areas as unisensory and (b) that the hierarchical and modular view, of unisensory processing followed by multisensory processing, may not be valid.

In addition, from studies of one particular multisensory brain area involved in directing attention, what appears to determine whether multiple inputs result in performance enhancement or decrement, is spatial and temporal congruency rather than simply the fact that both inputs are same–sense or different–sense inputs. It is possible that the principle of congruency applies to other brain areas involved in multisensory integration.

MRT is based on a huge amount of research suggesting that dual–task performance is better overall when the two tasks utilise different senses. This in fact is supported by neuroscientific findings that multisensory inputs are usually summated and therefore significantly different from either input on its own. However, the MRT principle of separate sensory resources may be misleading and oversimplistic. It is important that recent neuroscientific findings should be taken into consideration in the interpretation of dual–task test results.

6.2 Proposed Studies

It was proposed that the implications of introducing tactile and proprioceptive displays on workload be addressed in two studies:

(1) Study One — To examine whether two tactile tasks or two proprioceptive tasks can be performed at the same time without performance decrement

(2) Study Two — To examine whether tactile or proprioceptive tasks can be performed at the same time as visual or auditory tasks without performance decrement

The approach that was taken was the dual–task approach for reasons outlined in the Section Five of the Literature Review.

It was expected that there would be an effect of sense on performance (that different–sense tasks would be associated with significantly better performance than same–sense tasks), which is suggested by previous dual–task studies and by the neuroscientific findings of multisensory summation.

In Study One, any effect of sense would indicate that tactile and proprioceptive sub–senses are treated as different–sense inputs by the brain. However, if no effect of sense occurred in Study One, this would indicate that tactile and proprioceptive sub–senses are not treated as different–sense inputs.

Regardless of whether there was an effect of sense in Study One or not, it was important to examine whether each type of haptic input affected auditory and/ or visual workload capacity. There were many possible permutations and these are listed in the section entitled Introduction to Study Two.

Note that because dual–tasks studies, as outlined in Section Three, suggested that input 'type' or processing code also affects performance, this needed to be controlled and so each input was either verbal or spatial in nature. Therefore, a secondary expectation in both studies was that there would also be an effect of processing code upon performance. Jointly, evidence of both effects would mean that inputs that differed in terms of both processing code and sense would be associated with significantly better performance than inputs that were similar in either processing code or sense. However, it is feasible that one effect may occur but not the other and this would be revealed by the overall pattern of results.

As with visual tasks, the nature of using proprioceptive and tactile tasks means that the tactile and proprioceptive 'verbal' tasks may not be considered strictly verbal because they do not involve spoken letters/words. Tactile and proprioceptive verbal equivalents would be coded or symbolic representation of information. Visual 'verbal' tasks (i.e. written letters and words, or text) are essentially symbols as well; they certainly do not fall within the proper definition of 'verbal', but verbal is the term that cognitive scientists and psychologists use to describe the visual equivalent of the auditory verbal task. Therefore the same principle could be applied to haptic equivalents as well.

Indeed, evidence suggests that 'symbolic' information is processed verbally because it activates verbal 'labels' (Potter et al., 1980; Robinson & Eberts, 1987). This is supported by dual–task research specifically showing that abstract and non–abstract visual object processing is associated with greater interference by visual verbal tasks than visual spatial processing is, probably because the former activates verbal 'labels' whereas the latter does not (Postle et al., 2005). Therefore, the spatial versus verbal processing code effect should still be revealed by comparison of spatial tasks with non-spatial symbolic tasks. Care was taken to ensure that the symbolic verbal tasks were distinctly non–spatial in nature, so that these tasks would not require spatial processing. Assuming all of the non–spatial tasks could be considered (a) non–spatial and (b) ideally all of the same type i.e. symbolic of some verbal label, then any effects of processing code would be valid. To avoid confusion, the term verbal is used throughout, instead of using 'symbolic'. In addition, the term symbolic could be misunderstood; afterall symbology can be used to represent spatial information, in addition to being 'emblematic' of a verbal label. Therefore, use of the word verbal highlights the purpose of the haptic symbol and therefore the purpose of the haptic verbal task, i.e. to provide symbols that are emblematic of verbal labels. It is clear from the use of the word 'verbal' in the context of visual tasks (such as within Wickens' MRT model, 1984), that it is meant to describe the purpose of the task rather than suggesting, incorrectly, that the visual tasks employ spoken words (the proper definition of verbal). Thus, the same principle as used by Wickens (1984) for visual tasks was extended to the haptic tasks during this research: if the purpose of the task was to provide symbols that were emblematic of verbal labels then the task was termed verbal, whereas if the purpose of the task was to convey spatial information then the task was termed spatial.

Note that care was also taken to ensure that the auditory and visual inputs in Study Two were of a similar nature to the haptic inputs (i.e. non-spatial 'symbols' rather than spoken or written words). It is worth pointing out that multi–display environments such as the cockpit are full of visual displays that are primarily symbolic in nature rather than textual. Auditory warnings can be symbolic warning sounds as well as spoken words. Haptic displays for use in the cockpit, such as TSAS (see Section Two), are able to present two types of information: spatial and 'verbal' (where haptic inputs are symbolic or emblematic of verbal labels, e.g. 'friendly target' or 'enemy target'). This is also the case for proprioceptive displays that seek to not only provide spatial cues but symbolic cues regarding turbulence for example (see Section Two). Therefore one could argue that there is good reason to examine dual–task performance using symbolic inputs (be they haptic, auditory or visual in nature) as opposed to strictly verbal inputs (which by the proper definition can only be spoken auditory words).

Finally, the notion of spatial versus 'verbal' input separation within the haptic sense was suggested in Section One, when it was mentioned that although Ian Waterman lost all proprioception and cannot pick up a glass without visual feedback, he can smoothly produce gestures (clearly a haptic equivalent of auditory verbal communication) whilst he is speaking without any visual feedback (see Cole et al., 1998; McNeill, 1992). Therefore, this neurological evidence provides further support for the notion of separation between haptic spatial processing and haptic 'verbal' processing (albeit this evidence refers to processing involved in output production rather than input processing).

For the hypotheses, see Introduction to Study One and Introduction to Study Two.

The results of Study One and Study Two would have practical implications for the introduction of haptic displays into environments such as the cockpit i.e. can more than one haptic display be used at the same time and can both tactile and proprioceptive type displays be used at the same time as auditory and visual displays?

In addition, the results would contribute to our understanding of the haptic sense and to our understanding of multi–input processing in general, as well as being of interest to human factors and engineering practitioners.

III: STUDY ONE

7 Introduction to Study One

The purpose of Study One was to examine whether two tactile tasks or two proprioceptive tasks can be performed at the same time without performance decrement.

This would have implications for the introduction of haptic displays into environments such as the cockpit, which it has been suggested would benefit from haptic displays if this had the effect of reducing overall workload.

It was expected that there would be an effect of sense on performance (that different–sense tasks would be associated with significantly better performance than same–sense tasks), which is suggested by previous dual–task studies and by the neuroscientific findings of multisensory summation.

In Study One, any effect of sense would indicate that tactile and proprioceptive sub–senses are treated as different–sense inputs by the brain. However, if no effect of sense occurred in Study One, this would indicate that tactile and proprioceptive sub–senses are not treated as different–sense inputs.

It was also important to control processing code as described in Sections Three and Six of the Literature Review. Therefore a secondary expectation was that there would also be an effect of processing code on performance (different processing code inputs would be associated with better performance than same processing code inputs).

The methodological approach that was adopted was the dual–task technique, coupled with the on–screen effort allocation controls described, both of which were described in Section Five of the Literature Review. The methodological design, controls, equipment, participants and procedure are described in the section entitled Method for Study One.

The results were represented using performance operating characteristic (POC) curves (see Section Five for more on this) and the differences between (a) dual–task performance and single task performance and (b) performance on one dual–task against that on another dual–task, were tested using the analysis of variance (ANOVA) statistical technique. The results are presented in the section entitled Results for Study One.

Finally, the results are briefly discussed in the section entitled Discussion for Study One, before moving on to Study Two.

The hypotheses for Study One are described below.

7.1 Hypotheses for Study One:

Hypothesis One — Dual–task performance would be significantly worse when input sense for both tasks is the same.

Hypothesis Two — Dual–task performance would be significantly worse when input processing code for both tasks is the same.

8 Method for Study One

8.1 DESIGN

The overall design was repeated measures with counterbalancing. The measure chosen was the dual-task or secondary task measure. Participants were asked to perform a multitude of different tasks. First of all, each task was performed by itself (single task condition) and then each task was performed with the other tasks in pairs (dual–task condition). The goal was to see if certain dual–task combinations were easier to perform than other dual–task combinations. In order to measure performance, performance on each task within the dual–task pair was compared to respective single task performance.

Only one workload measure was used in this research, the dual-task or secondary task measure, as this measure was considered to be the most appropriate measure to make dual-task comparisons, control user effort and analyse the results for evidence of resource sharing (using the POC curve for example) (see Section Five for more on this decision). Comparing one measure against another was beyond the scope of this research. Finally, the complexity of the design meant that the number of participants and time required per participant were significant and, although the addition of another measure may have been interesting, it was not possible for these practical reasons.

8.1.1 INDEPENDENT VARIABLES

There were four independent variables (IVs): Task, Policy, Input Sense, and Input Processing Code, as described below.

Independent Variable One — Task

The first IV was task, which included nominal labels for the 'position' that each tasks holds within the dual–task, as follows:

- Task one (left–hand side)
- Task two (right–hand side)

Note that a particular task may be labelled task one in one dual–task combination and task two in another dual–task combination. This was dictated by the natural positioning of equipment in relation to other equipment and reflected in the position of task on–screen feedback. For example, if one piece of equipment was placed on the left on one dual–task then the on–screen feedback for that task would also be on the left–hand side of the screen. Left-hand feedback was always labelled task one. In another dual–task combination, the same task may positioned on the right and therefore labelled task two, usually because, with so many combinations, it was not possible to maintain the same relational position for each task all of the time. On–screen feedback for task two was always presented on the right–hand side of the screen.

Independent Variable Two — Policy

The second IV was policy or, more fully, resource allocation policy. Resource allocation policy was explained in Section Five. The levels included:

- 25%
- 50%
- 75%

Note that during dual–task conditions, resource allocation policies must add up to 100%; therefore, if the policy for task one is 25% then the policy for task two must be 75%; if the policy for task one is 50% then the policy for task two must also be 50%; and if the policy for task one is 75% then the policy for task two must be 25%.

Independent Variable Three — Input Sense

The third IV was input sense, which is the sensory modality used to convey inputs to participants during each task, as follows:

- Proprioceptive — inputs are conveyed using forces
- Tactile — inputs are conveyed using vibrations

Independent Variable Four — Input Processing Code

The fourth IV was input processing code, which is the type of category of information presented to the participant during each task, as follows:

- Spatial — Geometric data, e.g. directions in space such as waypoints and target localisation & proximity; reference frames such as for spatial orientation, speed awareness etc.; and border indicators pertaining, for example, to course and airspace restrictions.
- Haptic equivalent of verbal* — Coded information, e.g. flight related data such as altitude, fuel and engine alerts, radar signal identification etc.; target related data such as target discrimination & identification; and covert communication related data such as between crewmembers, between aircraft etc.

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* See Section 6.2 for explanation of the haptic equivalent of verbal

Combining Independent Variables Three & Four — Creating the Input Condition

Each task presented one category of processing code information through one sensory modality. Therefore IV three and IV four were combined within each task to create the following task *conditions*:

- Proprioceptive Spatial
- Proprioceptive Verbal
- Tactile Spatial
- Tactile Verbal

When it came to analysis of the results, any effect of condition would indicate that a significant difference between task performances had occurred. However, because it was not possible to separate input sense from input processing code, inferences about the relative effects of these IVs would need to be made by examining all the results as a whole, to see if a pattern emerged where an effect of condition had occurred and where it has not.

Proprioceptive feedback was provided using the Sidewinder Force Feedback two joystick, whereas all the tactile feedback was provided using the CyberGlove. Please refer to the section on Equipment for more details of these items. The tasks were as follows:

Tactile Verbal

The aim of this task was to respond to information that had been coded into vibration rhythms from the glove 'tactors'. There were two different rhythms (a series of short equal length pulses of vibration or a series of alternately medium then short pulses of vibration) and the participant received one or other of these rhythms through all the glove tactors in synchrony. The key difference between these vibrations was the nature of the inputs rather than any spatial references. Inputs did not vary as a result of spatial location but were designed to provide 'coded' information about 'events' using nominal associations that are reminiscent of Morse code. Responses were made using the thumb buttons on the joystick, which was gripped whilst wearing the glove. Participants were told that the rhythms represented 'friendly' or 'enemy' target alerts.

Tactile Spatial

The aim of this task was to find a target using 'guiding' vibrations from the glove tactors. To be more specific, the participant's gloved hand gripped the joystick in a standardised way so that a specific tactor referred to 'forward', another referred to 'back', another to 'left' and another to 'right'. Vibrations indicated distance from target (the intensity of vibrations increased with distance from the target) and the idea was to move the joystick away from the vibrating tactor(s) until the vibrations stopped. Note that two tactors could vibrate at the same time to indicate that a diagonal correction was required. When the vibrations stopped the participant had to press the 'fire' thumb button on the joystick to acknowledge the target and kick–start the process again. This was essential to ensure that the participant had registered that the vibrations had stopped and therefore they realised subsequent vibrations related to another target (otherwise confusion could set in). This task was reminiscent of TSAS, whereby spatial guidance is provided to pilots via vibrating tactors within the device (which is worn, however, as a jacket rather than a glove). Participants were told that they were 'flying' over a target area and had to manoeuvre the 'aircraft' towards the target in question. This task was a spatial task because the inputs provided spatial cues and despite the fact that inputs could provide proximity as well as location cues, the nature of these cues remained the same throughout, varying only as a result of spatial factors.

Proprioceptive Verbal

The aim of this task was to respond to information that has been coded into forces using the force–feedback joystick. Participants gripped the joystick in question and they moved it backwards and forwards at any pace that felt most natural to them. They received two types of force feedback: resistance (a friction would be felt for a few seconds making the joystick more difficult to move) or force (a discrete 'nudge' would be felt that would promptly 'push' or 'pull' the joystick towards a random direction). The key difference between these inputs was their nature and how the nature of the inputs provided information about 'events' rather than having the same type of input at different locations to provide spatial references. The inputs did not vary as a result of spatial factors but were designed to provide 'coded' information about an event in the form of nominal associations. Responses were made using the joystick, by pressing the button that corresponded with that force. The participants were told that the different forces represented 'aircraft flying handling' feedback.

Proprioceptive Spatial

The aim of this task was to find the location of a target using the forces from the joystick. The participant had to firstly locate the path (walled by resistance on each side) then follow that path to its end to find the target (indicated by a discrete 'nudge'). Responses were made by pressing the joystick 'fire' button once the target force had been located. Similarly to the tactile spatial task, this task was specifically spatial in nature as the feedback was the same throughout, with the only varying factor being spatial location. Participants were told that they could guide their tractor beam/ missile to the target by following the path of least resistance where upon they would get a nudge indicating target acquisition and then the process started again with a new path and target.

Note that during each of these tasks, participants were provided with a scenario so that interest, memory of the task and a sense of urgency could be encouraged. Because the goal was to get as many 'hits' as possible, it was important that participants responded promptly and did not lose interest in these rather simple and repetitive tasks. Each task scenario was slightly different but the context remained closely related (that of 'flying' an 'aircraft') so that no matter what the task combination was, plausibility could be maintained. The choice of tasks was informed through consultation with an RAF pilot during the pilot trials.

Summary of the Tasks' Information Processing Requirements

Spatial tasks – both distance and direction to target needed to be processed.

TS – Participants needed to process vibrations. The location of vibrations indicated direction. Subsequent changes in location of vibrations on movement of stick provide feedback on direction. Diminishing or increasing vibration frequency indicated distance to target. Cessation of vibrations indicated that the target had been reached.

PS – Participants needed to process forces. The location and direction of an initial 'nudge' indicated direction. Subsequent changes in central and side forces on movement of the stick provide feedback on direction. The diminishing or increasing distance between side forces (the 'width' of 'path') indicated distance to target. A short 'jolt' indicated that the target had been reached.

Verbal tasks – two different inputs symbolic of two items of information needed to be discriminated between.

TV – Participants needed to process vibrations. There were two different vibration rhythms symbolic of two different items of information (respectively).

PV – Participants needed to process forces. There were two different types of forces symbolic of two different items of information (respectively).

8.1.2 DEPENDENT VARIABLE — DUAL–TASK PERFORMANCE

The dependent variable (DV) was dual–task performance i.e. the number of hits per minute on each task performed within the dual–task combination. The following table (Table 1) indicates the DV for each task:

Table 1: The dependent variables for Study One

Task Condition (IV 3 & IV 4)	**Dependent Variable**
Proprioceptive Spatial	Number of targets correctly positioned (referred to as hits) using force feedback
Proprioceptive Verbal	Number of correct responses (referred to as hits) to warning–related information pertaining to aircraft flying handling, presented through force feedback
Tactile Spatial	Number of times the aircraft is correctly oriented (referred to as hits) towards a target, using vibration feedback
Tactile Verbal	Number of correct responses (referred to as hits) to target–related information presented using vibration feedback

The DV levels included:

- Number of hits for Task one at 25%
- Number of hits for Task one at 50%
- Number of hits for Task one at 75%
- Number of hits for Task two at 25%
- Number of hits for Task two at 50%
- Number of hits for Task two at 75%

The DV results always came in pairs (as there were two tasks in the dual–task condition). Because resource allocation policies for each dual–task condition had to add up to 100%, the DV pairs for each dual–task condition were as follows:

- Task one 25% & Task two 75% (e.g. TSTV 25_75)
- Task one 50% & Task two 50% (e.g. TSTV 50_50)
- Task one 75% & Task two 25% (e.g. TSTV 75_25)

8.1.3 CONDITIONS IN DETAIL

Single Task Conditions

The single task conditions (listed below) were performed in order to have a control by which to compare dual–task performance. They were performed by themselves and therefore allow 100% resource allocation. Note that the single task condition is different from the hypothetical dual–task condition where resource allocation is 100_0 or 0_100, because, in the latter, two tasks are presented at the same time despite 100% allocation towards one of the tasks. In the latter case, distraction may occur and this cannot be said to be a fair representation of single–task performance. It was important to use true single tasks as the comparison to the dual–tasks so that a true reflection of any dual–task decrement or enhancement could be obtained.

Each single task condition lasted for one minute. The four single task conditions included:

1. Proprioceptive Spatial (PS)
2. Proprioceptive Verbal (PV)
3. Tactile Spatial (TS)
4. Tactile Verbal (TV)

Dual–Task Conditions

The dual–task conditions required two tasks to be performed at the same time and therefore potentially required a certain amount of resource division. As mentioned, the policies adopted were 25_75, 50_50 and 75_25. The six dual–task conditions included:

1. Proprioceptive Spatial & Proprioceptive Verbal (PSPV)
2. Tactile Spatial & Proprioceptive Spatial (TSPS)
3. Tactile Spatial & Proprioceptive Verbal (TSPV)
4. Tactile Spatial & Tactile Verbal (TSTV)
5. Tactile Verbal & Proprioceptive Spatial (TVPS)
6. Tactile Verbal and Proprioceptive Verbal (TVPV)

The following table shows the six dual–task conditions that make up one experiment. Each of the six conditions lasted three minutes (there were three variations of resource allocation priority and each one lasted a minute), therefore, the total time was eighteen minutes.

Table 2: The dual-tasks for Study One in more detail

Independent Variables					Dependent Variables
1. PSPV	Task One	Proprioceptive	Spatial	25%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	75%	Hits as % of single task hits
	Task One	Proprioceptive	Spatial	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	50%	Hits as % of single task hits
	Task One	Proprioceptive	Spatial	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	25%	Hits as % of single task hits
2. TSPS	Task One	Tactile	Spatial	25%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	75%	Hits as % of single task hits
	Task One	Tactile	Spatial	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	50%	Hits as % of single task hits
	Task One	Tactile	Spatial	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	25%	Hits as % of single task hits
3. TSPV	Task One	Tactile	Spatial	25%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	75%	Hits as % of single task hits
	Task One	Tactile	Spatial	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	50%	Hits as % of single task hits
	Task One	Tactile	Spatial	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	25%	Hits as % of single task hits
4. TSTV	Task One	Tactile	Spatial	25%	Hits as % of single task hits
	Task Two	Tactile	Verbal	75%	Hits as % of single task hits
	Task One	Tactile	Spatial	50%	Hits as % of single task hits
	Task Two	Tactile	Verbal	50%	Hits as % of single task hits
	Task One	Tactile	Spatial	75%	Hits as % of single task hits
	Task Two	Tactile	Verbal	25%	Hits as % of single task hits
5. TVPS	Task One	Tactile	Verbal	25%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	75%	Hits as % of single task hits
	Task One	Tactile	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	50%	Hits as % of single task hits
	Task One	Tactile	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	25%	Hits as % of single task hits
6. TVPV	Task One	Tactile	Verbal	25%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	75%	Hits as % of single task hits
	Task One	Tactile	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	50%	Hits as % of single task hits
	Task One	Tactile	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	25%	Hits as % of single task hits

8.1.4 CONTROLS

Control Comparison

The baseline from which to compare dual–task scores was single task scores.

Pilot Trials

Pilot trials were conducted to establish the following:

- Intensity thresholds for each task
- Difficulty levels for each task
- Practice requirements
- Interference from the resource allocation feedback (which required visual monitoring of visuals on a screen in front of the participant); this needed to be minimal or ideally nil
- Other issues such as task scenarios

See Appendix A for full details of Pilot Trials.

Counterbalancing

Practice always took place first, then the single task conditions and finally, the dual–task conditions. However, within those restraints, the presentation of tasks was randomly ordered. This was done by literally pulling the practise task, single task or dual–task pair out of a hat.

The other element that was varied during the practise, single and dual task conditions was resource allocation priority order (i.e. the order in which resource allocation priorities within a dual–task condition were presented, e.g. TSTV 25–75 then TSTV 50_50 versus TSTV 50_50 then TSTV 25–75). Again, this was done by pulling the policy order out of a hat.

Counterbalancing was important to counteract any fatigue or practice effects. Practice effects and fatigue effects are a concern in experiments where participants must perform for an extended period of time. However, in order to achieve the resource allocation feedback, single tasks were always performed before dual–tasks. Counterbalancing the order of single versus dual–task presentation would have been ideal in theory but would have meant (a) an extra single task trial would have been required prior to dual–tasking so that resource allocation feedback could be achieved and this would have extended the total experimental time, perhaps exacerbating any practice and fatigue effects; and (b) in cases where the 'proper' single task was presented after the dual–task, the resource allocation feedback would still need to be based on the 'extra' before–dual–task single task score and therefore, may be different from the 'proper' after–dual–task single task score.

Practice

Before single task scores were recorded, each participant was given three attempts at the single task conditions without the on–screen resource allocation feedback then two minutes with the feedback. This was based on the results of the pilot trials (see Appendix A), which indicated that three attempts were sufficient to train participants to the point when performance plateaued (ceased to improve).

Output/ Response

The output or response that participants had to make to the feedback they received was controlled. Responses were always made manually (as opposed to vocally or a combination of the two types of responses) by pressing the buttons on the joystick being held for each task. However, responses are believed to require separate resources from inputs and therefore, variations in input difficulty is not likely to effect response output, and vice versa (Wickens, 1980, 1984). Finally, when the only factors being systematically manipulated are related to input, it was assumed that subsequent effects occurred as a result of input and not response, which was controlled as mentioned.

Difficulty Level

The difficulty level was informed by the pilot trials (see Appendix A). Difficulty is normally manipulated in order to reveal any resource-limited performance decrements, which might not otherwise reveal themselves if the difficulty level is too easy (refer back to Section 3.2.1 for an explanation of resource-limited performance). However, this means a highly complex design. The pilot trials established the minimum level of difficulty necessary to yield resource-limited performance decrements, which allowed for a much simpler design.

Resource Allocation

Resource allocation was essential to ensure participant effort and task prioritisation were controlled. To elaborate, when participants perform a particular task by itself, they would normally allocate 100% of the available resources to that task. However, when they are asked to perform two tasks at the same time (dual–tasking) they will allocate proportions of the available resources to each task (for example, 25% to one task and 75% to the other task). The challenge for researchers is controlling overall effort and division of effort. This was done through resource allocation indicators on a screen in front of the participant, letting the participant know if he/she needed to put more or less effort into each task (this technique is explained in full in Section Five). This on–screen feedback had the potential to cause interference but because the single task controls were also performed with on–screen feedback, this risk was controlled.

The pilot trials (see Appendix A) indicated that it was only necessary to have three levels (25_75, 50_50 and 75_25) rather than the five previously thought necessary (0_100, 25_75, 50_50, 75_25 and 100_0). This significantly reduced the time each participant was required for (thereby reducing the risk of fatigue and practice effects). Finally, this approach lent itself to representation of the results using Performance Operating Characteristic (POC) curves, which was ideal.

Performance Standardisation

Each participant's dual task scores (in terms of number of hits) were converted to percentages (this is not the same as the policy percentages) — Single Task Performance was treated as 100% and Dual–Task Performance on each task was converted into a percentage of the associated Single Task Performance scores.

This was important so that results from different participants could be averaged and so that the average for one dual–task condition could be directly compared to the average from another dual–task condition. For example: If the single task score for Tactile Verbal was ten (hits per minute), and under a particular dual–task condition the Tactile Verbal score was five (hits per minute), then when the dual–task score was converted to a percentage (of the single task score) it would be 50%.

Participant Controls

See below for participant details.

8.2 PARTICIPANTS

Participants comprised an opportunity sample of seventy eight participants. Of these, twenty five were female and fifty three were male, five were left–handed and seventy three were right–handed. The youngest participant was fourteen and the oldest was sixty. Age breakdown was as follows:

10–19 yr olds — four
20–29 yr olds — fifty
30–39 yr olds — nineteen
40–49 yr olds — four
50–59 yr olds — zero

60–69 yr olds — one

Note that although age, gender and handedness were recorded, these details were not relevant to test the effect of condition on dual–task performance, because participants acted as their own controls. Each participant's dual–task score was standardised into percentages of his/her single task (100%) score and it was the percentage of *change* from that participant's single to dual–task condition that was of interest.

8.3 EQUIPMENT

The equipment, which was the same for both studies, included the following:

- One x *CyberGlove*
- Two x *Sidewinder Force–Feedback two* joysticks
- One x *Haptic Tester* software controlling the equipment on two PCs.
- Two PCs plus two monitors.

8.3.1 *CyberGlove*

CyberGlove (Immersion Technologies*)* is fitted with *CyberTouch* 'tactors' (also Immersion Technologies) to give vibrotactile (vibration) feedback to the user.

Figure 10: CyberGlove (Reproduced by permission of Immersion Corporation, Copyright © 2008 Immersion Corporation. All rights reserved)

There are six tactors in total on the glove and these are located near the end of each finger and thumb and also in the centre of the palm and these can be varied in terms of intensity, frequency and rhythm.

8.3.2 *Sidewinder Force Feedback Two* JOYSTICKS

Two *Sidewinder Force Feedback two* joysticks *(*Microsoft*)* were used for the proprioceptive tasks. The joystick can provide force–feedback to the participant, which is felt as either resistance or 'nudges' to the hand and arm when the stick is held. Feedback can be configured to give a wide variety of sensations and responses are made using the buttons on the joystick.

8.3.3 *Haptic Tester* & GENERAL PC INFORMATION

Haptic Tester (designed by myself, built by Isca Software Services Ltd.) is a program specifically designed to manage every aspect of the experiments, including:

- Equipment configuration and control
- Condition configuration and control
- Equipment & condition 'profile' generation
- Up to four pieces of equipment to be simultaneously controlled
- Individual participant detail records
- Raw results records (hits, misses, response profiles)
- Data files (selected results organised by condition & participant)
- Automatic standardisation of the selected results and calculation of means
- Optional re–formatting of the data into headed columns and rows for SPSS

However, perhaps the key is how *Haptic Tester* controls resource allocation:

- It allows up to four tasks to be simultaneously performed & monitored
- Haptic Tester gives constant resource allocation priority feedback to the participant. Then, Haptic Tester displays any discrepancy between actual and expected number of hits on the screen in the form of moving bars, so that effort can be directed where required.
- Tasks can be split into multiple blocks. Each block is configurable in terms of resource allocation priority.
- Difficulty is also fully configurable.

Additional features of *Haptic Tester* include:

- An optional countdown timer that can be displayed during the experiment
- Optional performance feedback can be displayed for task familiarisation.
- Optional task reference points that can be displayed if necessary.

Two networked computers (both with Windows 98 and USB) are managed by *Haptic Tester* so that two joysticks can be operated at the same time. Two PC monitors were required, one to display the on–screen resource allocation feedback to the participant, and one monitor to display condition and performance related information to the experimenter.

8.3.4 TASK INPUT INFORMATION

Tactile alerts were delivered through vibrating 'tactors' on the ends of the fingers and centre of the palm of the *CyberGlove*, which was worn on the left hand. Responses were made using buttons on the left joystick (gripped by the gloved hand). The vibration frequency was standardised across vibration inputs and set to almost the maximum that the CyberGlove would allow (frequency of 250 hertz). This level is well above the minimum frequency detection threshold for tactile receptors; in fact the optimal frequency of vibration for the rapid response Pacinian receptor is 200–250 hertz (Bolanowski, et al., 1988). Note, however, that in the tactile spatial task, bursts of vibration (at the standardised frequency) increased in terms of burst duration and inter–burst gap, with reduced proximity from target. Conversely, as proximity from target increased, burst duration reduced as well as the gap between bursts, giving a greater sense of urgency, as the bursts of vibrations appeared quicker and more 'stocatto–ed'.

The force alerts were delivered through a joystick and responses were made by pressing the buttons on that joystick stick. The alerts came in the form of forces (delivered either as 'nudges' or resistance). The forces used could be adjusted to be within a limited range from minimum to maximum intensity. This range was selected in the pilot trials (see Appendix A), and was the minimum force obviously noticeable without being jarring or requiring much effort to resist, so to avoid risk of injury. Exact forces were not measured but the forces exerted were undoubtedly above detection threshold in the pilot trials and this is not surprising given the very low detection threshold of the force sensors in the joints and tendons (Tan et al., 1994).

All responses were made using a joystick and this meant that participants had to use two joysticks at the same time to make their responses. The exception to this was when participants were presented with two tactile tasks at the same time. In this circumstance, all feedback came via the same glove and all responses were made using the same joystick (albeit through three different thumb buttons, one for the tactile spatial task and two for the tactile verbal task).

8.4 PROCEDURE

8.4.1 OVERVIEW

The experimenter set up the experiments beforehand by using Haptic Tester to create 'profiles'.

Participants read detailed instructions for each task in turn (the order of which depended upon random allocation). Each set of instructions was accompanied by a demonstration of the task in question, followed by the first practise session, during which the participant received verbal guidance and answers to any questions. Once the task had been introduced in this way, the participant received two practise sessions on that task without guidance. This process was repeated for each task. The aim was to fast–track participants to a standard that stopped improving by the third attempt. This was achievable as the tasks were relatively simple and each practise session lasted one minute (which was ample).

The participant then read instructions on how to use the on–screen resource allocation feedback that they had to follow throughout the dual–task conditions. This was followed by a fourth practise session on each task, this time with the on–screen resource allocation feedback, accompanied by verbal guidance where necessary. Finally a fifth practise session with the on–screen feedback was provided but this time without guidance. It was important firstly to familiarise participants with the feedback and to practice altering their effort accordingly and secondly to confirm that performance did not get worse due to visual interference. Because each practise session lasted one minute, this meant a total of five minutes practice on each task.

Single task conditions were then performed, with resource allocation feedback on the screen as in the fourth and fifth practise sessions. Each single task condition lasted one minute. Participants were randomly allocated to a single task order (literally by pulling an order out of a hat).

Dual–task conditions were then performed, again with the resource allocation feedback on the screen. Each dual–task condition lasted three minutes (one minute per resource allocation policy). Participants were randomly allocated to a dual–task order (again by pulling an order out of a hat).

A time breakdown for each study (not including time for reading instructions) can be seen in the following table:

Table 3: The time breakdown per participant for Study One

Time Breakdown per Participant for Study One	
Practise sessions (four tasks, five practise sessions per task)	Twenty minutes
Single Task conditions (four tasks)	Four minutes
Dual Task conditions (six task pairs, three resource allocation policies per pair)	Eighteen minutes
TOTAL	**Forty two minutes**

8.4.2 USING *Haptic Tester*

All of the trials were set up and run by the experimenter using *Haptic Tester*, which was designed from scratch for the purpose of this PhD, as described in the Equipment section. The reason that Haptic Tester is mentioned in this section on procedure is that it was imperative that each single task score was manually entered into *Haptic Tester* before the dual-task conditions were performed, so that they could be used to control the resource allocation bars essential for these dual-task conditions. *Haptic Tester* could then turn that participant's dual-task score into a percentage of his/her single task score, thereby standardising the results. However, although this part of the process could in the future be conducted automatically by the software, it actually provided useful opportunity for the experimenter to check that single task scores were not vastly different from practise session scores, because if they were, then that could indicate that something had gone wrong (be that participant or software related). This issue did come up once or twice and in those instances was caused by a pc 'crash'. The participants in question were given the opportunity to conduct the single task in question once more and the incident was noted by the experimenter.

Refer to Appendix B for full details of using Haptic Tester.

9 Results for Study One

9.1 Overview

Participants first performed each task on its own (single task condition) and then performed two different tasks at the same time (dual–task condition). There were four different tasks in Study Two (proprioceptive spatial (PS); proprioceptive verbal (PV); tactile spatial (TS); and tactile verbal (TV)), therefore the total number of dual–task conditions was six (PSPV; TSPS; TSPV; TSTV; TVPS; and TVPV). Performance on each task was measured in terms of number of hits and this figure was converted to a percentage of the corresponding single task score, which served to standardize the results.

Participants were also asked to vary the proportion of effort they allocated to each task within each combination (25% (T1) and 75% (T2); 50% (T1) & 50% (T2); and 75% (T1) & 25% (T2)). It was assumed that effort requires some kind of cognitive resource and that when performing a task by itself (single task condition) a participant is able to allocate 100% of that resource to that task. A sample mean was calculated for each task (T1 and T2) at each allocation policy (25%_75%, 50%_50% and 75%_25%), amounting to three means per task and therefore six means for each dual–task condition (or three pairs of means). As mentioned, the scores were percentages of single task scores and as such the means were averages of the percentages not averages of the absolute number of hits.

The three pairs of means for each dual–task were plotted in a scatterplot (one scatterplot per dual–task condition) to produce three points and a reference line connecting each point to produce the POC curve. Note that the points at 100% for each task were the corresponding single task results. If dual–task hits were to exceed single task hits then the scale would be extended beyond 100% but this does not apply for Study One. The position of the curve in relation to the 100% points represents the performance decrement as a function of resource sharing. The further away the points on the curve are from 100%, the greater the performance decrement. When the curve sits about the 50% position or less then total sharing of resources is indicated, as each task will have suffered at least a 50% decrement in performance. A blue reference line has been drawn on each scatterplot at the 50% position.

These results are split into two sections; the first section contains the POC curves and the second section contains the statistical analyses.

For the latter section, repeated measures ANOVA was used to test whether there were any significant differences firstly between each dual–task condition and the respective single task conditions, then secondly between different dual–task conditions. The statistical analyses are described in a little more detail in the next section.

9.1.1 Statistical Analyses

The design was the same for each set of statistical analyses (see Table 4). Each set of results begins with a table displaying the descriptive statistics. This is followed by a description of the ANOVA results. Finally, where significance was found, post hoc results are described and illustrated using graphs. This process is described in more detail in the next section.

Table 4: The generic experimental design for Study One

	Policy	Dependent Variable
Single Task Condition	100 (%)	Number of hits for PS at 100%
Dual Task Condition	25 (%)	Number of hits for PS at 25%
	50 (%)	Number of hits for PS at 50%
	75 (%)	Number of hits for PS at 75%

Significance of Differences between Dual–Task and Single Task Conditions

There were six dual–tasks in Study One and as each dual–task contained two tasks, both of these tasks had to be compared to their respective single task scores, amounting to twelve comparisons. For example, in the PSPV dual–task, the PS and PV scores were separated and then PS was compared to the PS single task score, while PV was compared to the PV single task score. However, within each task from a dual–task, there were three different policies (allocation of effort policies), including 25%, 50% and 75%. The key was to see if there was a significant difference between performance at these policies and performance in the single task condition (100% allocation of effort). The significance of these differences was tested using Within–Subjects ANOVA (this is described in more detail in the next section). If the task had been easy to perform then there would be no significant difference between performance at each of the dual–task policies and at the single task condition policy of 100%.

Significant of Differences between Dual–Task Conditions

As there were six dual–task conditions in Study One, the total number of comparisons was fifteen (PSPV_TSPS; PSPV_TSPV; PSPV_TSTV; PSPV_TVPS; PSPV_TVPV; TSPS_TSPV; TSPS_TSTV; TSPS_TVPS; TSPS_TVPV; TSPV_TSTV; TSPV_TVPS; TSPV_TVPV; TSTV_TVPS; TSTV_TVPV; TVPS_TVPV). Therefore, this section contains fifteen sub–sections, i.e. one set of results per comparison.

Each set of results begins with a table displaying the descriptive statistics and then a description of the ANOVA results. Prior to ANOVA testing, Mauchly's Test of Sphericity was conducted wherever the factor POLICY was involved (either as the main effect or interaction effect) as this factor has three levels (25_75, 50_50 and 75_25). This statistical test is used to determine whether the data entered into the repeated measures ANOVA meet the assumption of sphericity and is only useful for factors with three or more levels (sphericity is assumed for factors with fewer than three levels). If it is significant (less than 0.05) then the assumption of sphericity has been violated. In this instance, one can either conduct multivariate tests (e.g. Wilks Lambda) or do correlations using Epsilon (i.e. Greenhouse–Geisser), which adjusts the degrees of freedom (df) for ANOVA. The latter was chosen for convenience (Greenhouse–Geisser is automatically reported in the ANOVA table that SPSS produces). Note that where the Greenhouse–Geisser correction is applied, the df are always reduced, making it slightly more difficult to get a significant result, because one of the assumptions for ANOVA (that of equal variances) has been violated.

If the ANOVA test finds that there is a significant difference between a particular dual–task condition and another dual–task condition, then the F–ratio sig. value for the term CONDITION will be equal to or less than 0.05. Only results relevant to the focus of the thesis are displayed in the results section.

Finally, each set of results finishes with the post–hoc contrast results, which highlight any significant trends. However, only significant post–hoc results are illustrated (using tables of means and/ or graphs.

9.2 Individual Performance Operating Characteristic (POC) Curves

Proprioceptive Spatial & Proprioceptive Verbal (PSPV)

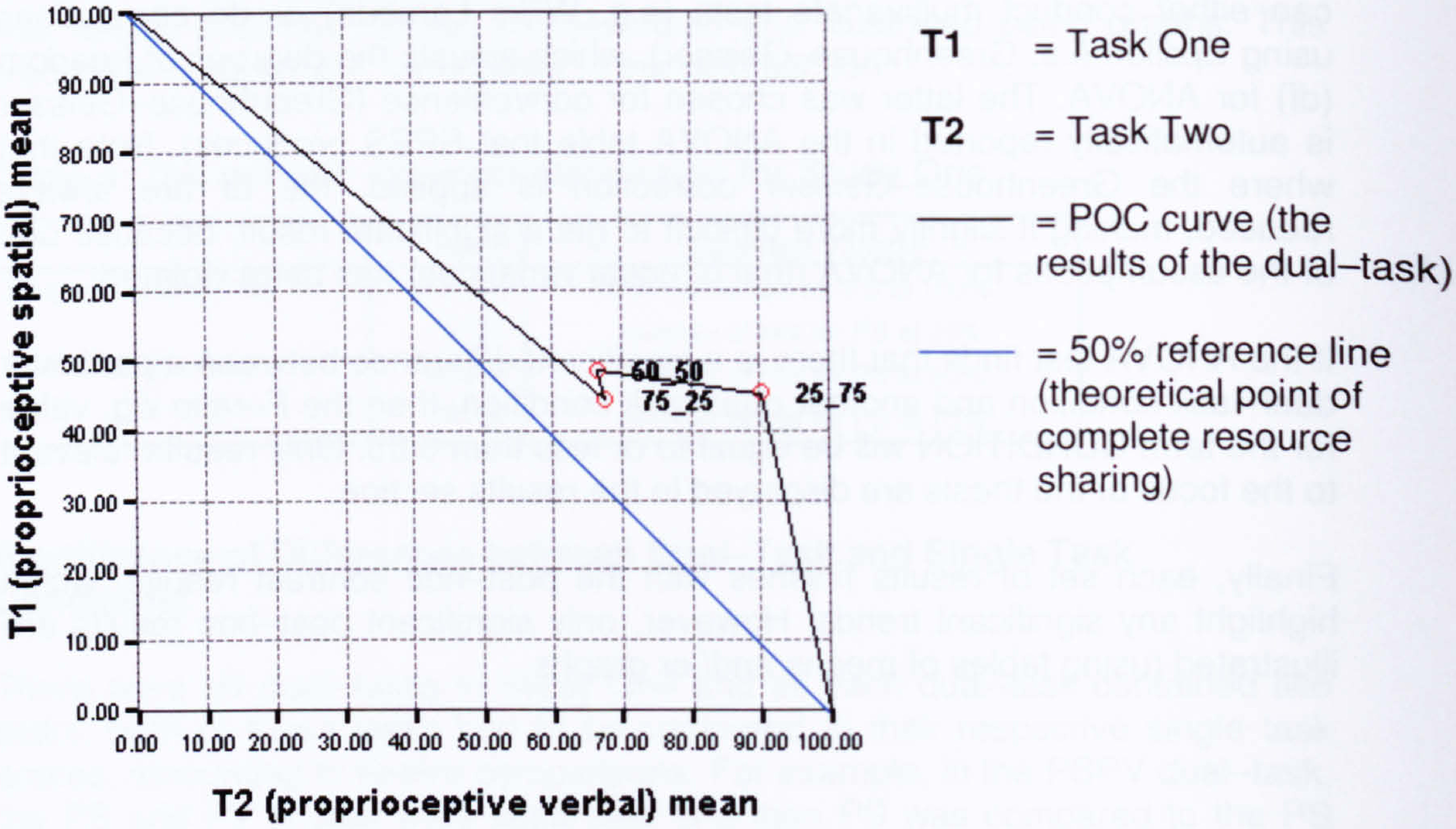


Figure 11: Proprioceptive Spatial (task one) performed at the same time as Proprioceptive Verbal (task two): mean percentage hits

The results of the proprioceptive spatial (task one) and proprioceptive verbal (task two) dual task condition (PSPV) are depicted in Figure 11. The curve almost cuts the graph in half, as each task suffered a significant decrement in performance (60.5% of single task scores), suggesting substantial (approaching total) sharing of resources.

Tactile Spatial & Proprioceptive Spatial (TSPS)

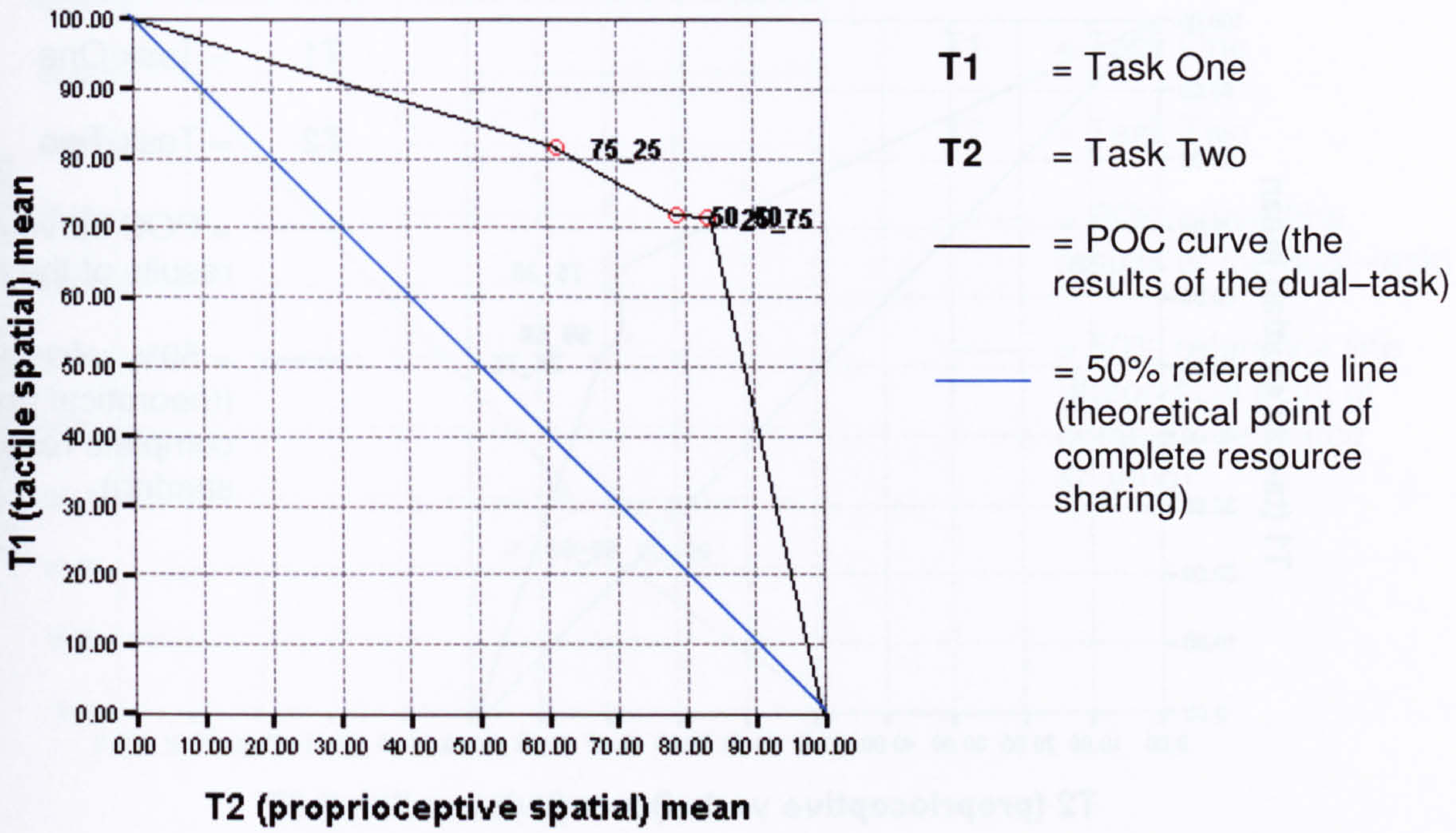


Figure 12: Tactile Spatial (task one) performed at the same time as Proprioceptive Spatial (task two): mean percentage hits

The results of the tactile spatial (task one) and proprioceptive spatial (task two) dual task condition (TSPS) are depicted in Figure 12. The curve sits at approximately 78.5% of single task scores, as each task suffered a decrement in performance of 20–25%. This suggests partial sharing of resources.

Tactile Spatial & Proprioceptive Verbal (TSPV)

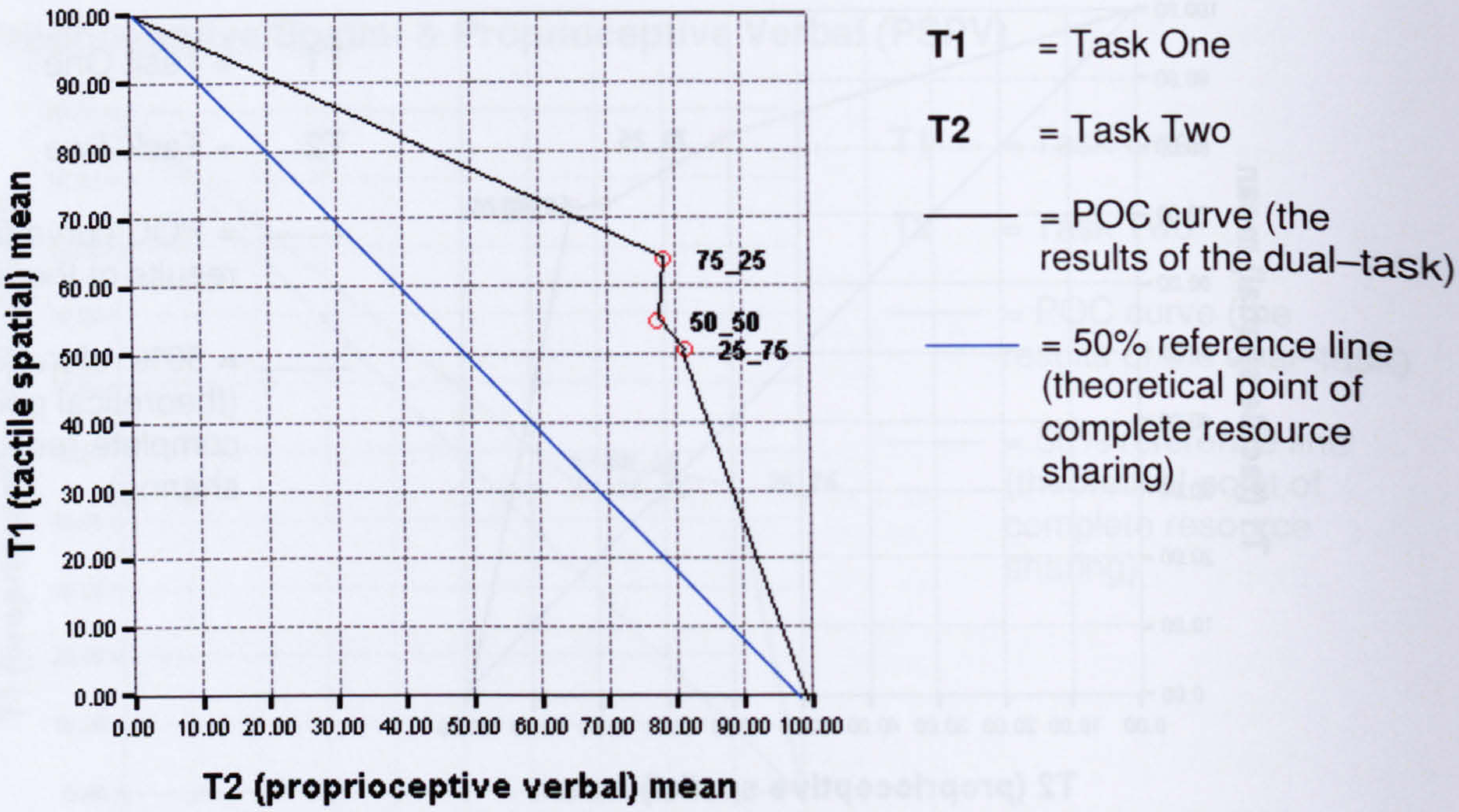


Figure 13; Tactile Spatial (task one) performed at the same time as Proprioceptive verbal (task two): mean percentage hits

The results of the tactile spatial (task one) and proprioceptive verbal (task two) dual task condition (TSPV) are depicted in Figure 13. The curve sits at approximately 70.25% of single task scores, as each task suffered a decrement in performance of about 30%. This suggests partial sharing of resources.

Tactile Spatial & Tactile Verbal (TSTV)

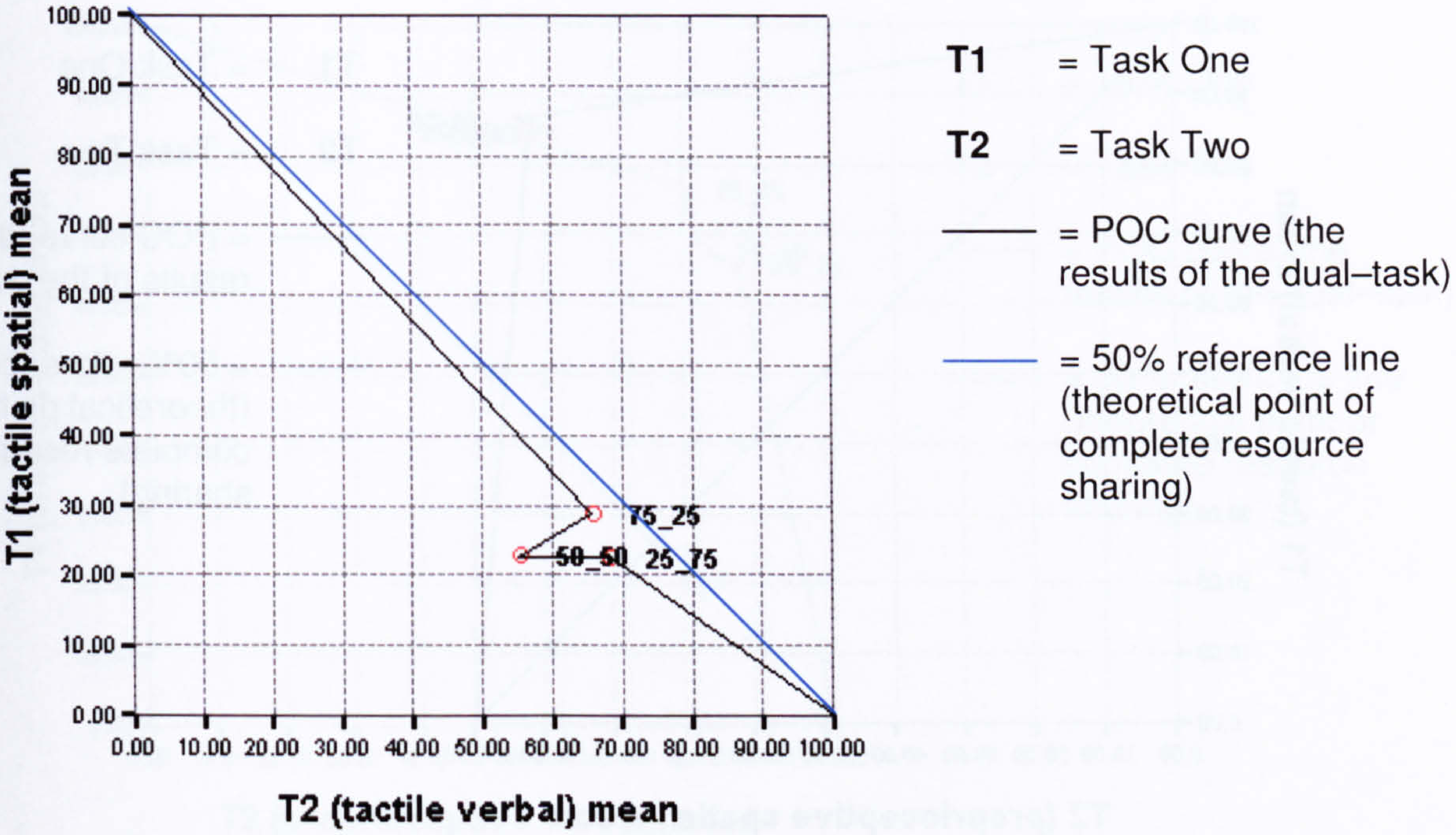


Figure 14: Tactile Spatial (task one) performed at the same time as Tactile Verbal (task two): mean percentage hits

The results of the tactile spatial (task one) and tactile verbal (task two) dual task conditions (TSTV) are depicted in Figure 14. The curve sits below the 50% reference line at approximately 45% of single task scores. Each task suffered a decrement of roughly 55%. This indicates total sharing of resources.

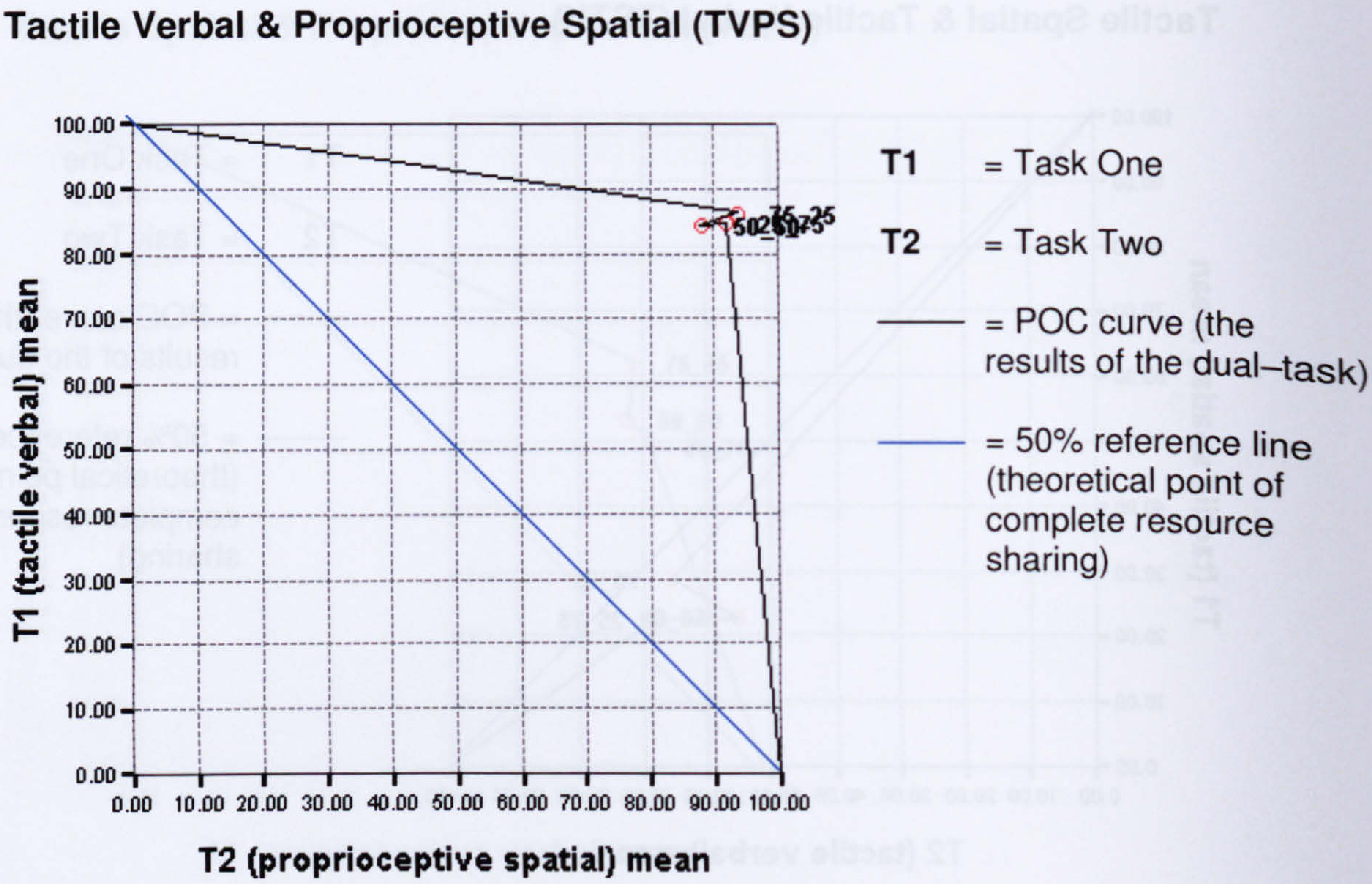


Figure 15: Tactile Verbal (task one) performed at the same time as Proprioceptive Spatial (task two): mean percentage hits

The results of the tactile verbal (task one) and proprioceptive spatial (task two) dual task condition (TVPS) are depicted in Figure 15. The curve sits at 89.5% of single task scores, as each task suffered a decrement in performance of only 10%. This indicates minimal sharing of resources.

Tactile Verbal & Proprioceptive Verbal (TVPV)

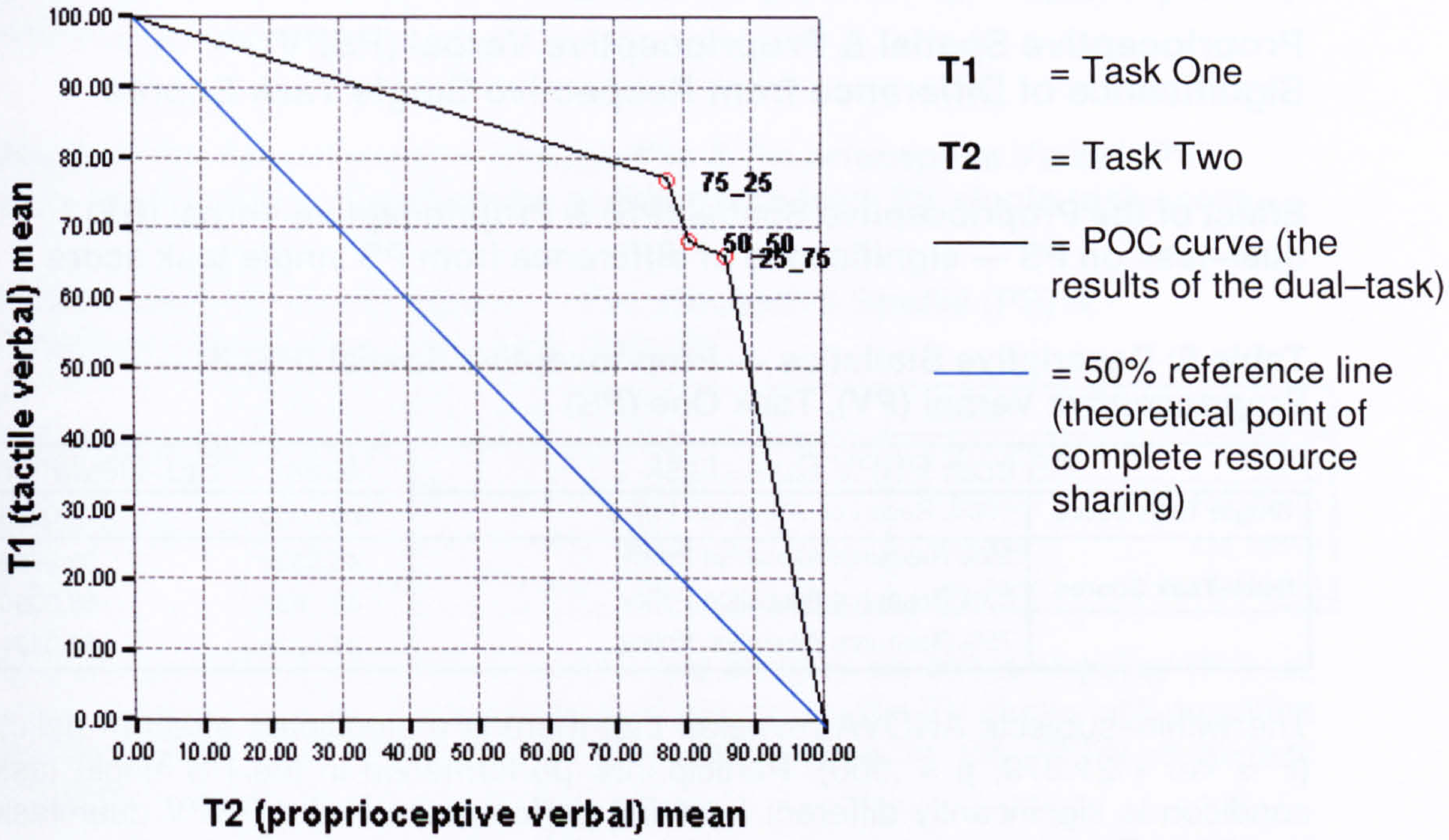


Figure 16: Tactile Verbal (task one) performed at the same time as Proprioceptive Verbal (task two): mean percentage hits

The results of the tactile verbal (task one) and proprioceptive verbal (task two) dual task condition (TVPV) are depicted in Figure 16. The curve sits at approximately 79.75% of single task scores, as each task suffered a decrement in performance of 20%. This suggests partial sharing of resources.

9.3 Significance of Differences between Dual-Tasks and Single Tasks

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) — Significance of Difference from Respective Single Task Scores

Effect of the Proprioceptive Spatial (PS) & Proprioceptive Verbal (PV) dual-task on PS — significance of difference from PS single task score

Table 5: Descriptive Statistics — Proprioceptive Spatial (PS) & Proprioceptive Verbal (PV), Task One (PS)

PS from PSPV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	45.5839	65.26520
	50% Resource Allocation Policy	48.7633	58.00903
	75% Resource Allocation Policy	44.5220	52.04211

The within-subjects ANOVA revealed that there is a significant effect of policy ($F_{(3, 135)} = 21.879$, $p = .000$). Participants' performance in the PS single task condition is significantly different from PS performance in the PSPV dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy ($F_{(1, 45)} = 55.197$, $p = .000$), and Figure 17 shows that single task scores are much higher than dual-task scores.

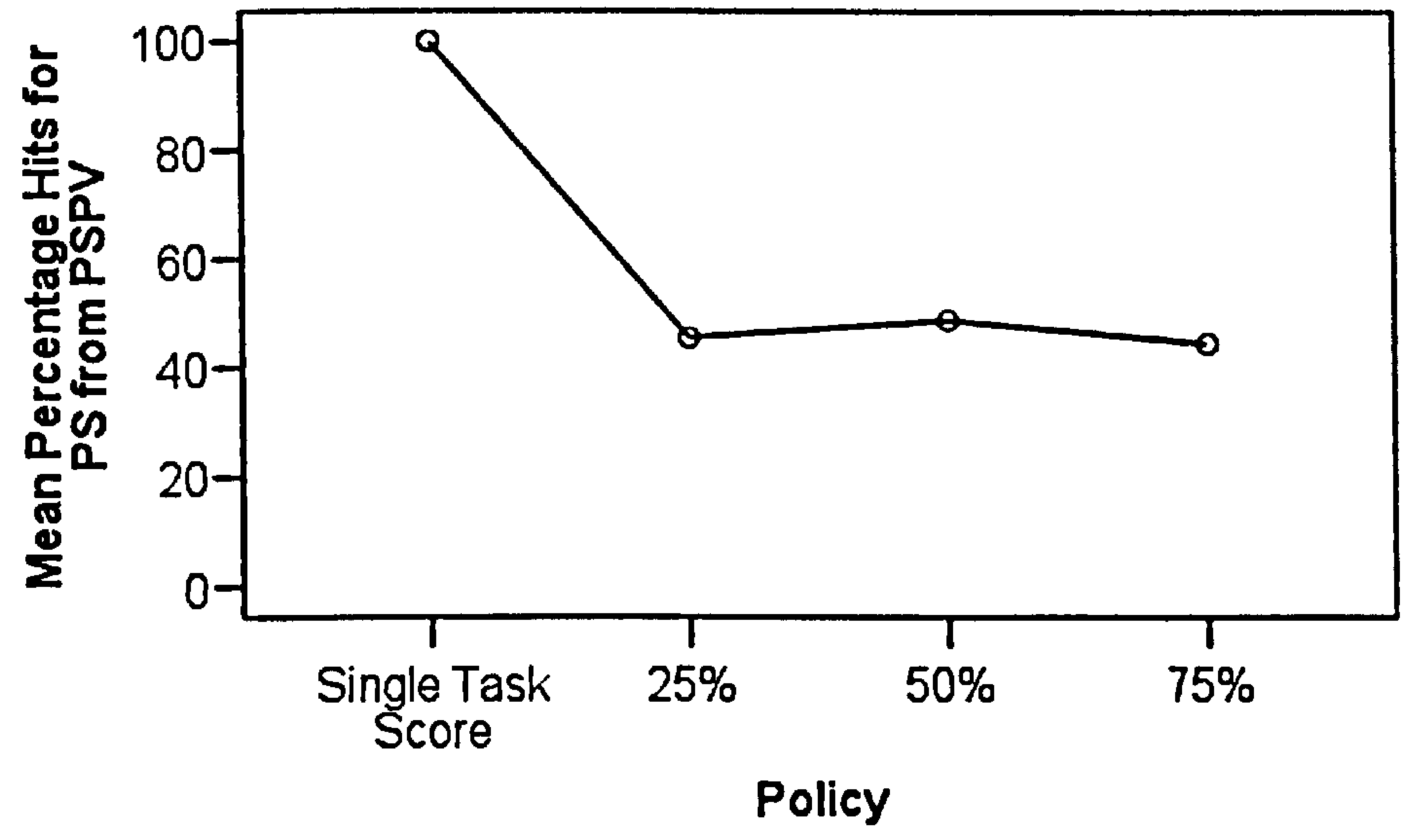


Figure 17: Mean Percentage Hits for Proprioceptive Spatial (PS) from Proprioceptive Spatial & Proprioceptive Verbal (PSPV) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 45) = 31.978, p = .000), at 50% (F (1, 45) = 35.886, p = .000) and at 75% (F (1, 45) = 52.274, p = .000) resource allocation.

Effect of the Proprioceptive Spatial (PS) & Proprioceptive Verbal (PV) dual–task on PV — significance of difference from PV single task score

Table 6: Descriptive Statistics — Proprioceptive Spatial (PS) & Proprioceptive Verbal (PV), Task Two (PV)

PV from PSPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	108.3329	125.20773
	50% Resource Allocation Policy	100.4660	228.28513
	25% Resource Allocation Policy	84.5406	116.41102

The within–subjects ANOVA revealed that there is no effect of policy (F $_{(1.121, 50.459)}$ = .495, p = .506). Participants' performance in the PV single task condition is not significantly different from PV performance in the PSPV dual–task condition.

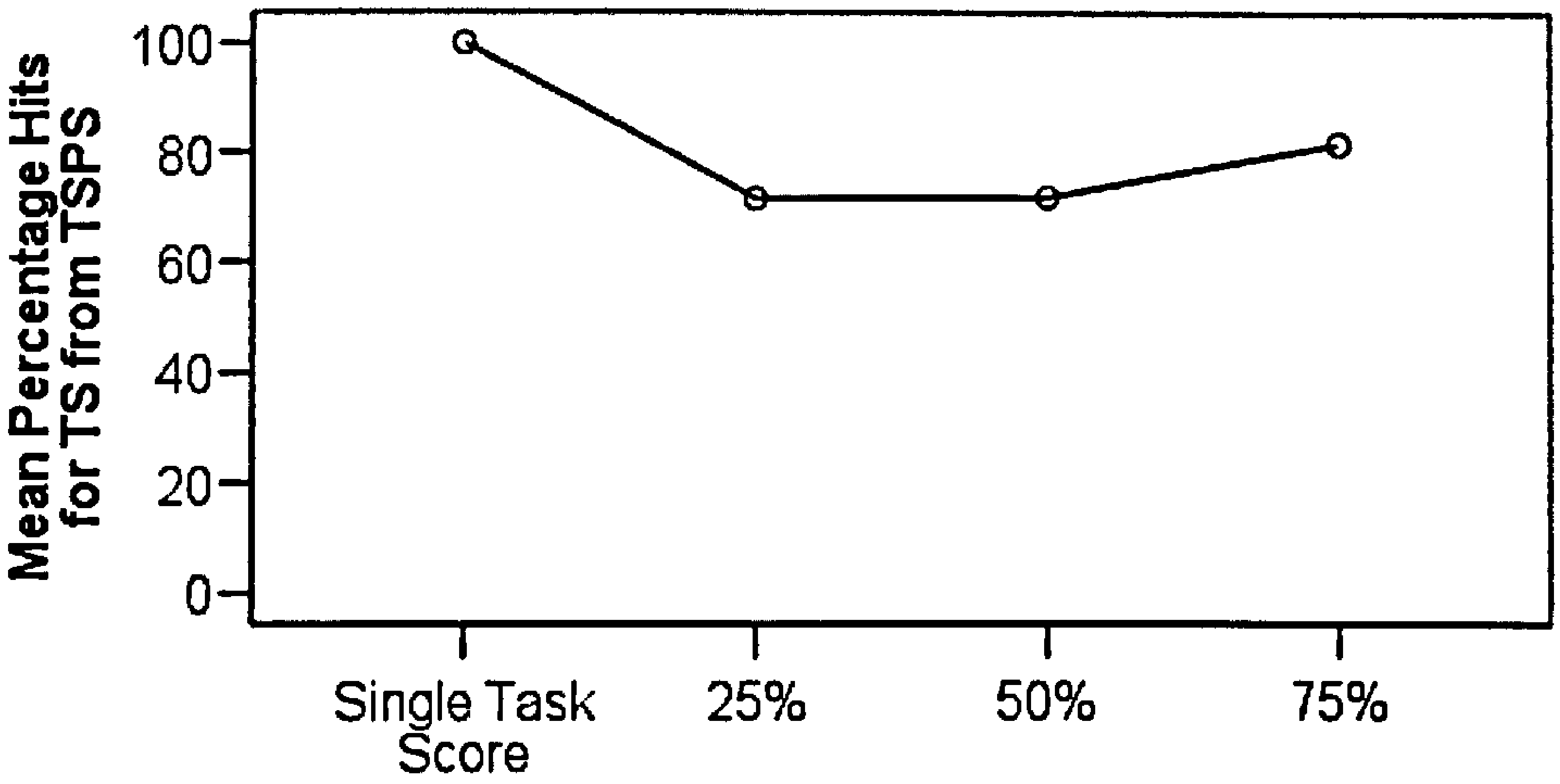
Tactile Spatial & Proprioceptive Spatial (TSPS) — Significance of Difference from Respective Single Task Scores

Effect of the Tactile Spatial (TS) & Proprioceptive Spatial (PS) dual–task on TS — significance of difference from TS single task score

Table 7: Descriptive Statistics — Tactile Spatial (TS) & Proprioceptive Spatial (PS), Task One (TS)

TS from TSPS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	71.5714	53.12671
	50% Resource Allocation Policy	71.8870	47.82571
	75% Resource Allocation Policy	81.6428	39.14684

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(2.427, 116.494)}$ = 9.575, p = .000). Participants' performance in the TS single task condition is significantly different from TS performance in the TSPS dual-task condition. Post–hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 48)}$ = 9.455, p = .003), and Figure 18 shows that single task scores are higher than dual–task scores.



Policy

Figure 18: Mean Percentage Hits for Tactile Spatial (TS) from Tactile Spatial & Proprioceptive Spatial (TSPS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 48) = 14.031, p = .000), at 50% (F (1, 48) = 16.931, p = .000) and at 75% (F (1, 48) = 10.775, p = .000) resource allocation.

Effect of the Tactile Spatial (TS) & Proprioceptive Spatial (PS) dual–task on PS — significance of difference from PS single task score

Table 8: Descriptive Statistics — Tactile Spatial (TS) & Proprioceptive Spatial (PS), Task Two (PS)

PS from TSPS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	83.2829	88.11503
	50% Resource Allocation Policy	78.7327	99.36222
	25% Resource Allocation Policy	61.3677	99.56910

The within–subjects ANOVA revealed that there is a significant effect of policy ($F_{(2.408,\ 115.584)}$ = 3.442, p = .027). Participants' performance in the PS single task condition is significantly different from PS performance in the TSPS dual-task condition. Post–hoc tests confirm that there is a significant linear trend for policy ($F_{(1,\ 48)}$ = 7.213, p = .010), and Figure 19 shows that single task scores are higher than dual–task scores.

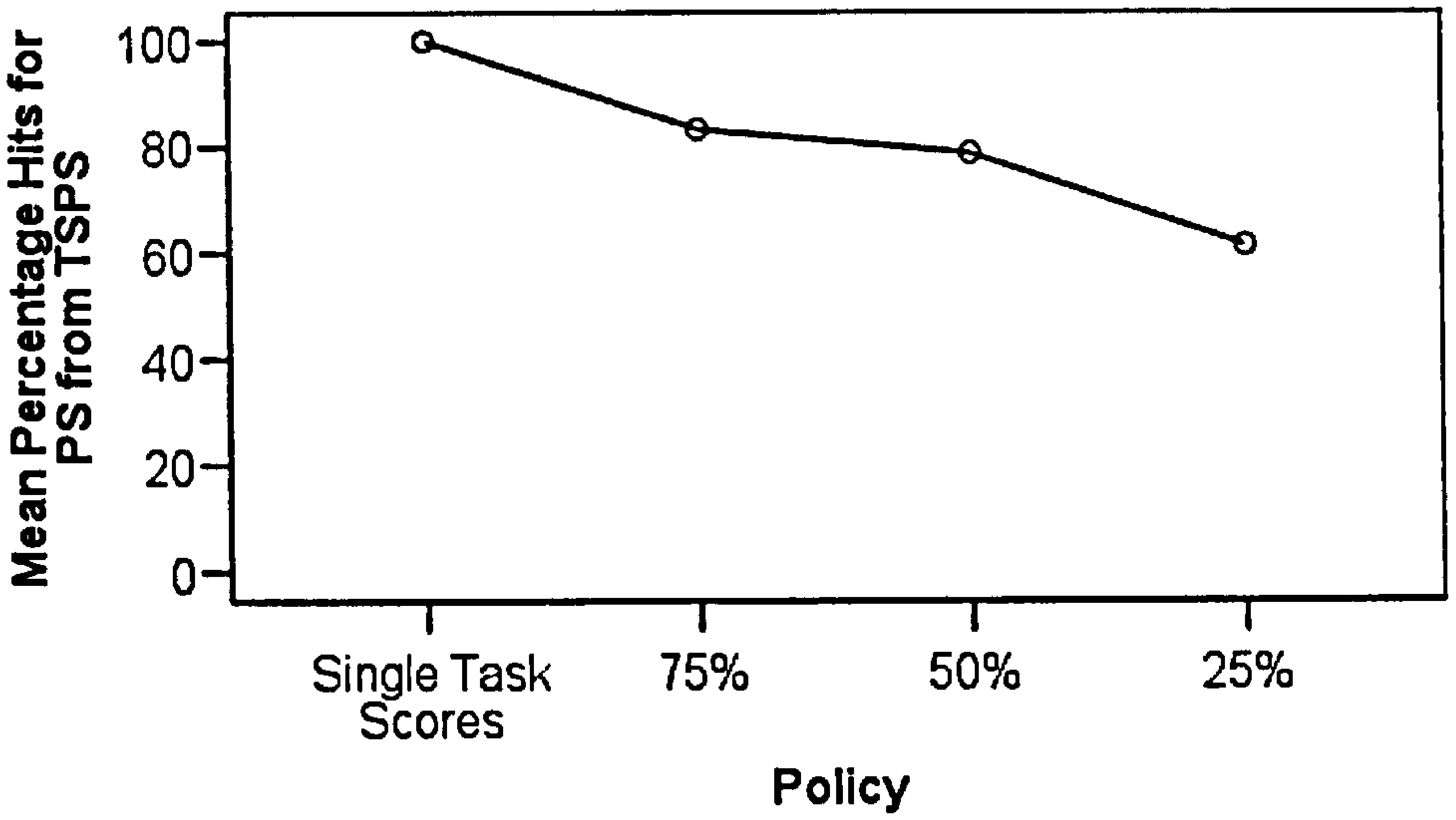


Figure 19: Mean Percentage Hits for Proprioceptive Spatial (PS) from Tactile Spatial & Proprioceptive Spatial (TSPS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 48) = 7.376, p = .009), but not at 50% (F (1, 48) = 2.245, p = .141) and not at 75% (F (1, 48) = 1.764, p = .190) resource allocation.

Tactile Spatial & Proprioceptive Verbal (TSPV) — Significance of Difference from Respective Single Task Scores

Effect of the Tactile Spatial (TS) & Proprioceptive Verbal (PV) dual–task on TS — significance of difference from TS single task score

Table 9: Descriptive Statistics — Tactile Spatial (TS) & Proprioceptive Verbal (PV), Task One (TS)

TS from TSPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	50.6416	35.29916
	50% Resource Allocation Policy	54.9748	43.33598
	75% Resource Allocation Policy	63.8518	39.43686

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(3,\ 153)}$ = 36.924, p = .000). Participants' performance in the TS single task condition is significantly different from TS performance in the TSPV dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy

(F $_{(1, 51)}$ = 38.429, p = .003), and Figure 20 shows that single task scores are higher than dual–task scores.

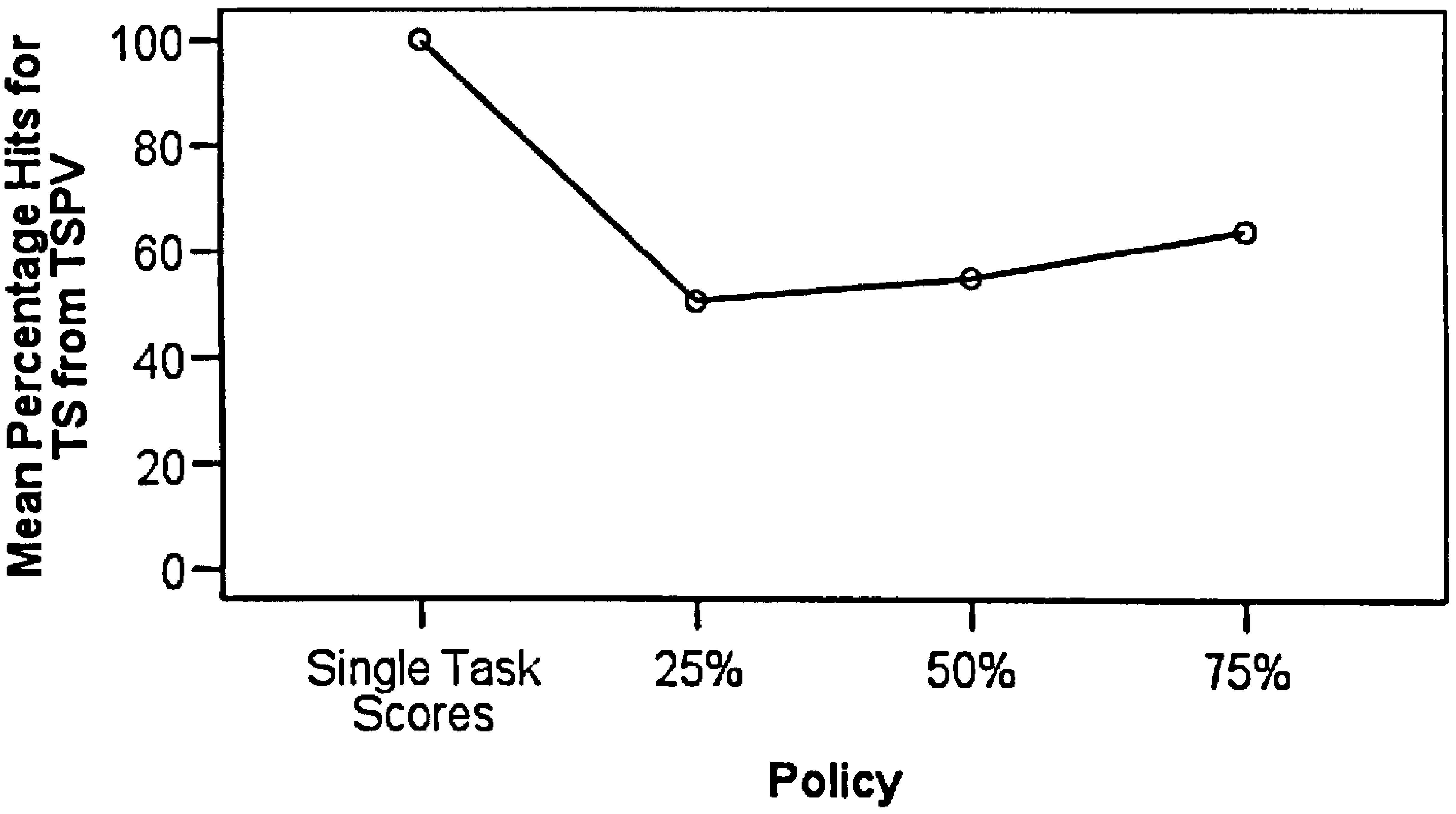


Figure 20: Mean Percentage Hits for Tactile Spatial (TS) from Tactile Spatial & Proprioceptive Verbal (TSPV) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 51) = 101.671, p = .000), at 50% (F (1, 51) = 56.133, p = .000) and at 75% (F (1, 51) = 43.689, p = .000) resource allocation.

Effect of the Tactile Spatial (TS) & Proprioceptive Verbal (PV) dual-task on PV — significance of difference from PV single task score

Table 10: Descriptive Statistics — Tactile Spatial (TS) & Proprioceptive Verbal (PV), Task Two (PV)

PV from TSPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	81.6509	46.12015
	50% Resource Allocation Policy	77.4477	48.85768
	25% Resource Allocation Policy	78.3738	64.52143

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(2.196, 111.972)}$ = 3.955, p = .019). Participants' performance in the PV single task condition is significantly different from PV performance in the TSPV dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy ($F_{(1, 51)} = 5.128$, $p = .028$), and Figure 21 shows that single task scores are higher than dual-task scores.

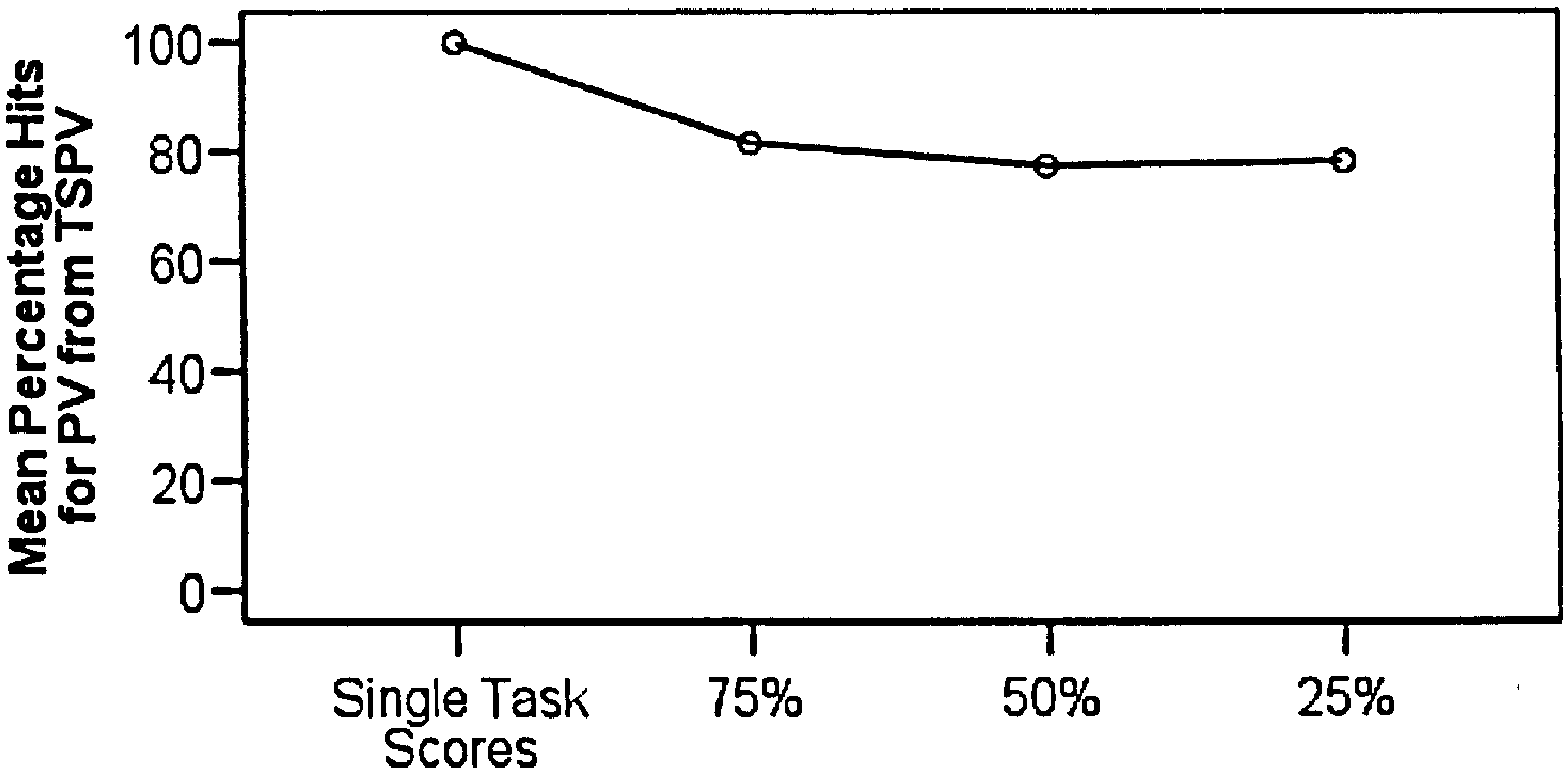


Figure 21: Mean Percentage Hits for Proprioceptive Verbal (PV) from Tactile Spatial & Proprioceptive Verbal (TSPV) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 51) = 5.842, p = .019), at 50% (F (1, 51) = 11.079, p = .002) and at 75% (F (1, 51) = 8.231, p = .006) resource allocation.

Tactile Spatial & Tactile Verbal (TSTV) — Significance of Difference from Respective Single Task Scores

Effect of the Tactile Spatial (TS & Tactile Verbal (TV) dual-task on TS — significance of difference from TS single task score

Table 11: Descriptive Statistics — Tactile Spatial (TS) & Tactile Verbal (TV), Task One (TS)

TS from TSTV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	22.6975	22.30710
	50% Resource Allocation Policy	23.0103	20.44931
	75% Resource Allocation Policy	28.9667	22.16609

The within-subjects ANOVA revealed that there is a significant effect of policy ($F_{(3, 141)} = 287.570$, $p = .000$). Participants' performance in the TS single task condition is significantly different from TS performance in the TSTV dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 47)}$ = 443.996, p = .000), and Figure 22 shows that single task scores are much higher than dual–task scores.

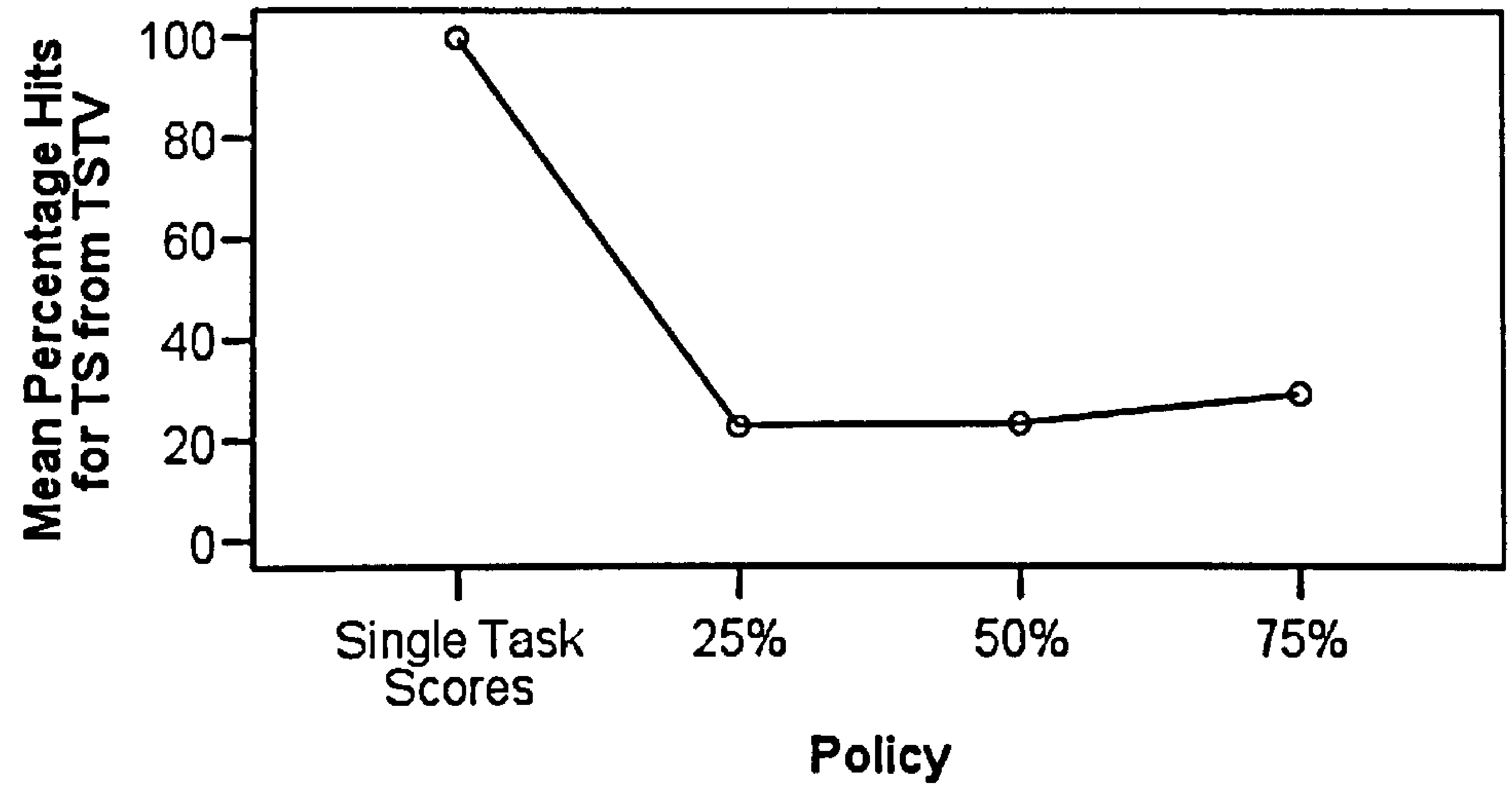


Figure 22: Mean Percentage Hits for Tactile Spatial (TS) from Tactile Spatial & Tactile Verbal (TSTV) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 47) = 576.424, p = .000), at 50% (F (1, 47) = 680.376, p = .000) and at 75% (F (1, 47) = 492.932, p = .000) resource allocation.

Effect of the Tactile Spatial (TS & Tactile Verbal (TV) dual–task on TV — significance of difference from TV single task score

Table 12: Descriptive Statistics — Tactile Spatial (TS) & Tactile Verbal (TV), Task Two (TV)

TV from TSTV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	68.3478	55.04287
	50% Resource Allocation Policy	55.4547	44.03788
	25% Resource Allocation Policy	65.7829	67.76410

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(1.973, 92.719)}$ = 11.270, p = .000). Participants' performance in the TV single task condition is significantly different from TV performance in the TSTV dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 47)}$ = 20.844, p = .000), and Figure 23 shows that single task scores are higher than dual–task scores.

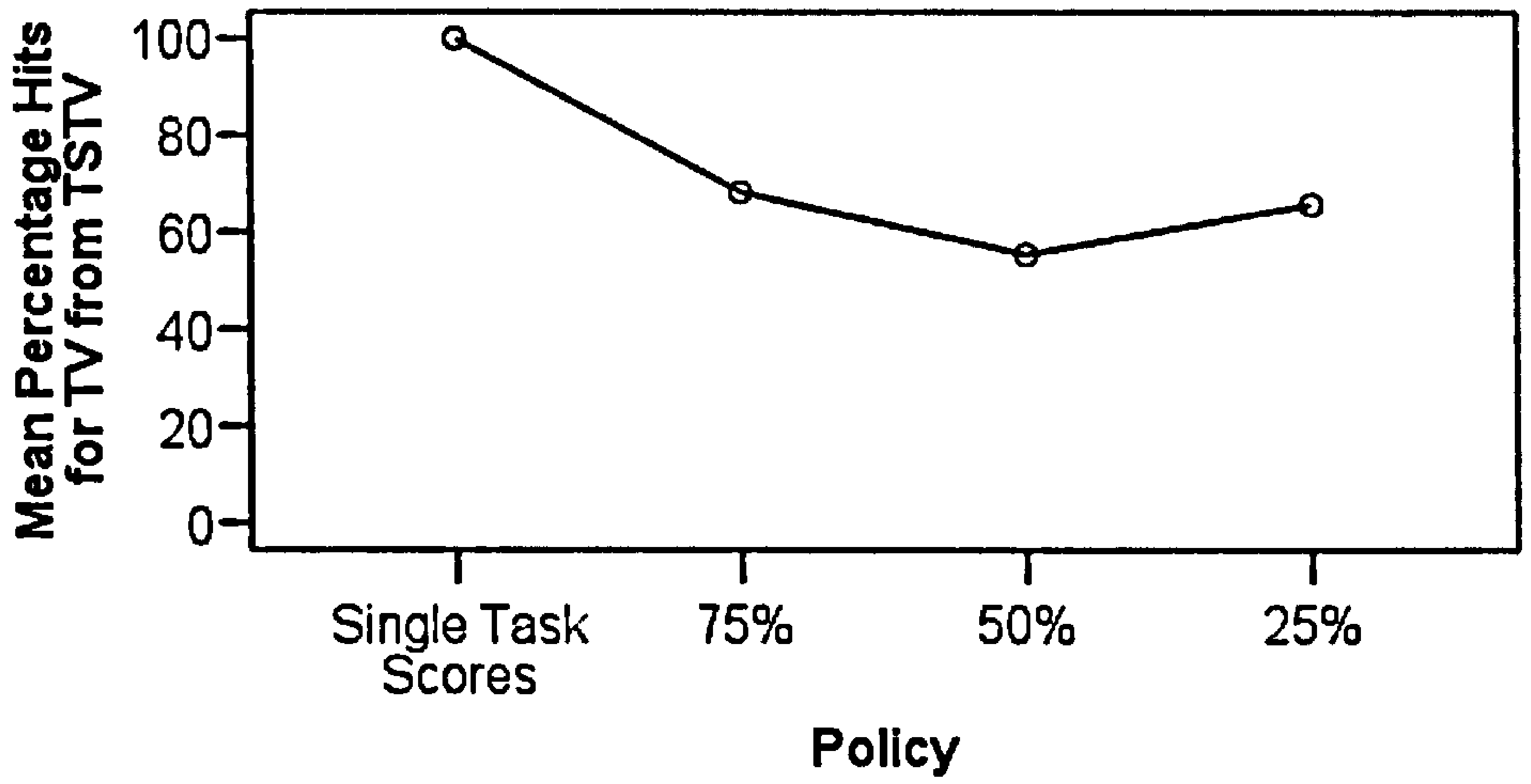


Figure 23: Mean Percentage Hits for Tactile Verbal (TV) from Tactile Spatial & Tactile Verbal (TSTV) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 47) = 12.238, p = .001), at 50% (F (1, 47) = 49.113, p = .000) and at 75% (F (1, 47) = 15.873, p = .000) resource allocation.

Tactile Verbal & Proprioceptive Spatial (TVPS) — Significance of Difference from Respective Single Task Scores

Effect of the Tactile Verbal (TV) & Proprioceptive Spatial (PS) dual–task on TV — significance of difference from TV single task score

Table 13: Descriptive Statistics — Tactile Verbal (TV) & Proprioceptive Spatial (PS), Task One (TV)

TV from TVPS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	84.5483	42.21528
	50% Resource Allocation Policy	84.3440	48.83923
	75% Resource Allocation Policy	86.1579	28.42665

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(2.153,\ 109.799)}$ = 3.574, p = .028). Participants' performance in the TV single task condition is significantly different from TV performance in the TVPS dual–

task condition. Post-hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 51)}$ = 10.195, p = .002), and Figure 24 shows that single task scores are higher than dual-task scores.

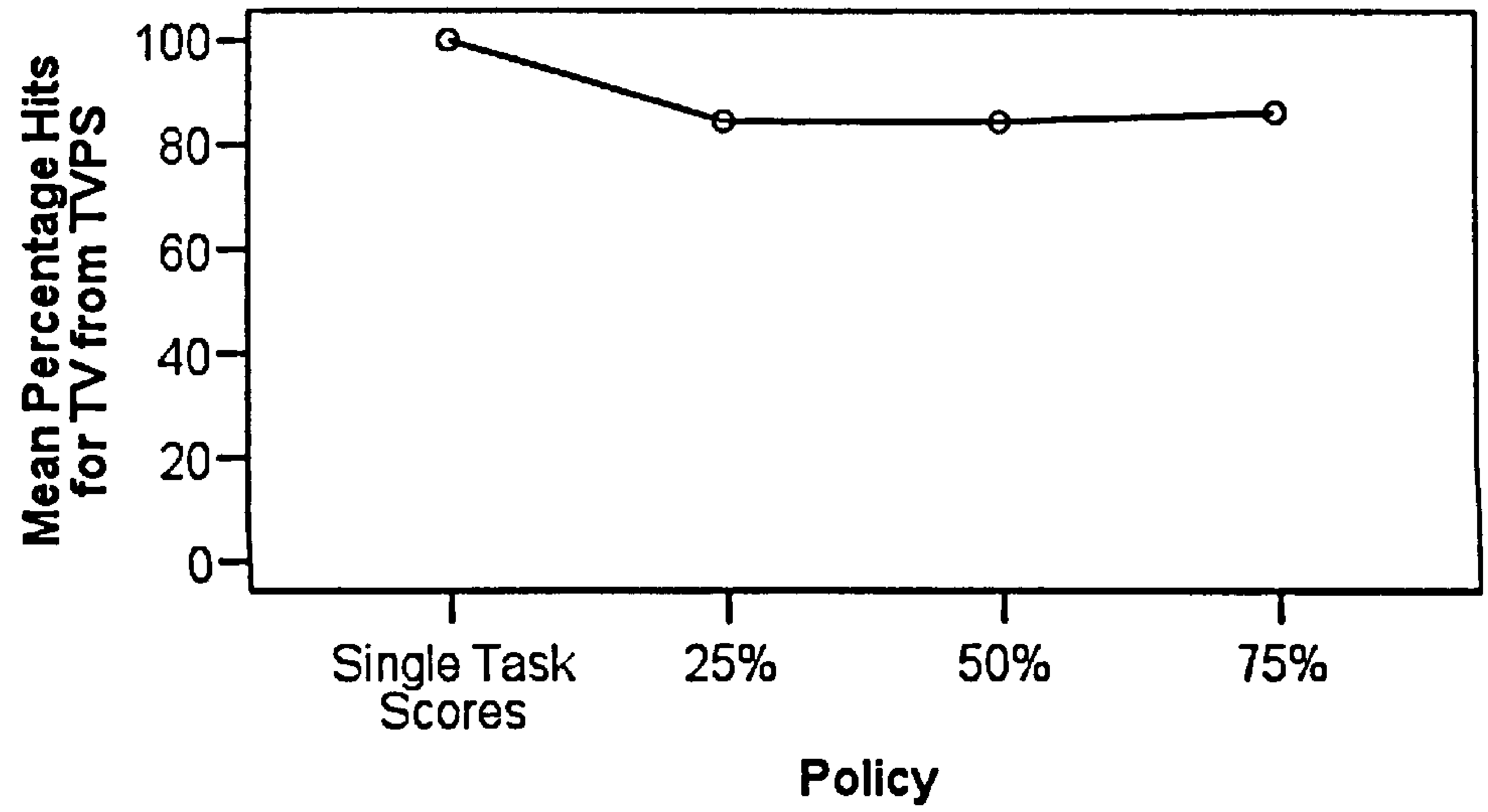


Figure 24: Mean Percentage Hits for Tactile Verbal (TV) from Tactile Verbal Proprioceptive Spatial (TVPS) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 51) = 6.967, p = .011), at 50% (F (1, 51) = 5.344, p = .025) and at 75% (F (1, 51) = 12.330, p = .001) resource allocation.

Effect of the Tactile Verbal (TV) & Proprioceptive Spatial (PS) dual-task on PS — significance of difference from PS single task score

Table 14: Descriptive Statistics — Tactile Verbal (TV) & Proprioceptive Spatial (PS), Task Two (PS)

TV from TVPS Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	75% Resource Allocation Policy	92.0826	75.89854
	50% Resource Allocation Policy	88.1755	75.71837
	25% Resource Allocation Policy	93.8235	103.66869

The within-subjects ANOVA revealed that there is no effect of policy (F $_{(1.973, 92.719)}$ = 11.270, p = .000). Participants' performance in the PS single task condition is not significantly different from PS performance in the TVPS dual-task condition.

Tactile Verbal & Proprioceptive Verbal (TVPV) — Significance of Difference from Respective Single Task Scores

Effect of the Tactile Verbal (TV) & Proprioceptive Verbal (PV) dual-task on TV — significance of difference from TV single task score

Table 15: Descriptive Statistics — Tactile Verbal (TV) & Proprioceptive Verbal (PV), Task One (TV)

TV from TVPV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	65.8252	62.05691
	50% Resource Allocation Policy	68.1624	50.78612
	75% Resource Allocation Policy	76.5715	47.91759

The within-subjects ANOVA revealed that there is a significant effect of policy ($F_{(2.402,\ 117.713)} = 10.504$, $p = .000$). Participants' performance in the TV single task condition is significantly different from TV performance in the TVPV dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy ($F_{(1,\ 49)} = 11.326$, $p = .001$), and Figure 25 shows that single task scores are higher than dual-task scores.

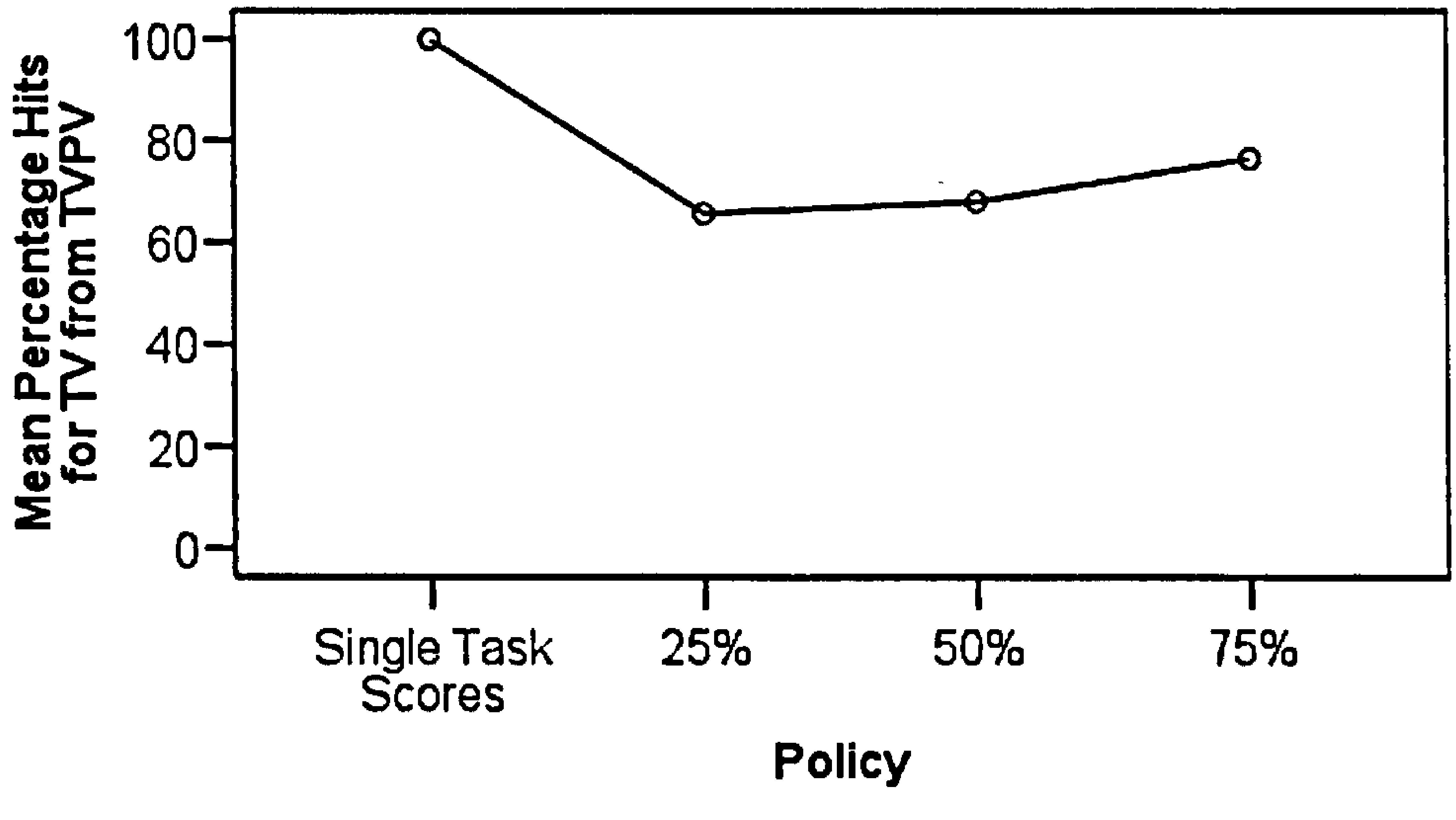


Figure 25: Mean Percentage Hits for Tactile Verbal (TV) from Tactile Verbal Proprioceptive Verbal (TVPV) — Single Task Scores — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 49) = 15.164, p = .000), at 50% (F (1, 49) = 19.650, p = .000) and at 75% (F (1, 49) = 11.953, p = .001) resource allocation.

Effect of the Tactile Verbal (TV) & Proprioceptive Verbal (PV) dual–task on PV — significance of difference from PV single task score

Table 16: Descriptive Statistics — Tactile Verbal (TV) & Proprioceptive Verbal (PV), Task Two (PV)

PV from TVPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	86.0843	36.04887
	50% Resource Allocation Policy	80.8911	60.27049
	25% Resource Allocation Policy	77.5659	82.66138

The within–subjects ANOVA revealed that there is no effect of policy (F $_{(1.639, 80.304)}$ = 2.778, p = .078). Participants' performance in the PV single task condition is not significantly different from PV performance in the TVPV dual–task condition.

SUMMARY

A summary of the results is displayed in Table 17, which shows the significances of differences between scores on each task within the dual–task combinations and their single task scores. Because each dual–task contains two tasks (task one and task two), two comparisons must be made per dual-task. Three dual–tasks (TSPS, TSPV and TSTV) show a significant difference between both tasks and their respective single task scores. However, where PSPV, TVPS and TVPV are concerned, a significant difference was found between task one and its single task score but not for task two. These results are discussed in the Discussion to Study One.

Table 17: Summary of Comparisons between Dual–Tasks and Single Tasks for Study One — Significance of Differences

Dual–Tasks		*Single Tasks*	*Significance of Difference*
PSPV	PS (Proprioceptive Spatial)	PS	Significant
	PV (Proprioceptive Verbal)	PV	Not Significant
TSPS	TS (Tactile Spatial)	TS	Significant
	PS (Proprioceptive Spatial)	PS	Significant
TSPV	TS (Tactile Spatial)	TS	Significant
	PV (Proprioceptive Verbal)	PV	Significant
TSTV	TS (Tactile Spatial)	TS	Significant
	TV (Tactile Verbal)	TV	Significant
TVPS	TV (Tactile Verbal)	TV	Significant
	PS (Proprioceptive Spatial)	PS	Not Significant
TVPV	TV (Tactile Verbal)	TV	Significant
	PV (Proprioceptive Verbal)	PV	Not Significant

9.4 Significance of Differences between Dual–Tasks

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Spatial (TSPS)

Table 18: Descriptive Statistics — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Spatial (TSPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
PSPV 25_75 Task One (PS at 25%)	39.0195	55.37852
PSPV 25_75 Task Two (PV at 75%)	88.7041	37.83397
PSPV 50_50 Task One (PS at 50%)	42.3434	50.46713
PSPV 50_50 Task Two (PV at 50%)	65.2372	32.16414
PSPV 75_25 Task One (PS at 75%)	37.3033	39.31192
PSPV 75_25 Task Two (PV at 25%)	64.0652	41.29844
TSPS 25_75 Task One (TS at 25%)	69.8731	55.34484
TSPS 25_75 Task Two (PS at 75%)	84.2242	92.10742
TSPS 50_50 Task One (TS at 50%)	71.6333	50.21664
TSPS 50_50 Task Two (PS at 50%)	83.6644	103.57888
TSPS 75_25 Task One (TS at 75%)	81.6216	39.87380
TSPS 75_25 Task Two (PS at 25%)	64.7428	103.34387

The within-subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,43)} = 9.582$, $p = .003$). Therefore, participants' performance in condition PSPV is significantly different from their performance in condition TSPS. There is no two–way interaction effect of condition by policy ($F_{(2, 86)} = 1.296$, $p = .279$), nor of condition by task ($F_{(1, 43)} = 2.419$, $p = .127$). There is no three–way interaction effect of policy by task by condition ($F_{(1.472, 63.276)} = 2.385$, $p = .115$).

There is a significant linear trend for condition ($F_{(1, 43)} = 9.582$, $p = .003$), and Table 19 shows a greater percentage of hits for TSPS than for PSPV.

Table 19: Estimated Marginal Means for CONDITION (input sense & input code) — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Spatial (TSPS)

condition	Mean	Std. Error
PSPV	56.112	4.080
TSPS	75.960	6.850

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Verbal (TSPV)

Table 20: Descriptive Statistics — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Verbal (TSPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
PSPV 25_75 Task One (PS at 25%)	39.0195	55.37852
PSPV 25_75 Task Two (PV at 75%)	88.7041	37.83397
PSPV 50_50 Task One (PS at 50%)	42.3434	50.46713
PSPV 50_50 Task Two (PV at 50%)	65.2372	32.16414
PSPV 75_25 Task One (PS at 75%)	37.3033	39.31192
PSPV 75_25 Task Two (PV at 25%)	64.0652	41.29844
TSPV 25_75 Task One (TS at 25%)	47.6627	32.92647
TSPV 25_75 Task Two (PV at 75%)	79.1137	45.24687
TSPV 50_50 Task One (TS at 50%)	50.7296	38.51846
TSPV 50_50 Task Two (PV at 50%)	75.9059	50.68398
TSPV 75_25 Task One (TS at 75%)	60.4322	34.81631
TSPV 75_25 Task Two (PV at 25%)	77.6686	67.07893

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = 2.640$, $p = .111$). Therefore, participants' performance in the PSPV condition is not significantly different from their performance in the TSPV condition. There is a two–way interaction effect of condition by policy ($F_{(2, 86)} = 4.684$, $p = .012$) but not of condition by task ($F_{(1, 43)} =.680$, $p = .414$). There is no three–way interaction effect of policy by task by condition ($F_{(2, 86)} = 1.395$, $p = .253$).

There is a significant linear interaction between condition and policy ($F_{(1, 43)} = 8.607$, $p = .005$). PSPV hits increase from 25_75, through 50_50, to 75_25. TSPV hits decrease from 25_75, through 50_50, to 75_25. This trend is illustrated in Figure 26.

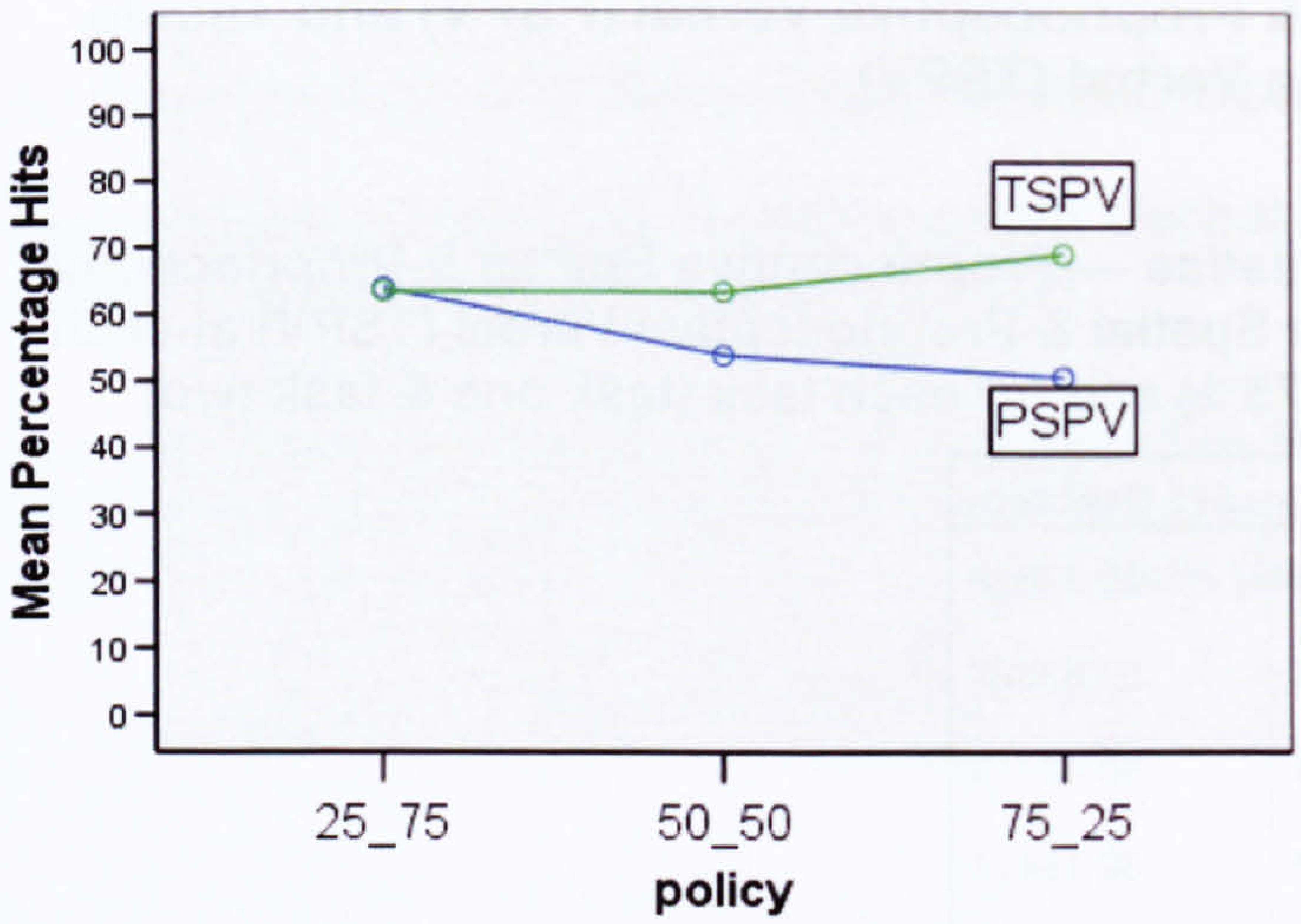


Figure 26: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — PSPV & TSPV) by POLICY (25_75%, 50_50% & 75–25%)

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Tactile Verbal (TSTV)

Table 21: Descriptive Statistics — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Tactile Verbal (TSTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
PSPV 25_75 Task One (PS at 25%)	39.9270	55.70194
PSPV 25_75 Task Two (PV at 75%)	89.3359	38.04617
PSPV 50_50 Task One (PS at 50%)	41.9328	50.98997
PSPV 50_50 Task Two (PV at 50%)	64.6077	32.26933
PSPV 75_25 Task One (PS at 75%)	36.7755	39.61909
PSPV 75_25 Task Two (PV at 25%)	64.3029	41.75674
TSTV 25_75 Task One (TS at 25%)	20.4016	20.82808
TSTV 25_75 Task Two (TV at 75%)	70.4763	57.72224
TSTV 50_50 Task One (TS at 50%)	21.4157	20.48061
TSTV 50_50 Task Two (TV at 50%)	57.4007	45.94975
TSTV 75_25 Task One (TS at 75%)	28.0520	23.04667
TSTV 75_25 Task Two (TV at 25%)	68.7931	70.95712

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,42)} = 3.557$, $p = .066$). Therefore, participants' performance in the PSPV condition is not significantly different from their performance in the TSTV condition. There is a two–way interaction effect of condition by policy ($F_{(1.649,\ 69.273)} = 3.481$, $p = .045$) but no effect of condition by task ($F_{(1,\ 42)} = .655$, $p = .423$). There is no three–way interaction effect of policy by task by condition ($F_{(1.641,\ 68.923)} = .594$, $p = .523$).

There is a significant linear interaction between condition and policy ($F_{(1,\ 42} = 12.208$, $p = .001$). PSPV hits decrease from 25_75, through 50_50, to 75_25. TSTV hits decrease from 25_75, to 50_50, before increasing at 75_25. This trend is illustrated in Figure 27, which shows that, essentially, the two conditions follow very similar patterns.

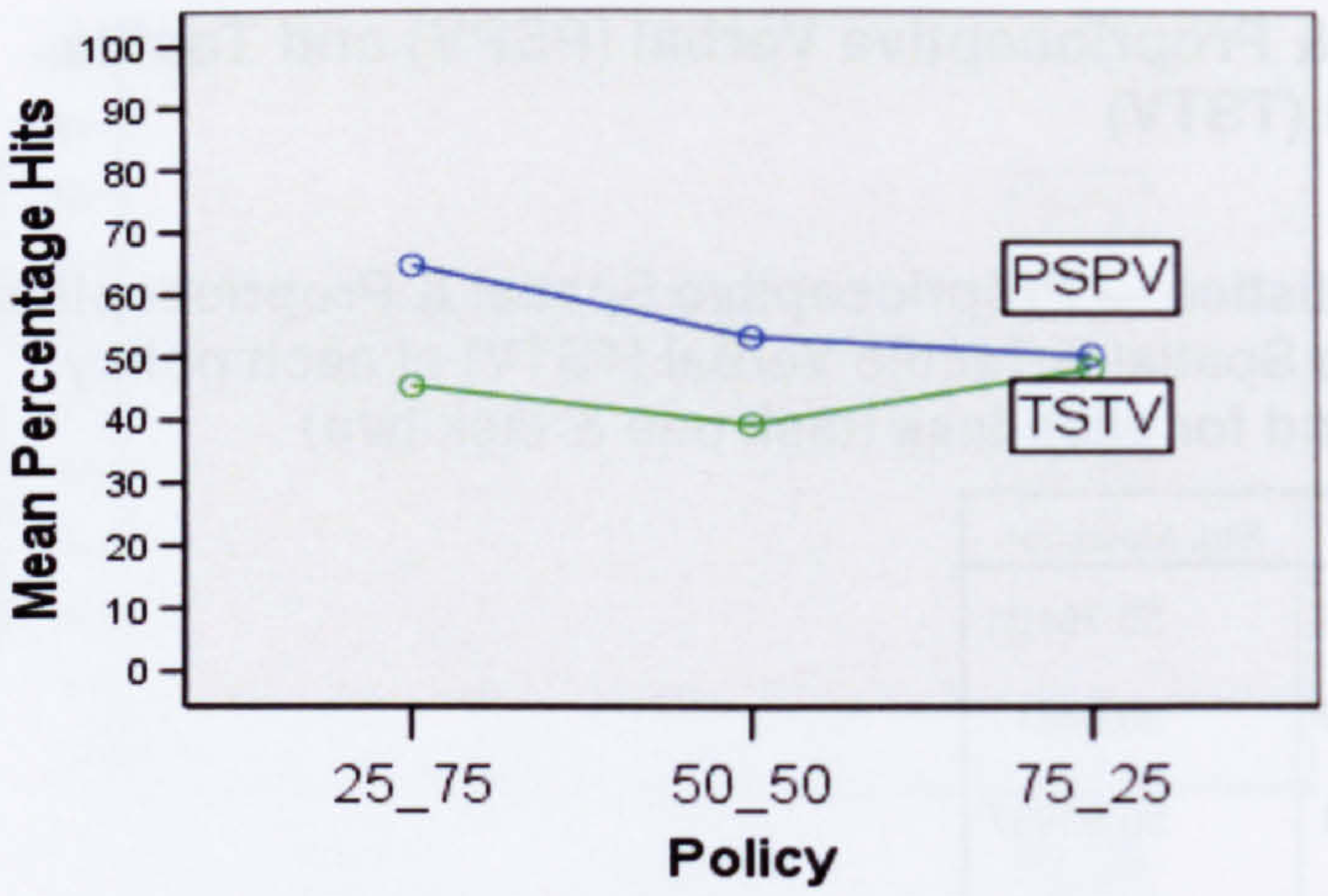


Figure 27: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — PSPV & TSTV) by POLICY (25_75%, 50_50% & 75–25%)

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

Table 22: Descriptive Statistics — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
PSPV 25_75 Task One (PS at 25%)	39.0195	55.37852
PSPV 25_75 Task Two (PV at 75%)	88.7041	37.83397
PSPV 50_50 Task One (PS at 50%)	42.3434	50.46713
PSPV 50_50 Task Two (PV at 50%)	65.2372	32.16414
PSPV 75_25 Task One (PS at 75%)	37.3033	39.31192
PSPV 75_25 Task Two (PV at 25%)	64.0652	41.29844
TVPS 25_75 Task One (TV at 25%)	83.8892	45.23078
TVPS 25_75 Task Two (PS at 75%)	90.7658	77.08925
TVPS 50_50 Task One (TV at 50%)	83.9126	52.89626
TVPS 50_50 Task Two (PS at 50%)	84.5899	70.03173
TVPS 75_25 Task One (TV at 75%)	86.1630	30.28076
TVPS 75_25 Task Two (PS at 25%)	87.5255	96.97974

The ANOVA revealed that there is a significant effect of condition ($F_{(1,43)}$ = 25.157, p = .000). Therefore, participants' performance in the PSPV condition is significantly different from their performance in the TVPS condition. There is no two–way interaction effect of condition by policy ($F_{(1.540,\ 66.211)}$ = 1.153, p = .311), nor of condition by task ($F_{(1,\ 43)}$ = 3.884, p = .055) and no three–way interaction effect of policy by task by condition ($F_{(1.734,\ 74.541)}$ = .801, p = .437).

There is a significant linear trend for condition ($F_{(1,\ 43)}$ = 25.157, p = .000), and Table 23 shows a greater percentage of hits for TVPS than for PSPV.

Table 23: Estimated Marginal Means for CONDITION (input sense & input code) — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

condition	Mean	Std. Error
PSPV	56.112	4.080
TVPS	86.141	5.928

Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV)

Table 24: Descriptive Statistics — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
PSPV 25_75 Task One (PS at 25%)	39.0195	55.37852
PSPV 25_75 Task Two (PV at 75%)	88.7041	37.83397
PSPV 50_50 Task One (PS at 50%)	42.3434	50.46713
PSPV 50_50 Task Two (PV at 50%)	65.2372	32.16414
PSPV 75_25 Task One (PS at 75%)	37.3033	39.31192
PSPV 75_25 Task Two (PV at 25%)	64.0652	41.29844
TVPV 25_75 Task One (TV at 25%)	57.0236	48.23653
TVPV 25_75 Task Two (PV at 75%)	85.2576	37.84502
TVPV 50_50 Task One (TV at 50%)	65.1340	45.19475
TVPV 50_50 Task Two (PV at 50%)	80.9537	63.94108
TVPV 75_25 Task One (TV at 75%)	68.9322	36.33922
TVPV 75_25 Task Two (PV at 25%)	76.9211	87.35160

The three–way within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,43)} = 5.610$, $p = .022$). Therefore, participants' performance in the PSPV condition is significantly different from their performance in the TVPV condition. There is no two–way interaction effect of condition by policy ($F_{(2, 86)} = 2.984$, $p = .056$), nor of condition by task ($F_{(1, 43)} = 2.457$, $p = .124$) and no three–way interaction effect of policy by task by condition ($F_{(2, 86)} = .508$, $p = .603$).

There is a significant linear trend for condition ($F_{(1, 43)} = 5.610$, $p = .022$), and Table 25 shows a greater percentage of hits for TVPV than for PSPV.

Table 25: Estimated Marginal Means for CONDITION (input sense & input code) — Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV)

condition	Mean	Std. Error
PSPV	56.112	4.080
TVPV	72.370	5.790

There is a significant linear interaction between condition and policy ($F_{(1, 43)} = 5.076$, $p = .029$). PSPV hits decrease from 25_75, through 50_50, to 75_25.

TVPV hits are roughly the same from 25_75, through 50_50, to 75_25. This trend is illustrated in Figure 28.

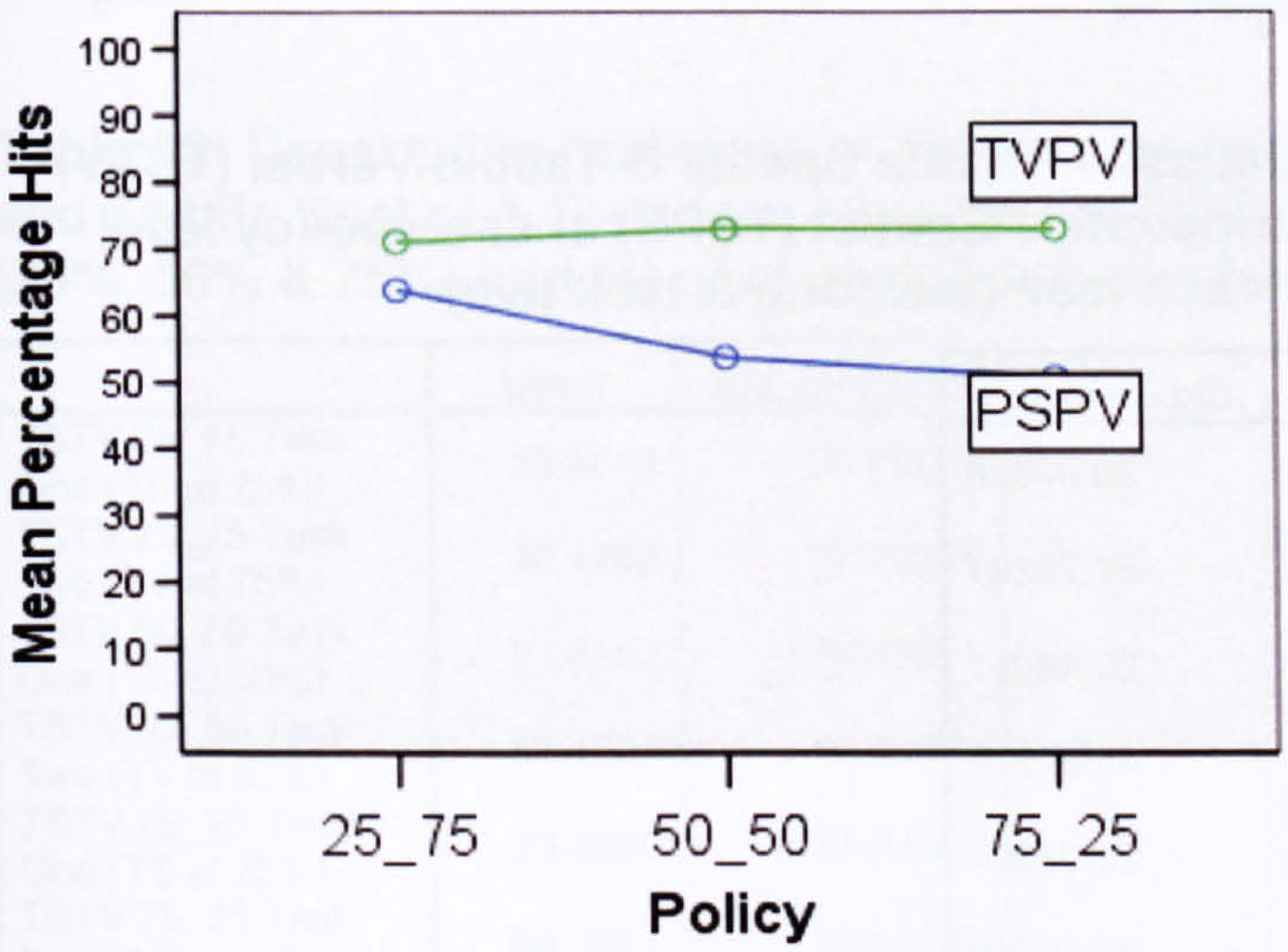


Figure 28: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — PSPV & TVPV) by POLICY (25_75%, 50_50% & 75–25%)

Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Spatial (TSPS)

Table 26: Descriptive Statistics — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Spatial (TSPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSTV 25_75 Task One (TS at 25%)	20.4016	20.82808
TSTV 25_75 Task Two (TV at 75%)	70.4763	57.72224
TSTV 50_50 Task One (TS at 50%)	21.4157	20.48061
TSTV 50_50 Task Two (TV at 50%)	57.4007	45.94975
TSTV 75_25 Task One (TS at 75%)	28.0520	23.04667
TSTV 75_25 Task Two (TV at 25%)	68.7931	70.95712
TSPS 25_75 Task One (TS at 25%)	69.8068	55.99806
TSPS 25_75 Task Two (PS at 75%)	85.7178	92.65679
TSPS 50_50 Task One (TS at 50%)	69.0709	47.81176
TSPS 50_50 Task Two (PS at 50%)	84.6798	104.58287
TSPS 75_25 Task One (TS at 75%)	79.0800	36.56209
TSPS 75_25 Task Two (PS at 25%)	65.3182	104.49557

The within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1, 42)} = 16.262$, $p = .000$). Therefore, participants' performance in the TSTV condition is significantly different from their performance in the TSPS condition. There is no significant two–way interaction effect of condition by policy ($F_{(1.558, 72.676)} = 1.558$, $p = .219$) and no significant two–way interaction effect of condition by task ($F_{(1, 42)} = 4.047$, $p = .051$). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(2, 84)} = 2.391$, $p = .098$).

For these data there is a significant linear trend for condition ($F_{(1, 42)} = 16.262$, $p = .000$), and Table 27 shows a greater percentage of hits for TSTV than for TSPS.

Table 27: Estimated Marginal Means for CONDITION (input sense & input code) — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Spatial (TSPS)

condition	Mean	Std. Error
TSTV	44.423	3.952
TSPS	75.612	7.002

Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Verbal (TSPV)

Table 28: Descriptive Statistics — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Verbal (TSPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSTV 25_75 Task One (TS at 25%)	20.4016	20.82808
TSTV 25_75 Task Two (TV at 75%)	70.4763	57.72224
TSTV 50_50 Task One (TS at 50%)	21.4157	20.48061
TSTV 50_50 Task Two (TV at 50%)	57.4007	45.94975
TSTV 75_25 Task One (TS at 75%)	28.0520	23.04667
TSTV 75_25 Task Two (TV at 25%)	68.7931	70.95712
TSPV 25_75 Task One (TS at 25%)	45.8113	30.91209
TSPV 25_75 Task Two (PV at 75%)	79.5224	45.70009
TSPV 50_50 Task One (TS at 50%)	49.5838	38.20803
TSPV 50_50 Task Two (PV at 50%)	76.5978	51.07312
TSPV 75_25 Task One (TS at 75%)	59.3006	34.39990
TSPV 75_25 Task Two (PV at 25%)	78.7593	67.47686

The within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,42)} = 15.186$, p = .000). Therefore, participants' performance in the TSTV condition is significantly different from that in the TSPV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2,84)} = .434$, p = .649) and no significant two–way interaction effect of condition by task ($F_{(1,42)} = 2.303$, p = .137). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(2,84)} = .424$, p = .656).

There is a significant linear trend for condition ($F_{(1,42)} = 15.186$, p = .000), and Table 29 shows a greater percentage of hits for TSPV than for PSPV.

Table 29: Estimated Marginal Means for CONDITION (input sense & input code) — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Verbal (TSPV)

condition	Mean	Std. Error
TSTV	44.423	3.952
TSPV	64.929	3.839

Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

Table 30: Descriptive Statistics — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Spatial (TVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSTV 25_75 Task One (TS at 25%)	20.4016	20.82808
TSTV 25_75 Task Two (TV at 75%)	70.4763	57.72224
TSTV 50_50 Task One (TS at 50%)	21.4157	20.48061
TSTV 50_50 Task Two (TV at 50%)	57.4007	45.94975
TSTV 75_25 Task One (TS at 75%)	28.0520	23.04667
TSTV 75_25 Task Two (TV at 25%)	68.7931	70.95712
TVPS 25_75 Task One (TV at 25%)	84.2122	45.71470
TVPS 25_75 Task Two (PS at 75%)	90.5510	77.98827
TVPS 50_50 Task One (TV at 50%)	84.0036	53.51879
TVPS 50_50 Task Two (PS at 50%)	84.6966	70.85691
TVPS 75_25 Task One (TV at 75%)	85.6087	30.41238
TVPS 75_25 Task Two (PS at 25%)	87.2354	98.10815

The within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,42)} = 43.414$, $p = .000$). Therefore, participants' performance in the TSTV condition is significantly different from their performance in the TVPS condition. There is no two–way interaction effect of condition by policy ($F_{(1.503, 63.133)} = .320$, $p = .664$) but there is a significant two–way interaction effect of condition by task ($F_{(1, 42)} = 6.708$, $p = .013$). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(1.627, 68.350)} = .131$, $p = .836$).

For these data there is a significant linear trend for condition ($F_{(1, 42)} = 43.414$, $p = .000$), and Table 31 shows a greater percentage of hits for TVPS than for TSTV.

Table 31: Estimated Marginal Means for CONDITION (input sense & input code) — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

condition	Mean	Std. Error
TSTV	44.423	3.952
TVPS	86.051	6.067

There is also a significant linear interaction between condition and task ($F_{(1, 42)} = 6.708$, $p = .013$). TVPS and task two have the greatest number of hits, whilst TSTV and task one have the least. This trend is illustrated in Figure 29.

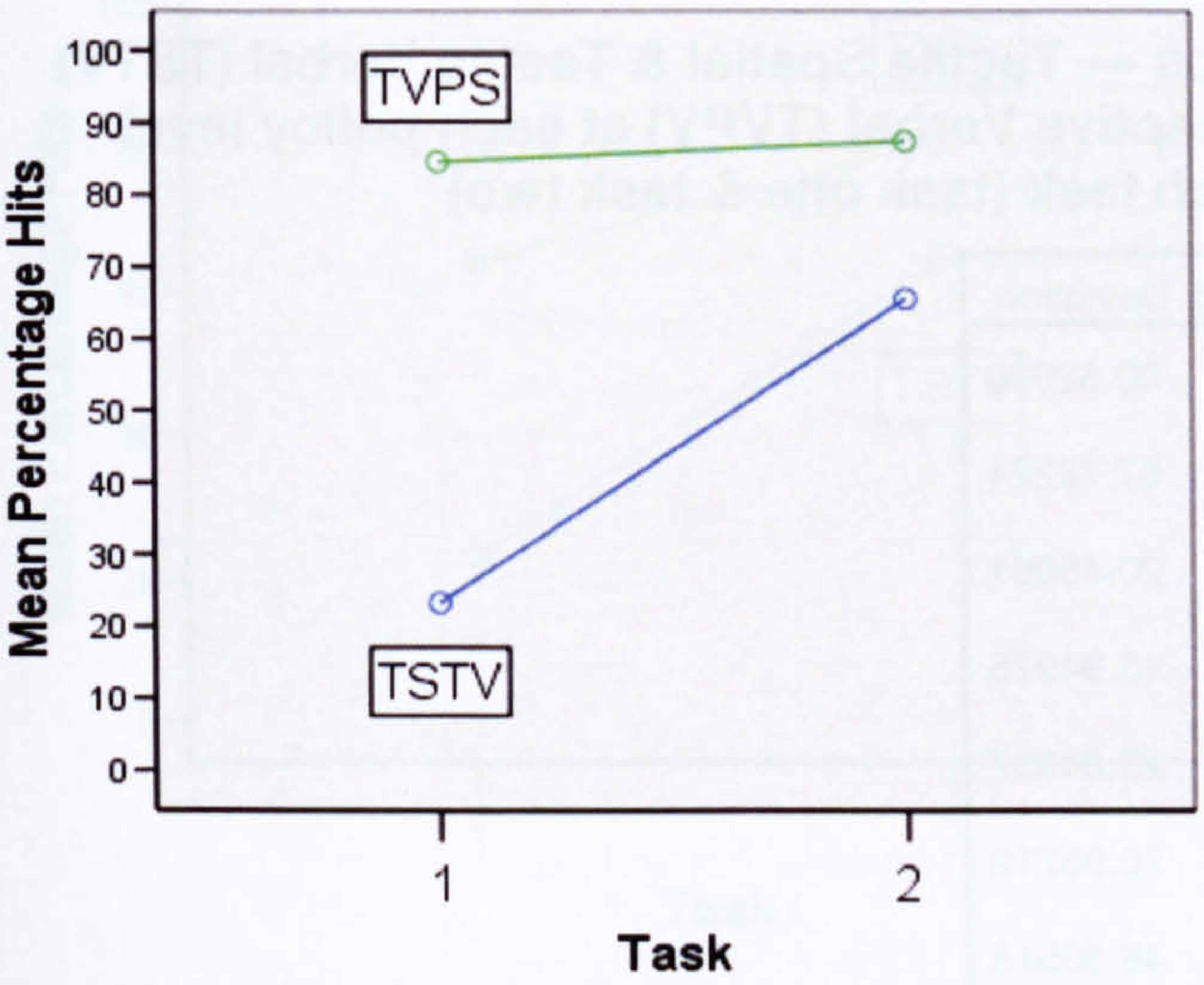


Figure 29: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — TSTV & TVPS) by TASK (task one & task two)

Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Verbal (TVPV)

Table 32: Descriptive Statistics — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Verbal (TVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSTV 25_75 Task One (TS at 25%)	20.4016	20.82808
TSTV 25_75 Task Two (TV at 75%)	70.4763	57.72224
TSTV 50_50 Task One (TS at 50%)	21.4157	20.48061
TSTV 50_50 Task Two (TV at 50%)	57.4007	45.94975
TSTV 75_25 Task One (TS at 75%)	28.0520	23.04667
TSTV 75_25 Task Two (TV at 25%)	68.7931	70.95712
TVPV 25_75 Task One (TV at 25%)	56.9544	48.80518
TVPV 25_75 Task Two (PV at 75%)	86.1670	37.80335
TVPV 50_50 Task One (TV at 50%)	65.9511	45.39960
TVPV 50_50 Task Two (PV at 50%)	82.1208	64.22186
TVPV 75_25 Task One (TV at 75%)	69.6051	36.49091
TVPV 75_25 Task Two (PV at 25%)	76.7422	88.37722

The within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,42)} = 17.233$, $p = .000$). Therefore, participants' performance in the TSTV condition is significantly different from their performance in the TVPV condition. There is no two–way interaction effect of condition by policy ($F_{(1.714, 72.002)} = 1.407$, $p = .251$) but there is a significant two–way interaction effect of condition by task ($F_{(1, 42)} = 4.115$, $p = .048$). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(2, 84)} = .490$, $p = .614$).

For these data there is a significant linear trend for condition ($F_{(1, 42)} = 17.223$, $p = .000$), and Table 33 shows a greater percentage of hits for TVPV than for TSTV.

Table 33: Estimated Marginal Means for CONDITION (input sense & input code) — Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Verbal (TVPV)

condition	Mean	Std. Error
TSTV	44.423	3.952
TVPV	72.923	5.899

There is also a significant linear interaction between condition and task ($F_{(1, 42)} = 4.155$, $p = .048$). TVPV and task two have the greatest hits, whilst TSTV and task one have the least. This trend is illustrated in Figure 30

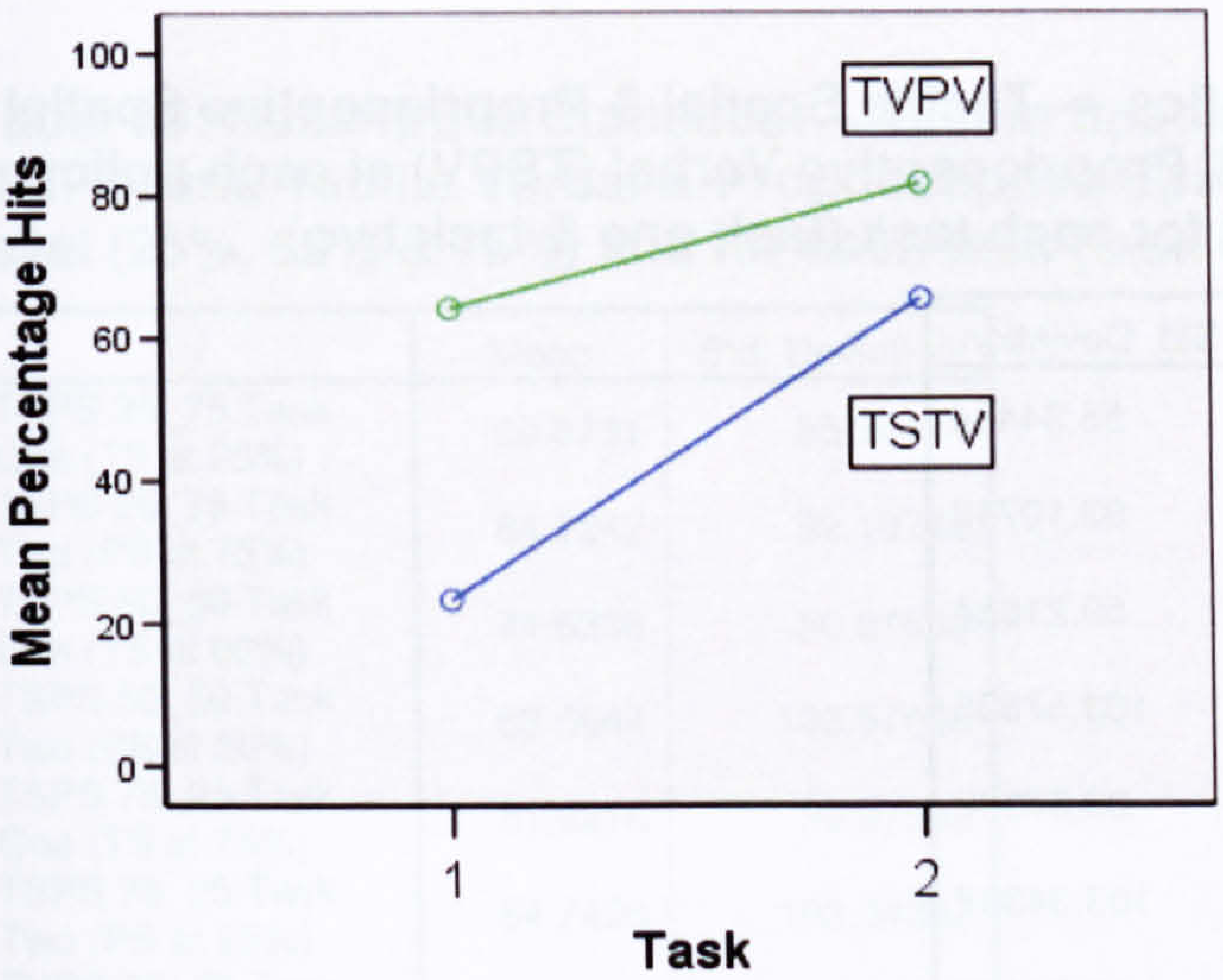


Figure 30: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — TSTV & TVPV) by TASK (task one & task two)

Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Spatial & Proprioceptive Verbal (TSPV)

Table 34: Descriptive Statistics — Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Spatial & Proprioceptive Verbal (TSPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSPS 25_75 Task One (TS at 25%)	69.8731	55.34484
TSPS 25_75 Task Two (PS at 75%)	84.2242	92.10742
TSPS 50_50 Task One (TS at 50%)	71.6333	50.21664
TSPS 50_50 Task Two (PS at 50%)	83.6644	103.57888
TSPS 75_25 Task One (TS at 75%)	81.6216	39.87380
TSPS 75_25 Task Two (PS at 25%)	64.7428	103.34387
TSPV 25_75 Task One (TS at 25%)	47.6627	32.92647
TSPV 25_75 Task Two (PV at 75%)	79.1137	45.24687
TSPV 50_50 Task One (TS at 50%)	50.7296	38.51846
TSPV 50_50 Task Two (PV at 50%)	75.9059	50.68398
TSPV 75_25 Task One (TS at 75%)	60.4322	34.81631
TSPV 75_25 Task Two (PV at 25%)	77.6686	67.07893

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = 2.057$, $p = .159$). There is no two–way interaction effect of condition by policy ($F_{(2, 86)} = .990$, $p = .376$), nor of condition by task ($F_{(1, 43)} = 1.987$, $p = .166$). There is no three–way interaction effect of condition by policy by task ($F_{(2, 86)} = .937$, $p = .396$).

Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Spatial (TVPS)

Table 35: Descriptive Statistics — Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Spatial (TVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSPS 25_75 Task One (TS at 25%)	69.8731	55.34484
TSPS 25_75 Task Two (PS at 75%)	84.2242	92.10742
TSPS 50_50 Task One (TS at 50%)	71.6333	50.21664
TSPS 50_50 Task Two (PS at 50%)	83.6644	103.57888
TSPS 75_25 Task One (TS at 75%)	81.6216	39.87380
TSPS 75_25 Task Two (PS at 25%)	64.7428	103.34387
TVPS 25_75 Task One (TV at 25%)	83.8892	45.23078
TVPS 25_75 Task Two (PS at 75%)	90.7658	77.08925
TVPS 50_50 Task One (TV at 50%)	83.9126	52.89626
TVPS 50_50 Task Two (PS at 50%)	84.5899	70.03173
TVPS 75_25 Task One (TV at 75%)	86.1630	30.28076
TVPS 75_25 Task Two (PS at 25%)	87.5255	96.97974

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = 2.946$, $p = .093$). Therefore, participants' performance in the TSPS condition is not significantly different from their performance in the TVPS condition. There is no two–way interaction effect of condition by policy ($F_{(1.629,\ 70.052)} = .260$, $p = .726$), nor of condition by task ($F_{(1,\ 43)} = .000$, $p = .989$) and no three–way interaction effect of policy by task by condition ($F_{(2,\ 86)} = 1.358$, $p = .263$).

Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Verbal (TVPV)

Table 36: Descriptive Statistics — Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Verbal (TVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSPS 25_75 Task One (TS at 25%)	69.8731	55.34484
TSPS 25_75 Task Two (PS at 75%)	84.2242	92.10742
TSPS 50_50 Task One (TS at 50%)	71.6333	50.21664
TSPS 50_50 Task Two (PS at 50%)	83.6644	103.57888
TSPS 75_25 Task One (TS at 75%)	81.6216	39.87380
TSPS 75_25 Task Two (PS at 25%)	64.7428	103.34387
TVPV 25_75 Task One (TV at 25%)	57.0236	48.23653
TVPV 25_75 Task Two (PV at 75%)	85.2576	37.84502
TVPV 50_50 Task One (TV at 50%)	65.1340	45.19475
TVPV 50_50 Task Two (PV at 50%)	80.9537	63.94108
TVPV 75_25 Task One (TV at 75%)	68.9322	36.33922
TVPV 75_25 Task Two (PV at 25%)	76.9211	87.35160

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = .139$, $p = .711$). Therefore, participants' performance in the TSPS condition is not significantly different from their performance in the TVPV condition. There is no two–way interaction effect of condition by policy ($F_{(2, 86)} = .320$, $p = .727$), nor of condition by task ($F_{(1, 43)} = .649$, $p = .425$) and no three–way interaction effect of policy by task by condition ($F_{(2, 86)} = .859$, $p = .427$).

Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

Table 37: Descriptive Statistics — Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSPV 25_75 Task One (TS at 25%)	47.6627	32.92647
TSPV 25_75 Task Two (PV at 75%)	79.1137	45.24687
TSPV 50_50 Task One (TS at 50%)	50.7296	38.51846
TSPV 50_50 Task Two (PV at 50%)	75.9059	50.68398
TSPV 75_25 Task One (TS at 75%)	60.4322	34.81631
TSPV 75_25 Task Two (PV at 25%)	77.6686	67.07893
TVPS 25_75 Task One (TV at 25%)	83.8892	45.23078
TVPS 25_75 Task Two (PS at 75%)	90.7658	77.08925
TVPS 50_50 Task One (TV at 50%)	83.9126	52.89626
TVPS 50_50 Task Two (PS at 50%)	84.5899	70.03173
TVPS 75_25 Task One (TV at 75%)	86.1630	30.28076
TVPS 75_25 Task Two (PS at 25%)	87.5255	96.97974

The within–subjects ANOVA revealed that there is a significant effect of condition ($F_{(1,43)} = 9.271$, p = .004). Therefore, participants' performance in the TSPV condition is significantly different from their performance in the TVPS condition. There is no significant two–way interaction effect of condition by policy ($F_{(1.593,\ 68.489)} = .301$, p = .691) and no significant two–way interaction effect of condition by task ($F_{(1,\ 43)} = 2.093$, p = .155). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(1.540,\ 66.234)} = .177$, p = .781).

For these data there is a significant linear trend for condition ($F_{(1,\ 43)} = 9.271$, p = .004), and Table 38 shows a greater percentage of hits for TVPS than for TSPV.

Table 38: Estimated Marginal Means for CONDITION (input sense & input code) — Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

condition	Mean	Std. Error
TSPV	65.252	3.765
TVPS	86.141	5.928

Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV)

Table 39: Descriptive Statistics — Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TSPV 25_75 Task One (TS at 25%)	47.6627	32.92647
TSPV 25_75 Task Two (PV at 75%)	79.1137	45.24687
TSPV 50_50 Task One (TS at 50%)	50.7296	38.51846
TSPV 50_50 Task Two (PV at 50%)	75.9059	50.68398
TSPV 75_25 Task One (TS at 75%)	60.4322	34.81631
TSPV 75_25 Task Two (PV at 25%)	77.6686	67.07893
TVPV 25_75 Task One (TV at 25%)	57.0236	48.23653
TVPV 25_75 Task Two (PV at 75%)	85.2576	37.84502
TVPV 50_50 Task One (TV at 50%)	65.1340	45.19475
TVPV 50_50 Task Two (PV at 50%)	80.9537	63.94108
TVPV 75_25 Task One (TV at 75%)	68.9322	36.33922
TVPV 75_25 Task Two (PV at 25%)	76.9211	87.35160

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = 2.026$, $p = .162$). Therefore, participants' performance in the TSPV condition is not significantly different from their performance in the TVPV condition. There is no significant two-way interaction effect of condition by policy ($F_{(2, 86)} = .530$, $p = .591$) and no significant two-way interaction effect of condition by task ($F_{(1, 43)} = .975$, $p = .329$). Finally, there is no significant three-way interaction effect of policy by task by condition ($F_{(2, 86)} = .150$, $p = .861$).

Tactile Verbal & Proprioceptive Spatial (TVPS) and Tactile Verbal & Proprioceptive Verbal (TVPV)

Table 40: Descriptive Statistics — Tactile Verbal & Proprioceptive Spatial (TVPS) and Tactile Verbal & Proprioceptive Verbal (TVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
TVPS 25_75 Task One (TV at 25%)	83.8892	45.23078
TVPS 25_75 Task Two (PS at 75%)	90.7658	77.08925
TVPS 50_50 Task One (TV at 50%)	83.9126	52.89626
TVPS 50_50 Task Two (PS at 50%)	84.5899	70.03173
TVPS 75_25 Task One (TV at 75%)	86.1630	30.28076
TVPS 75_25 Task Two (PS at 25%)	87.5255	96.97974
TVPV 25_75 Task One (TV at 25%)	57.0236	48.23653
TVPV 25_75 Task Two (PV at 75%)	85.2576	37.84502
TVPV 50_50 Task One (TV at 50%)	65.1340	45.19475
TVPV 50_50 Task Two (PV at 50%)	80.9537	63.94108
TVPV 75_25 Task One (TV at 75%)	68.9322	36.33922
TVPV 75_25 Task Two (PV at 25%)	76.9211	87.35160

The three-way within-subjects ANOVA revealed that there is no effect of condition ($F_{(1,43)} = 2.739$, $p = .105$). Therefore, participants' performance in the TVPS condition is not significantly different from their performance in the TVPV condition.

There is no two-way interaction effect of condition by policy ($F_{(1.436,\ 61.736)} = .179$, $p = .763$) and no two-way interaction effect of condition by task ($F_{(1,\ 43)} = 1.037$, $p = .314$). Finally, there is no three-way interaction effect of policy by task by condition ($F_{(1.495,\ 64.274)} = .336$, $p = .653$).

Summary of Results

Table 41 summarises the results of the ANOVA tests with regards to the effect CONDITION (input sense and input code). It shows which conditions (which combinations of input sense and input code) were significantly different from one another and which were not. Each comparison is accompanied by snapshot reminders of the relevant POC curves.

Eight comparisons yielded significant differences, including:

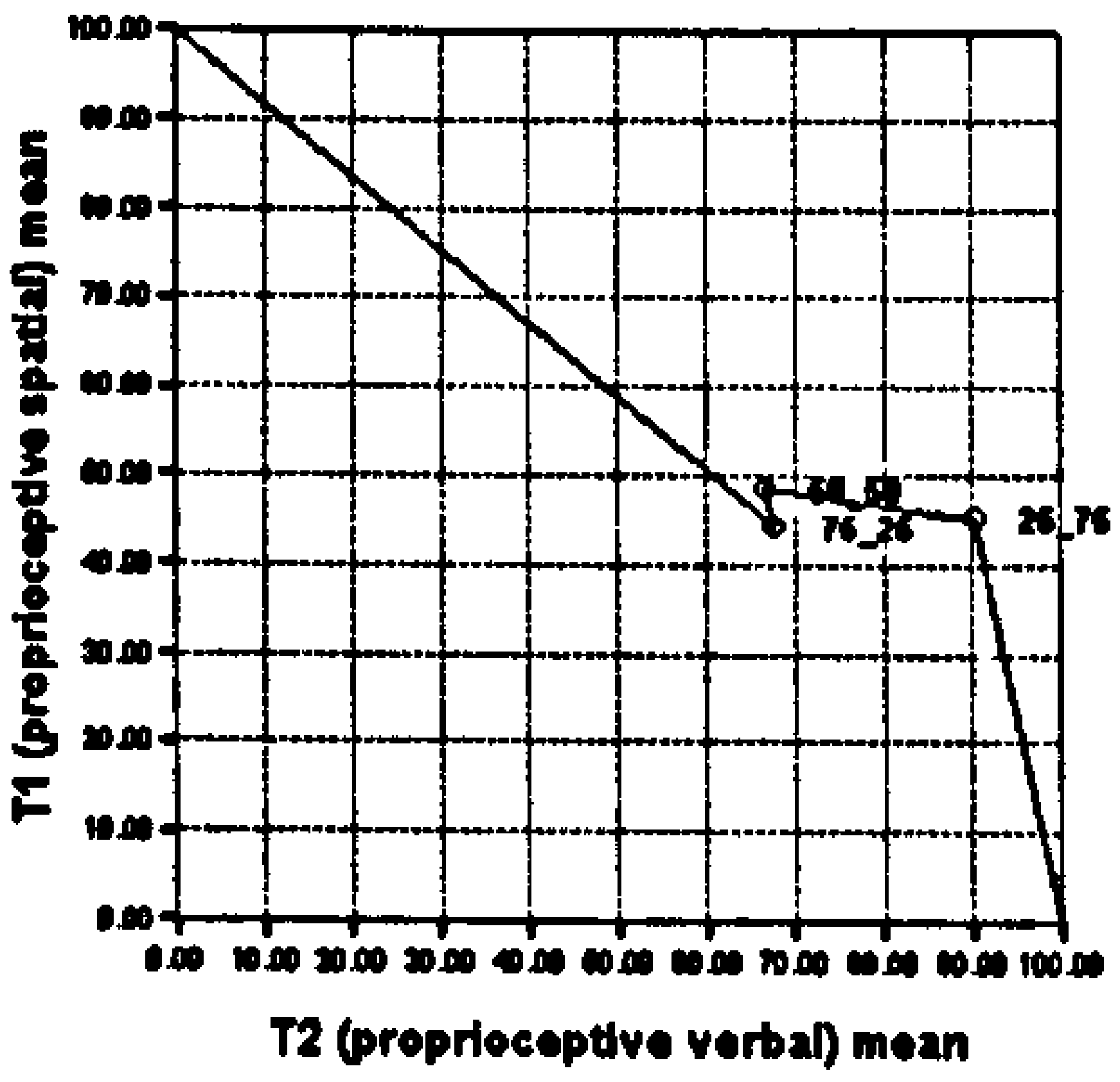
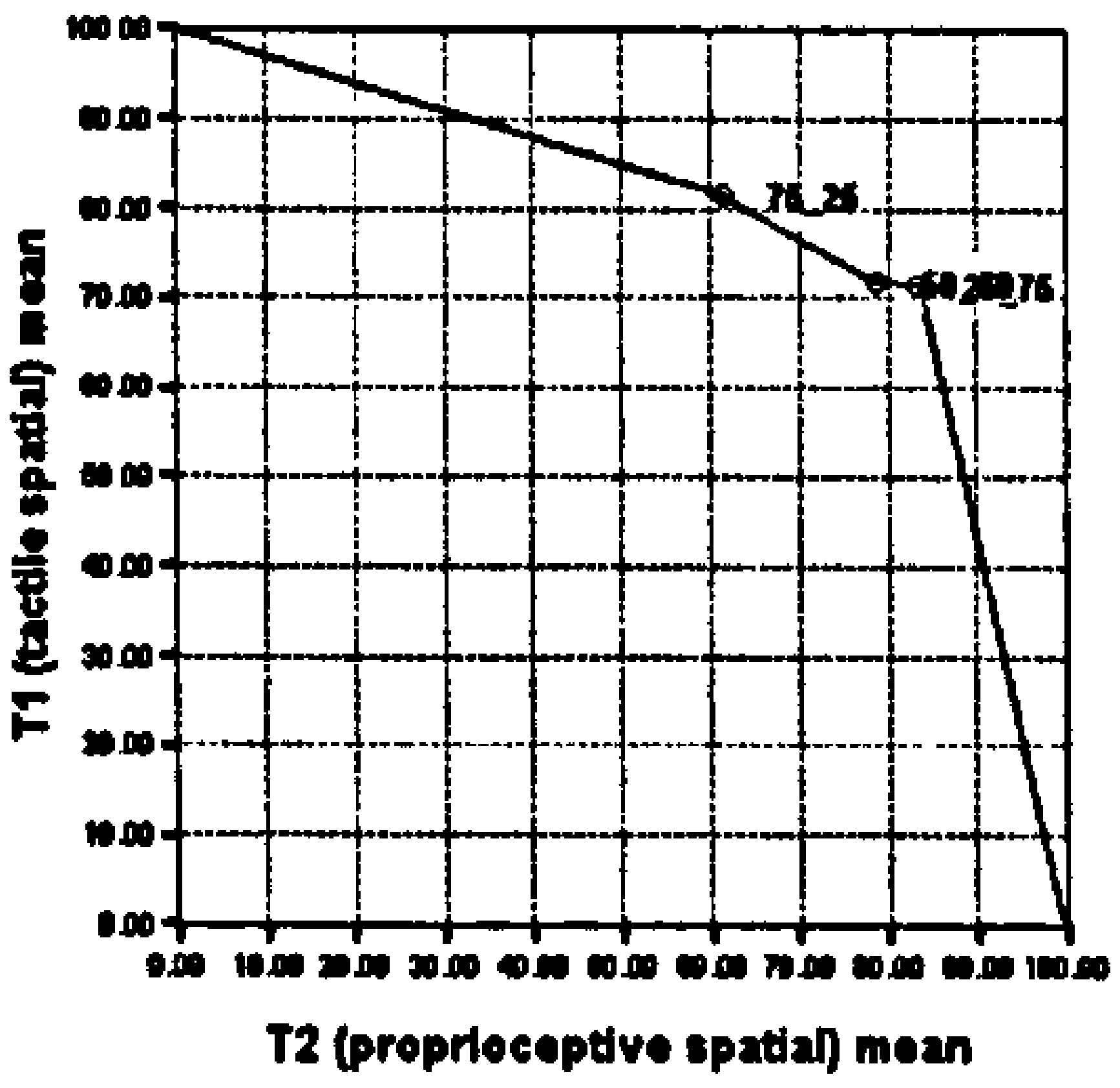
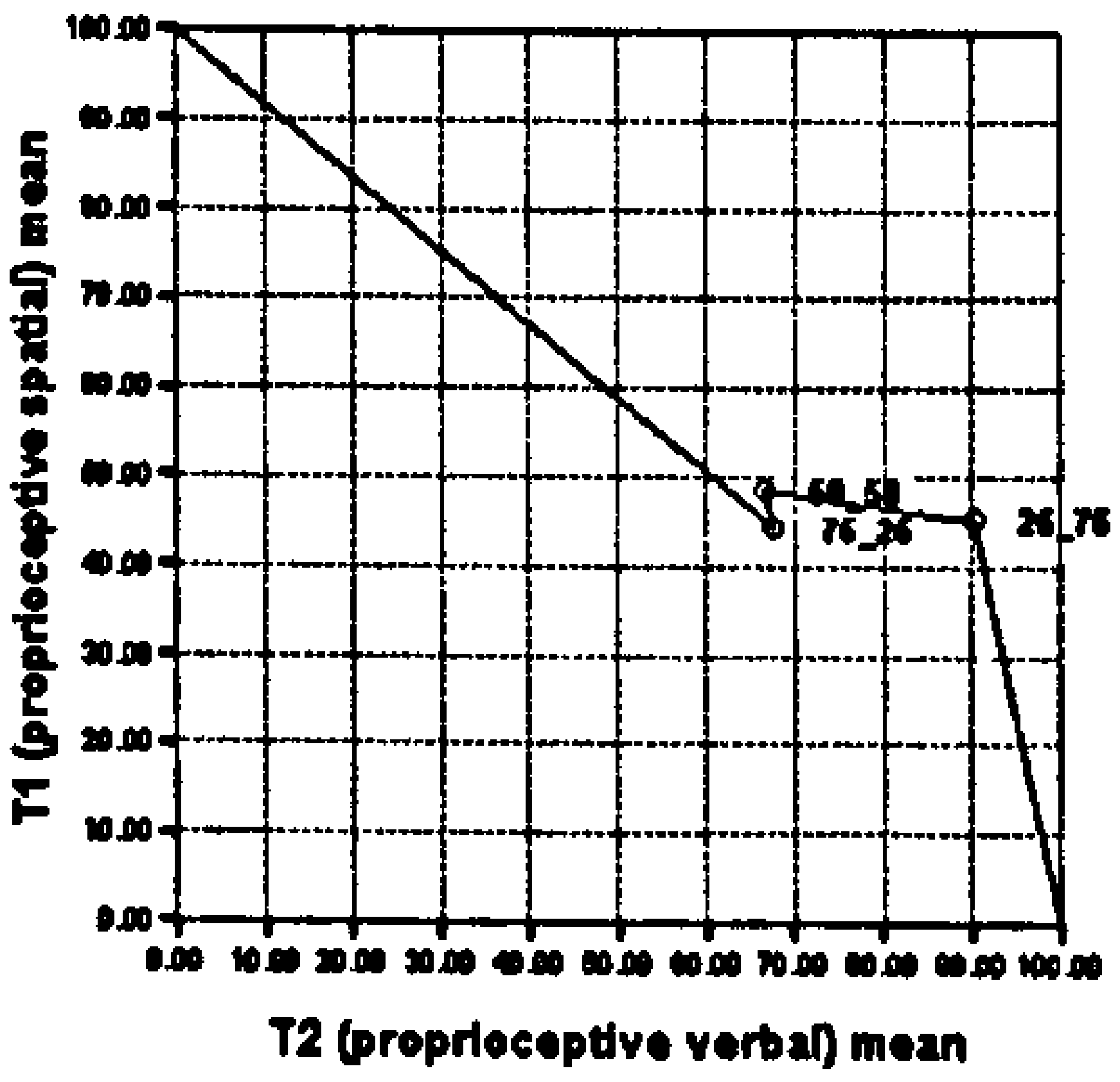
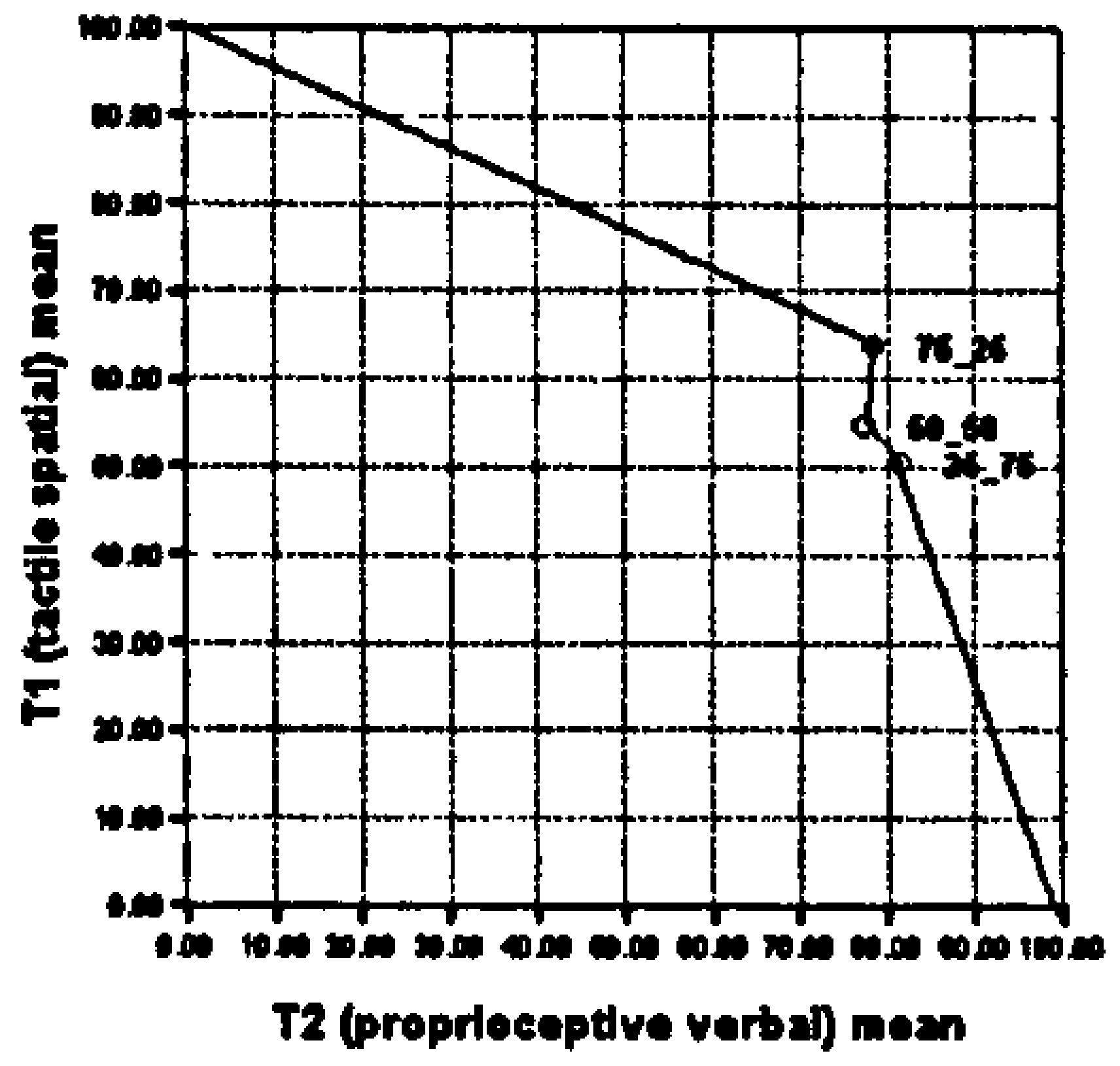
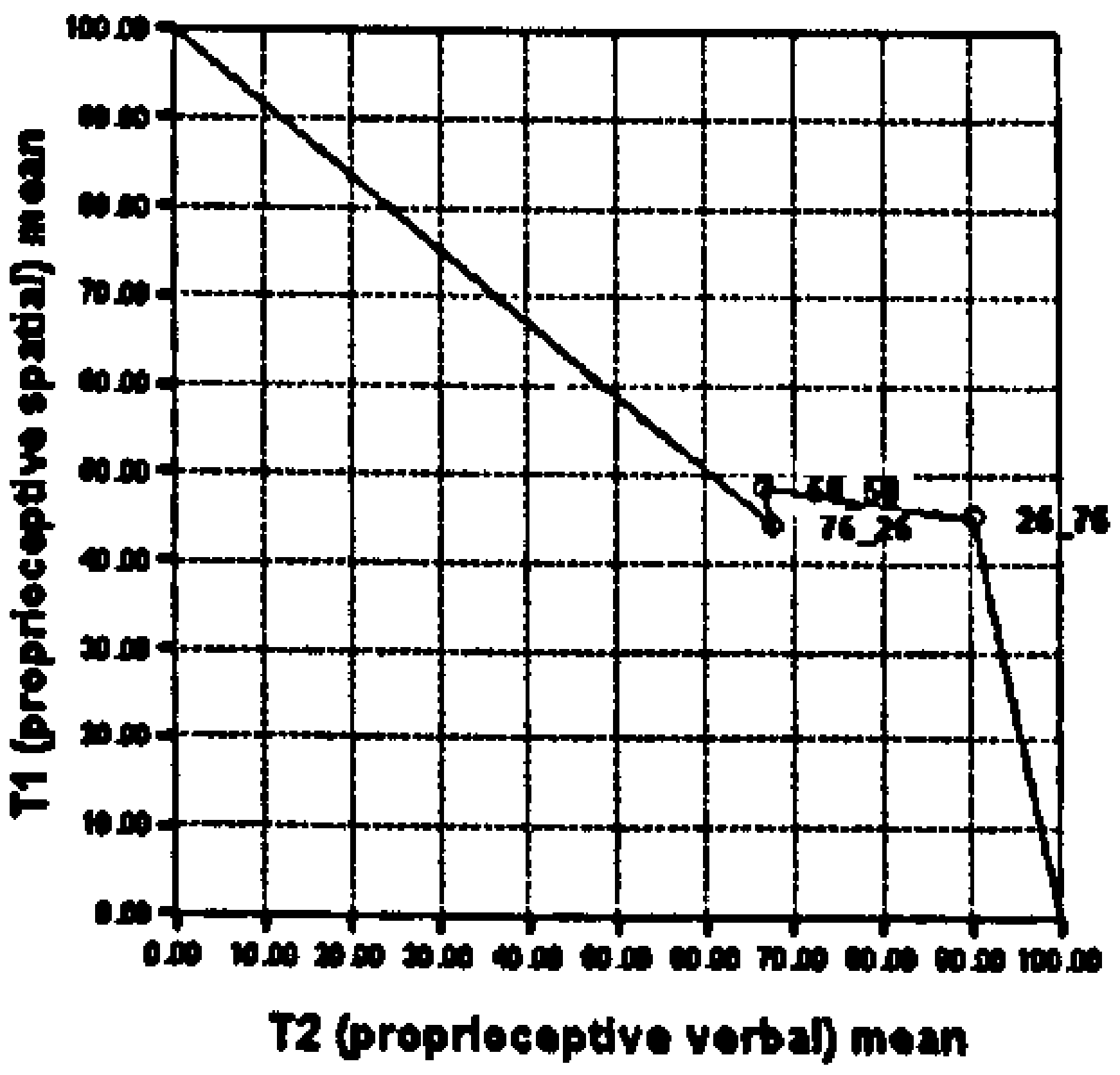
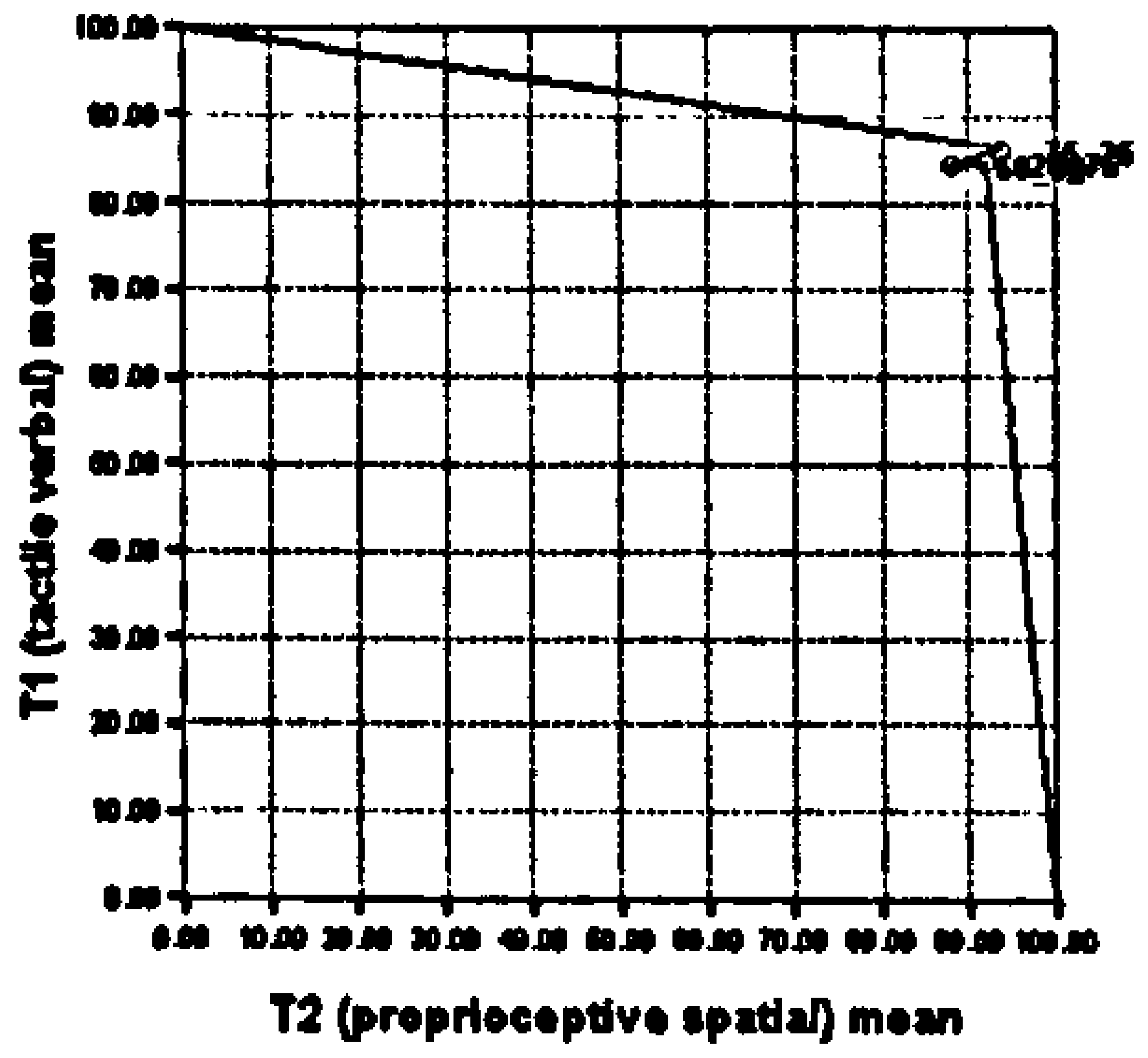
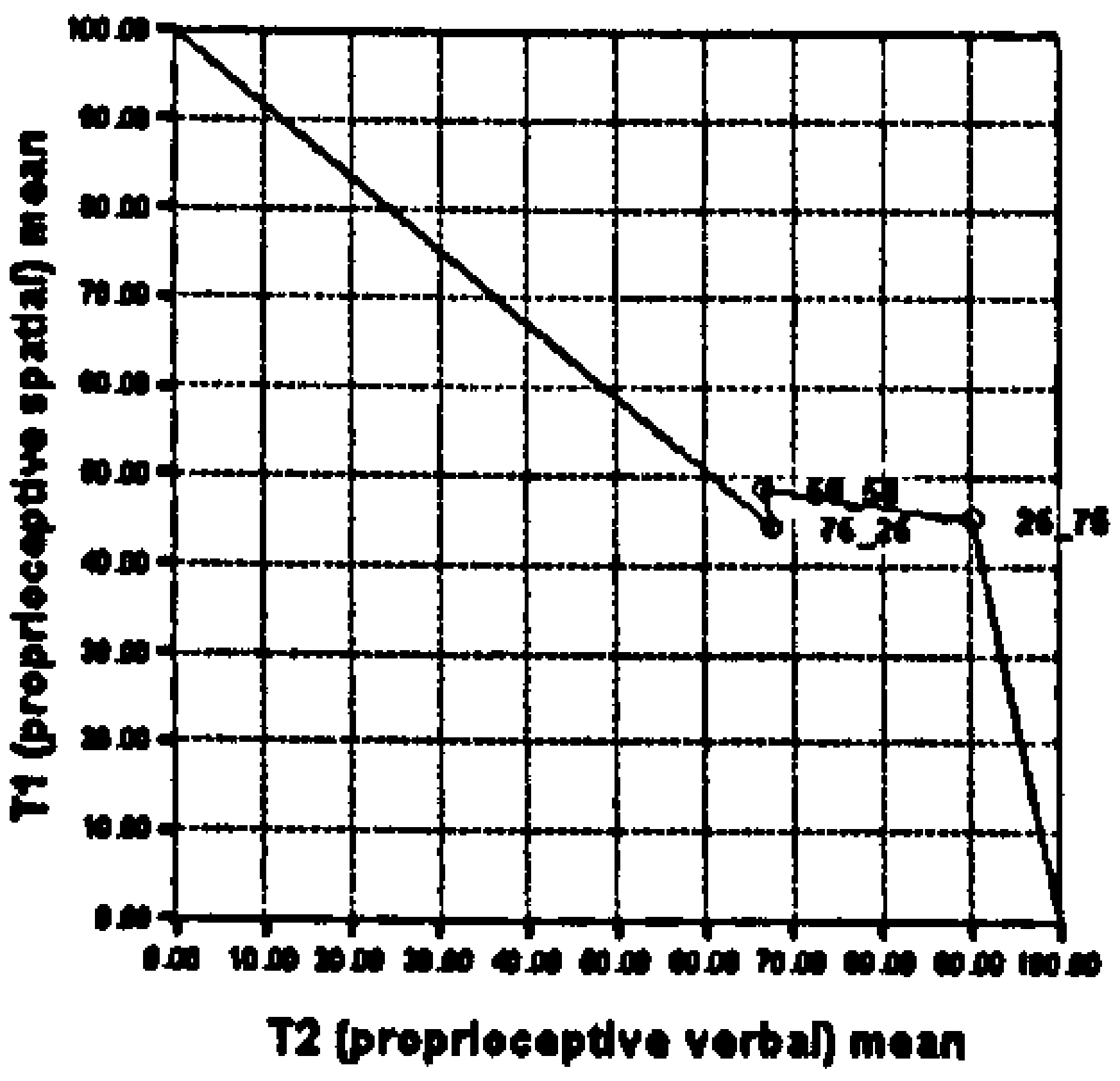
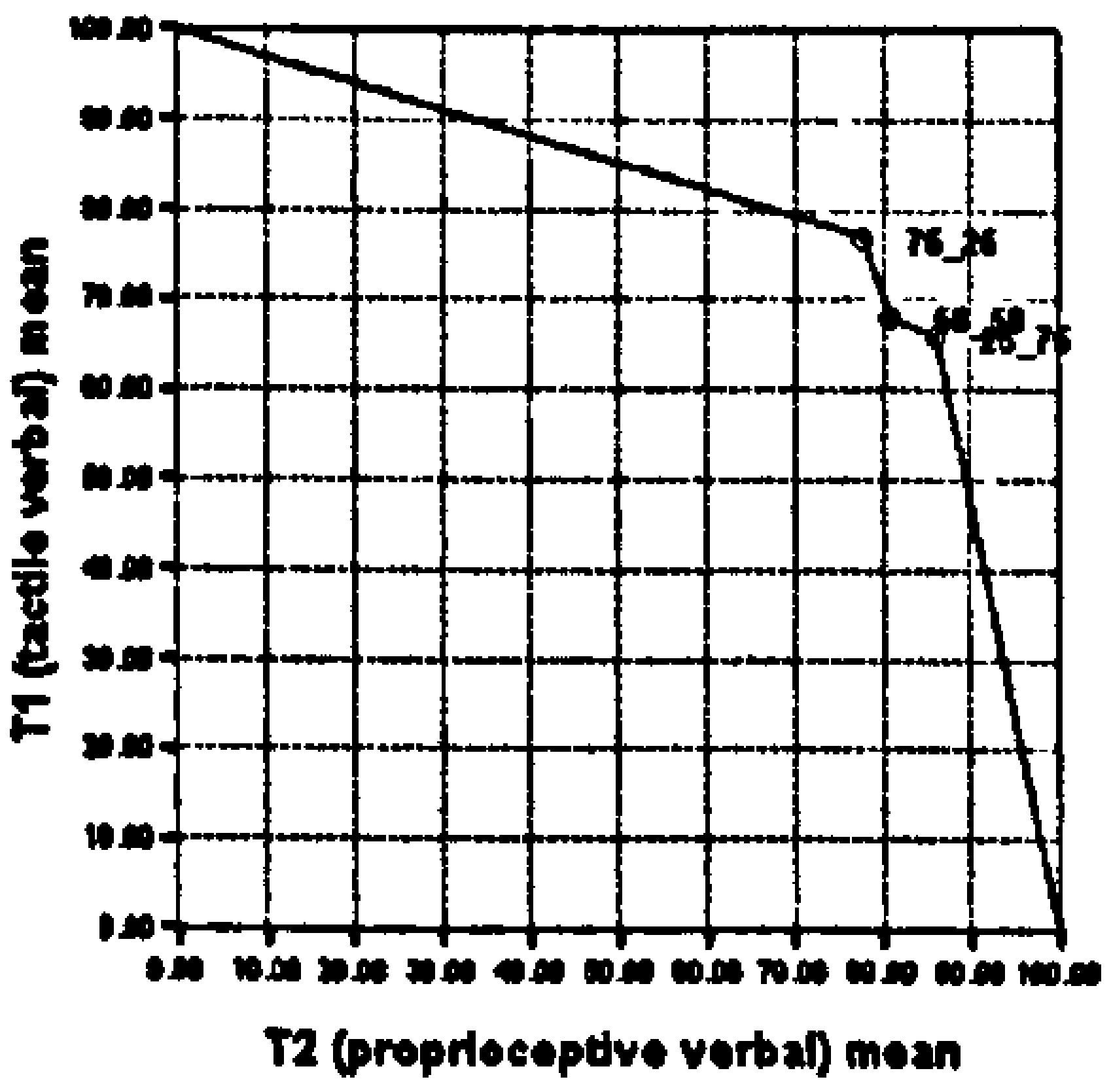
- Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Spatial (TSPS)
- Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)
- Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV)
- Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Spatial (TSPS)
- Tactile Spatial & Tactile Verbal (TSTV) and Tactile Spatial & Proprioceptive Verbal (TSPV)
- Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Spatial (TVPS)
- Tactile Spatial & Tactile Verbal (TSTV) and Tactile Verbal & Proprioceptive Verbal (TVPV)
- Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Spatial (TVPS)

The remaining seven comparisons yielded non–significant differences, including:

- Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Proprioceptive Verbal (TSPV)
- Proprioceptive Spatial & Proprioceptive Verbal (PSPV) and Tactile Spatial & Tactile Verbal (TSTV)
- Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Spatial & Proprioceptive Verbal (TSPV)
- Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Spatial (TVPS)
- Tactile Spatial & Proprioceptive Spatial (TSPS) and Tactile Verbal & Proprioceptive Verbal (TVPV)
- Tactile Spatial & Proprioceptive Verbal (TSPV) and Tactile Verbal & Proprioceptive Verbal (TVPV)
- Tactile Verbal & Proprioceptive Spatial (TVPS) and Tactile Verbal & Proprioceptive Verbal (TVPV)

These results are discussed in the following Discussion section.

Table 41: Study One Summary of Results — Effect of CONDITION

<table>
<tr><th colspan="3">EFFECT OF CONDITION</th></tr>
<tr><th colspan="2">COMPARISON</th><th>SIGNIFICANCE OF DIFFERENCE</th></tr>
<tr><td>PSPV
 </td><td>TSPS
 </td><td>Significant</td></tr>
<tr><td>PSPV
 </td><td>TSPV
 </td><td>Not Significant</td></tr>
<tr><td>PSPV
 </td><td>TVPS
 </td><td>Significant</td></tr>
<tr><td>PSPV
 </td><td>TVPV
 </td><td>Significant</td></tr>
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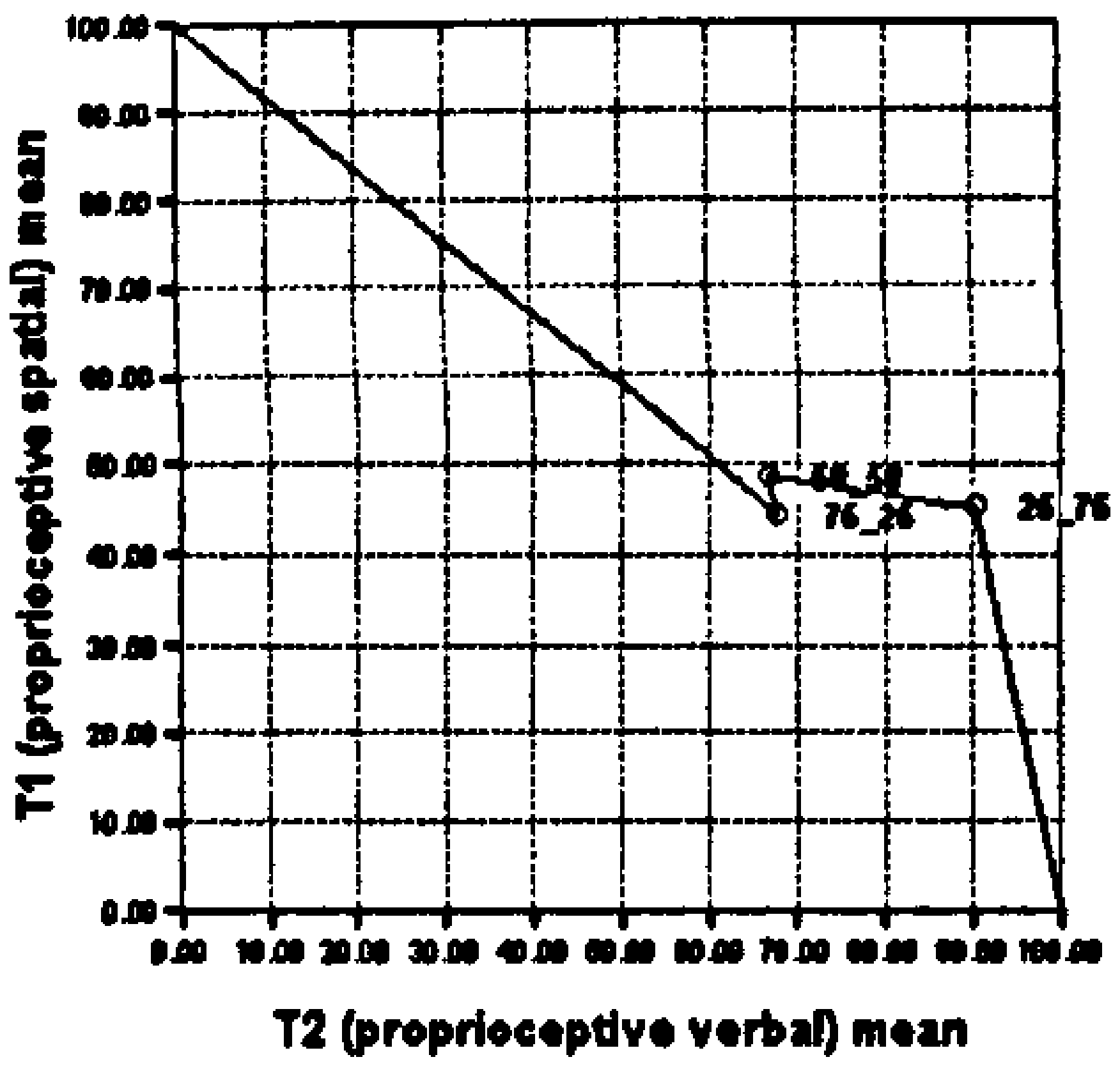
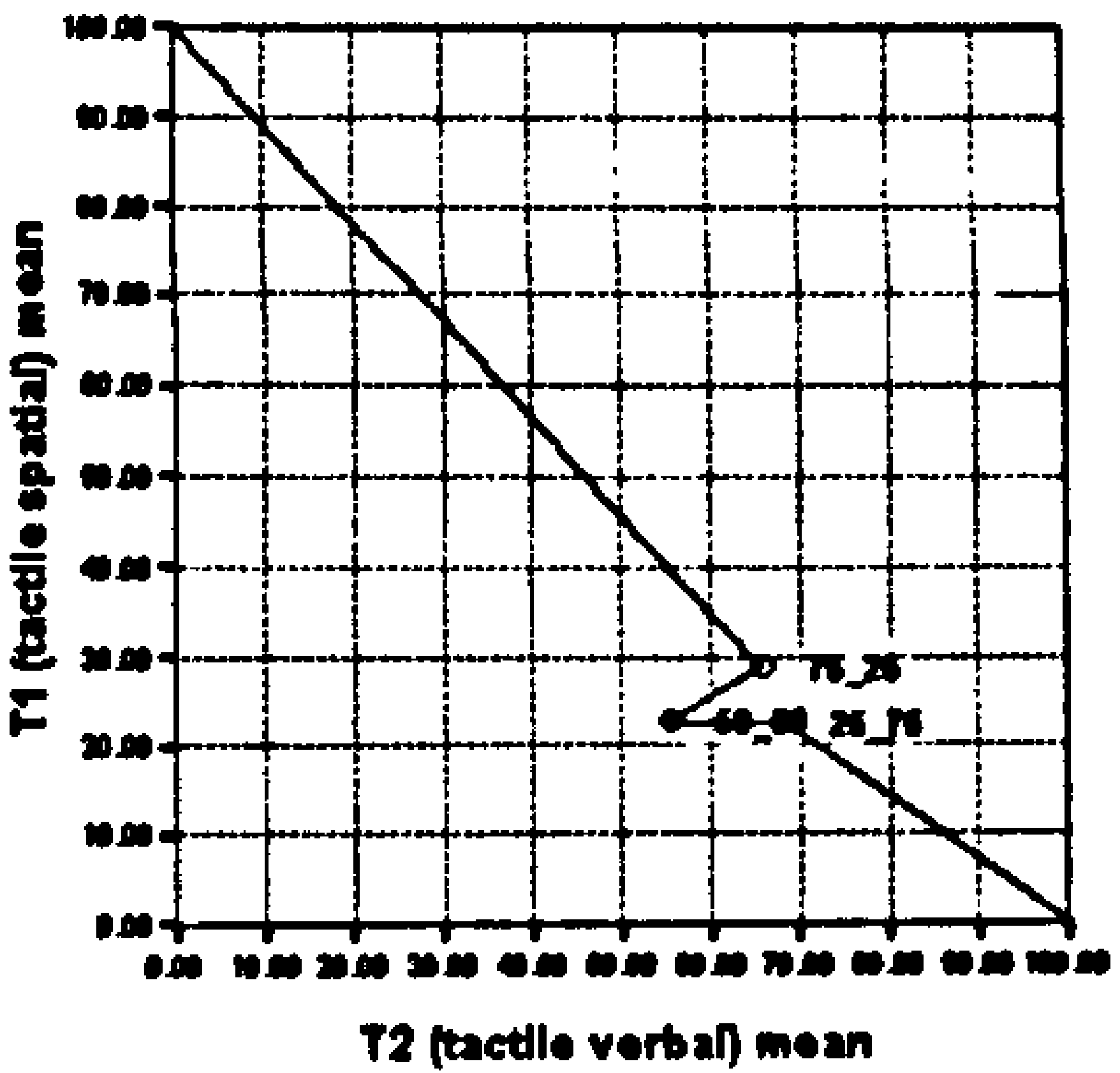
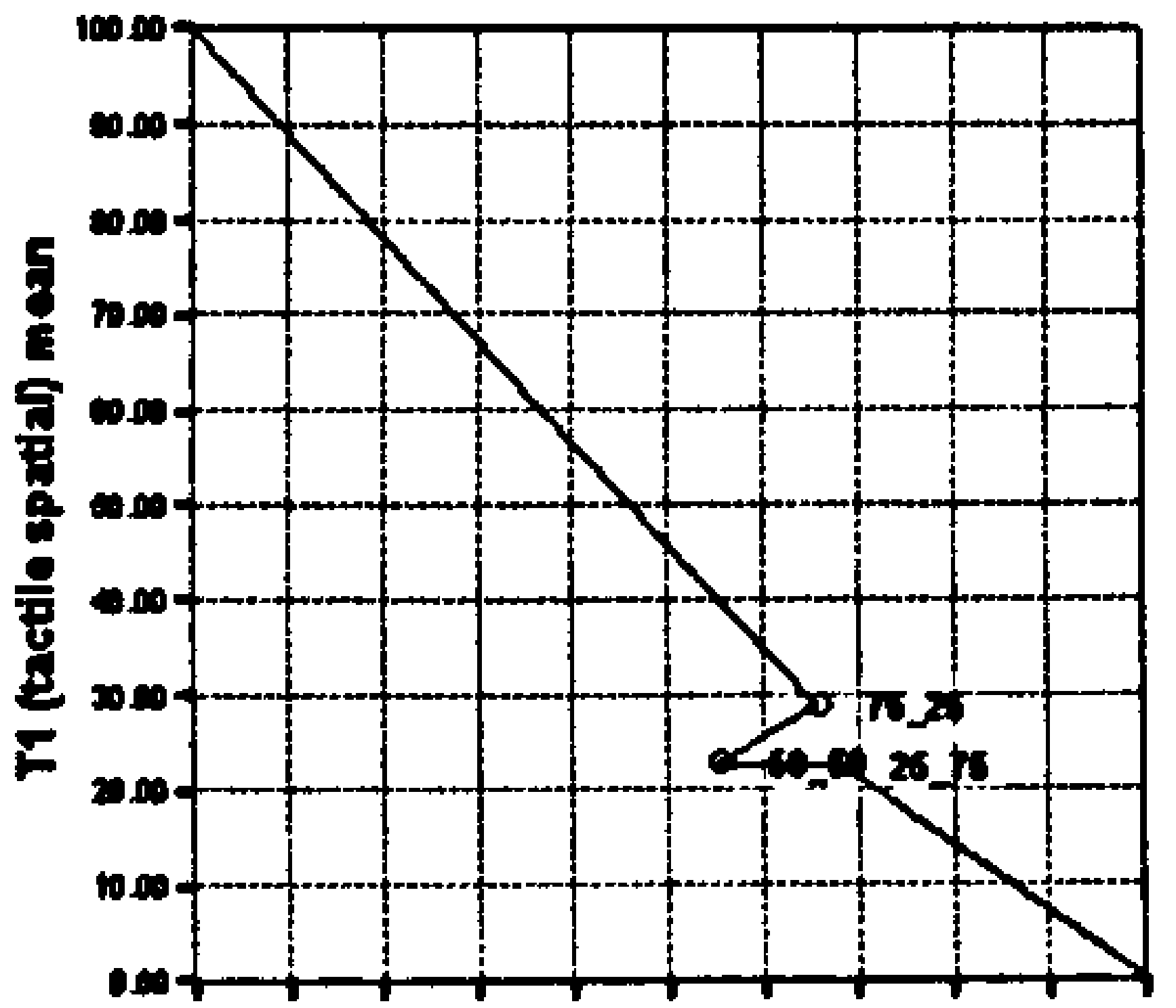
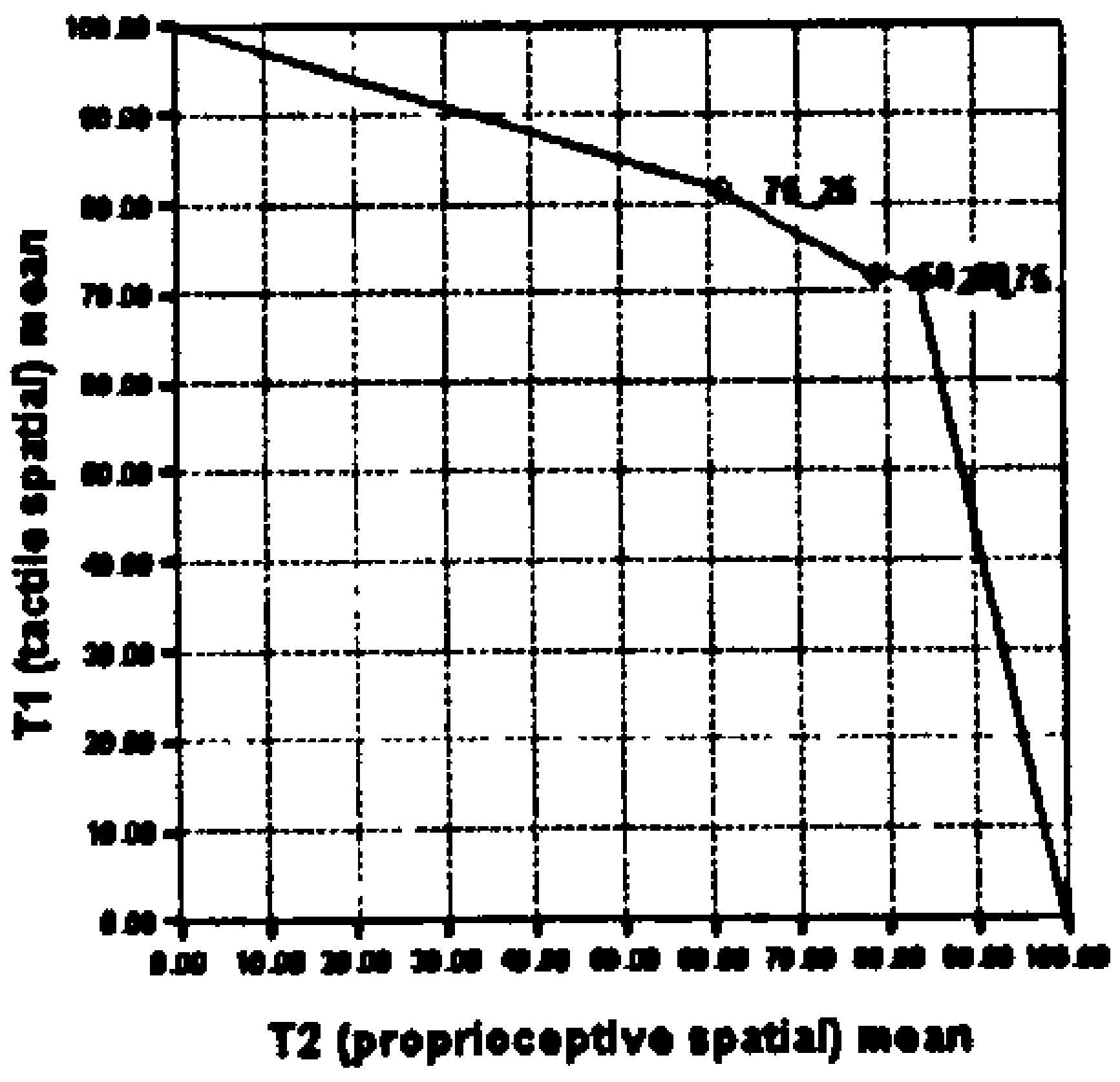
PSPV **TSTV** **Not Significant**



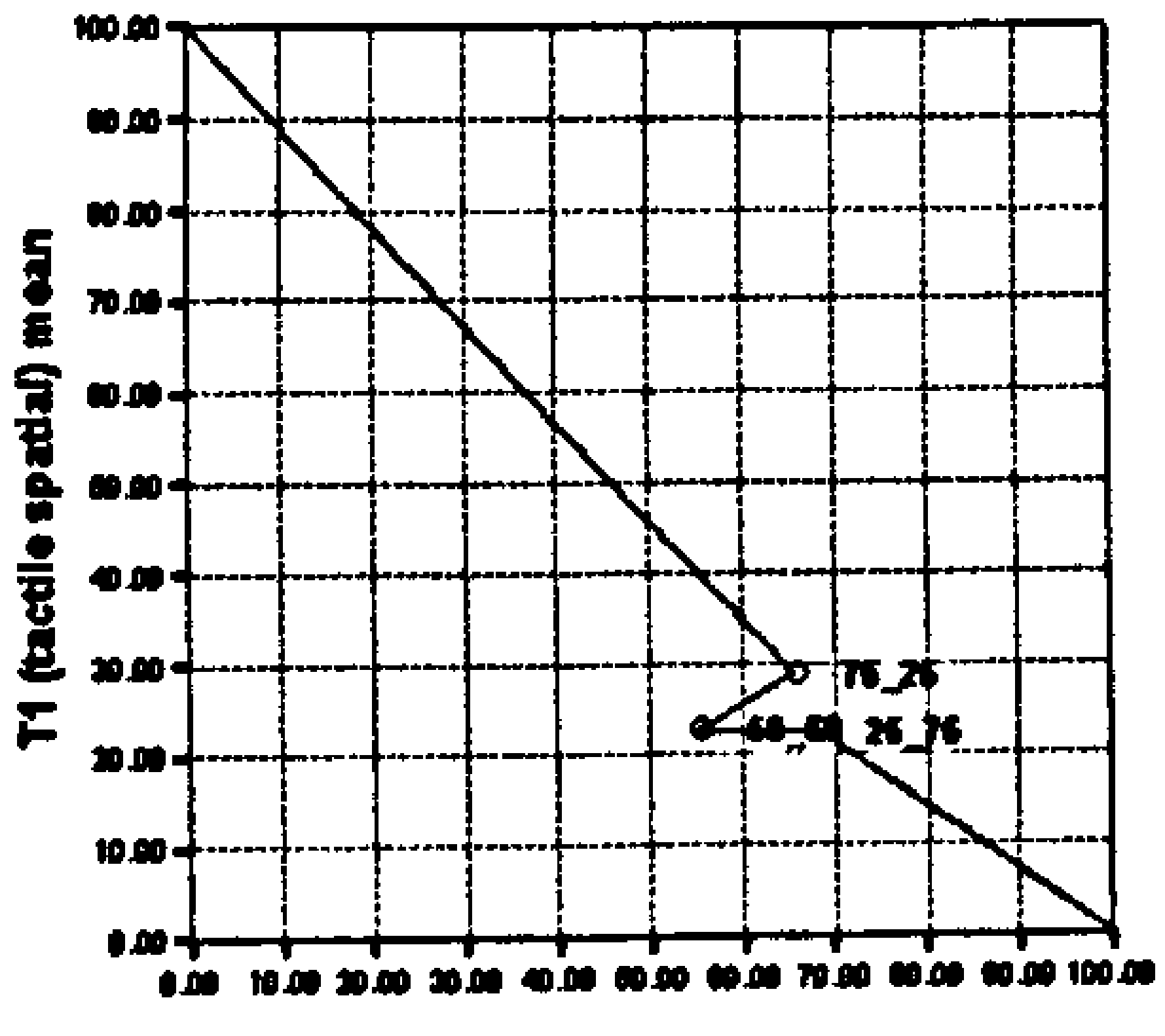


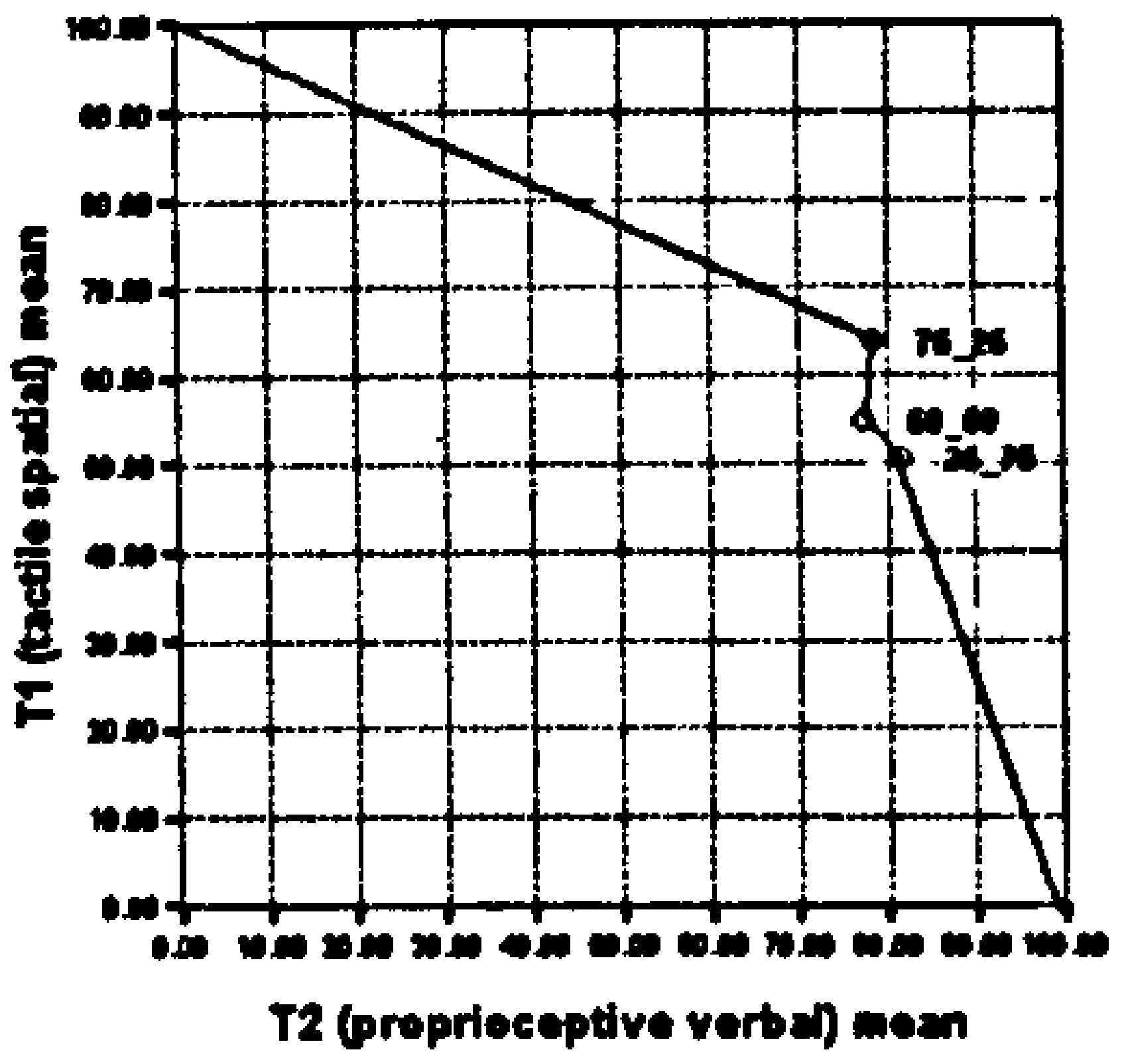
TSTV **TSPS** **Significant**



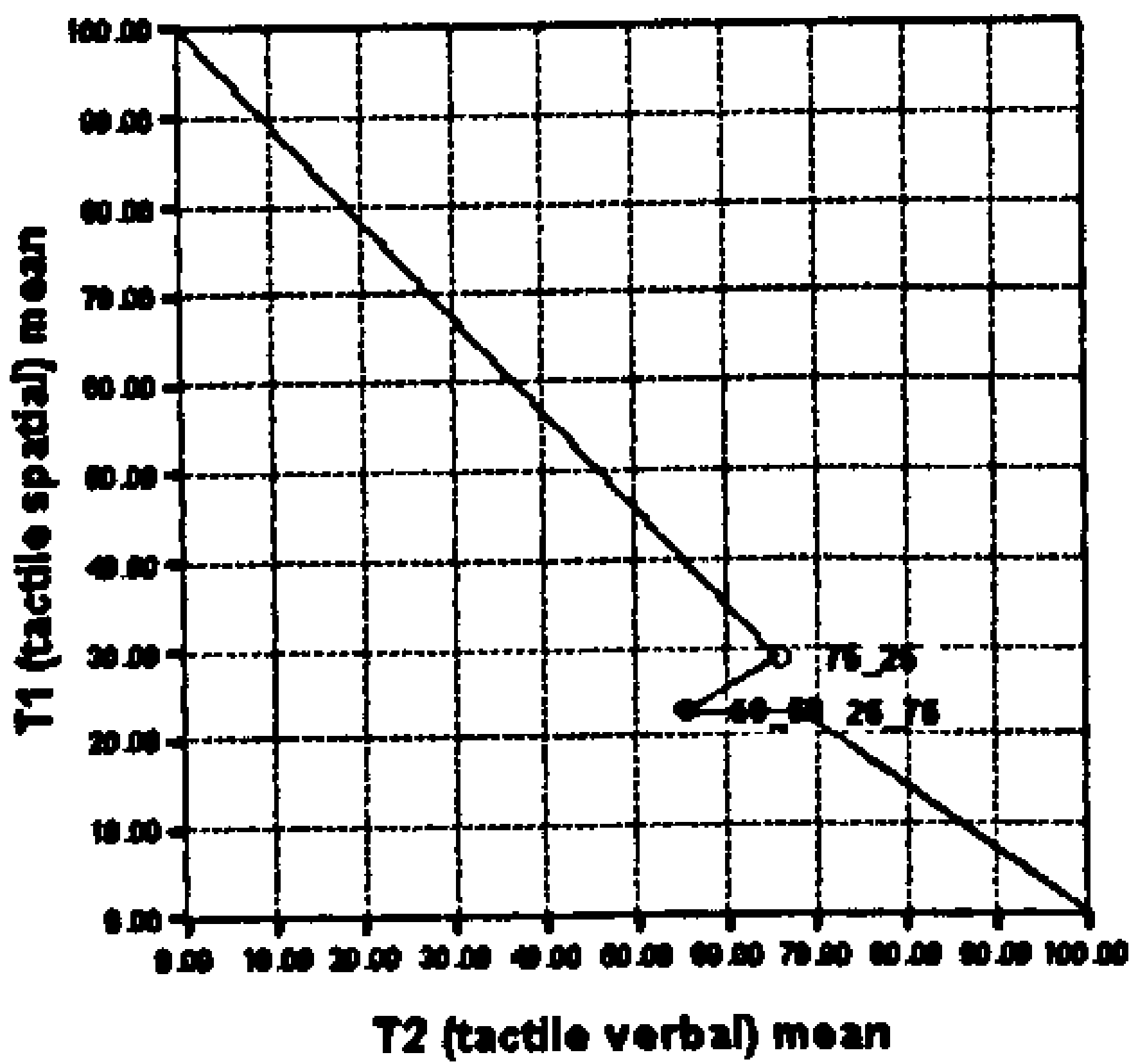


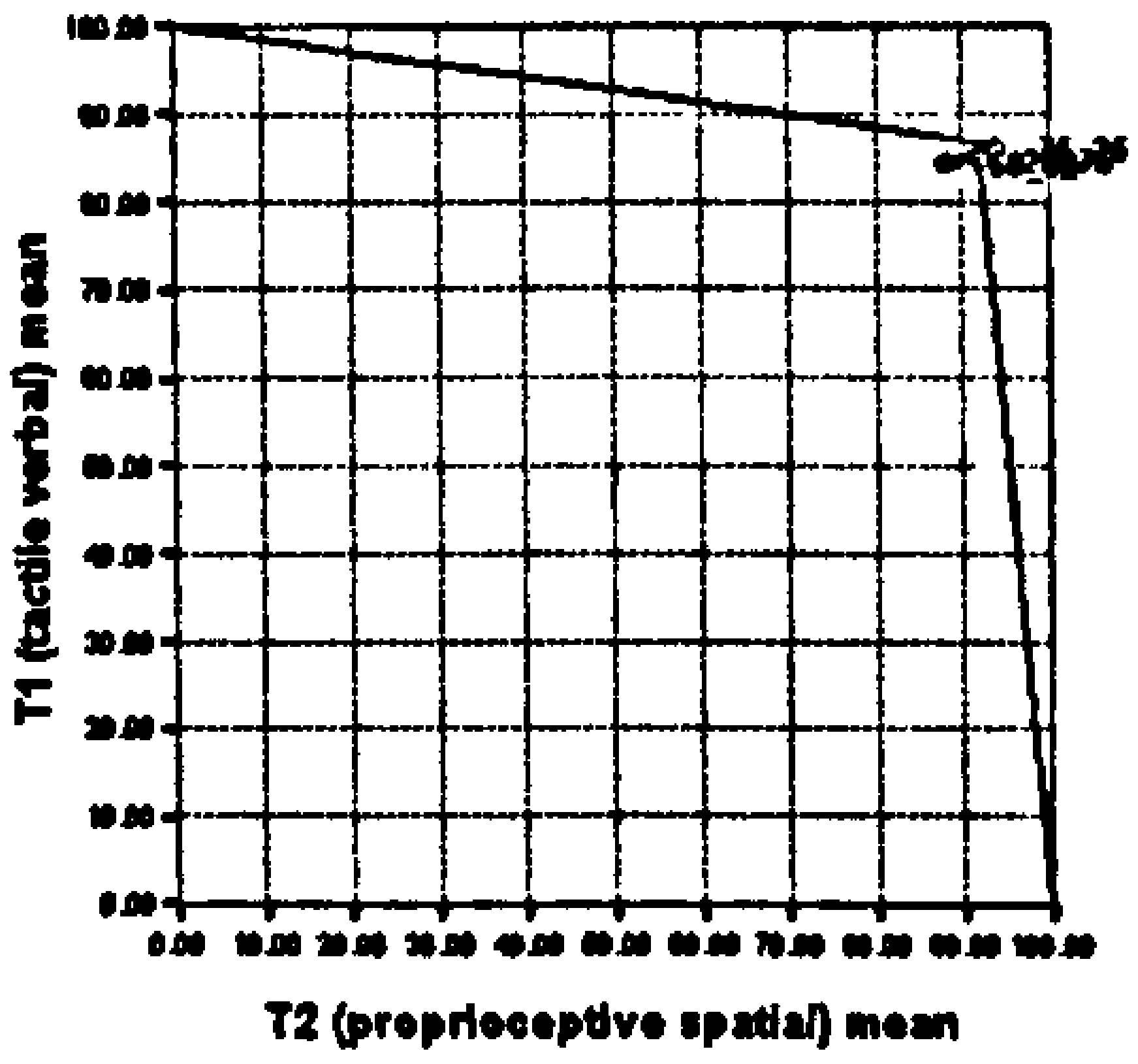
TSTV **TSPV** **Significant**



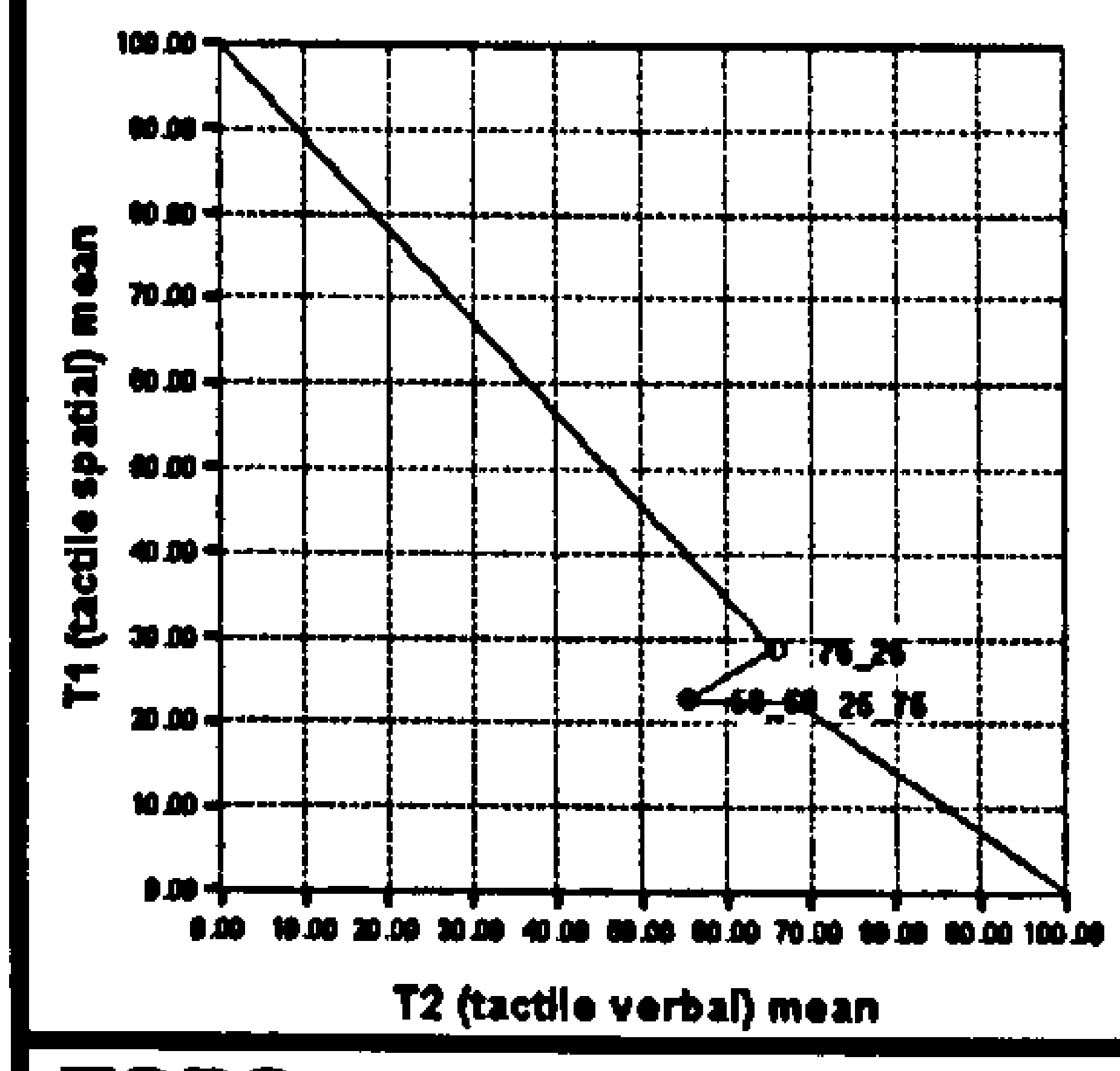


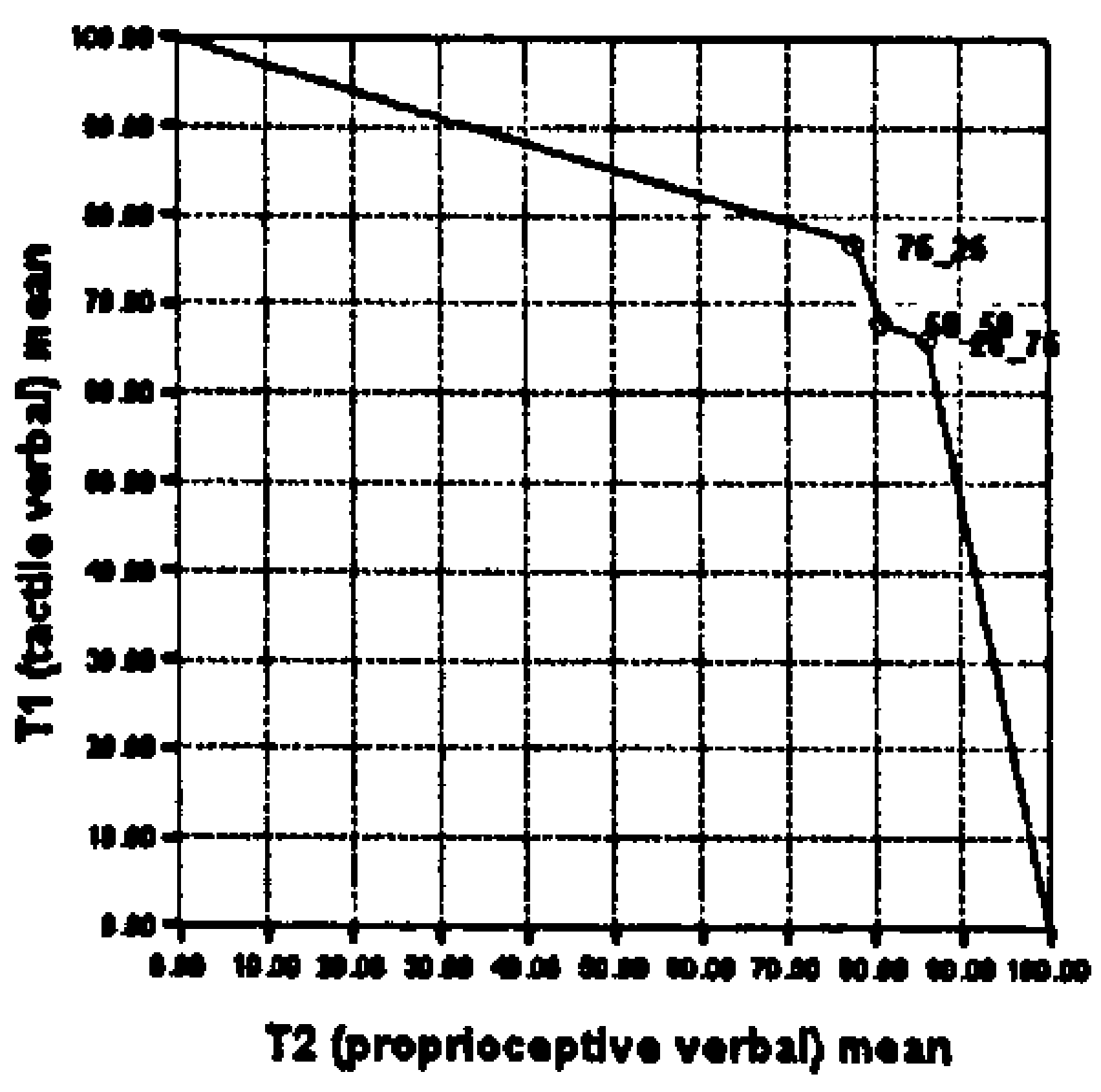
TSTV **TVPS** **Significant**



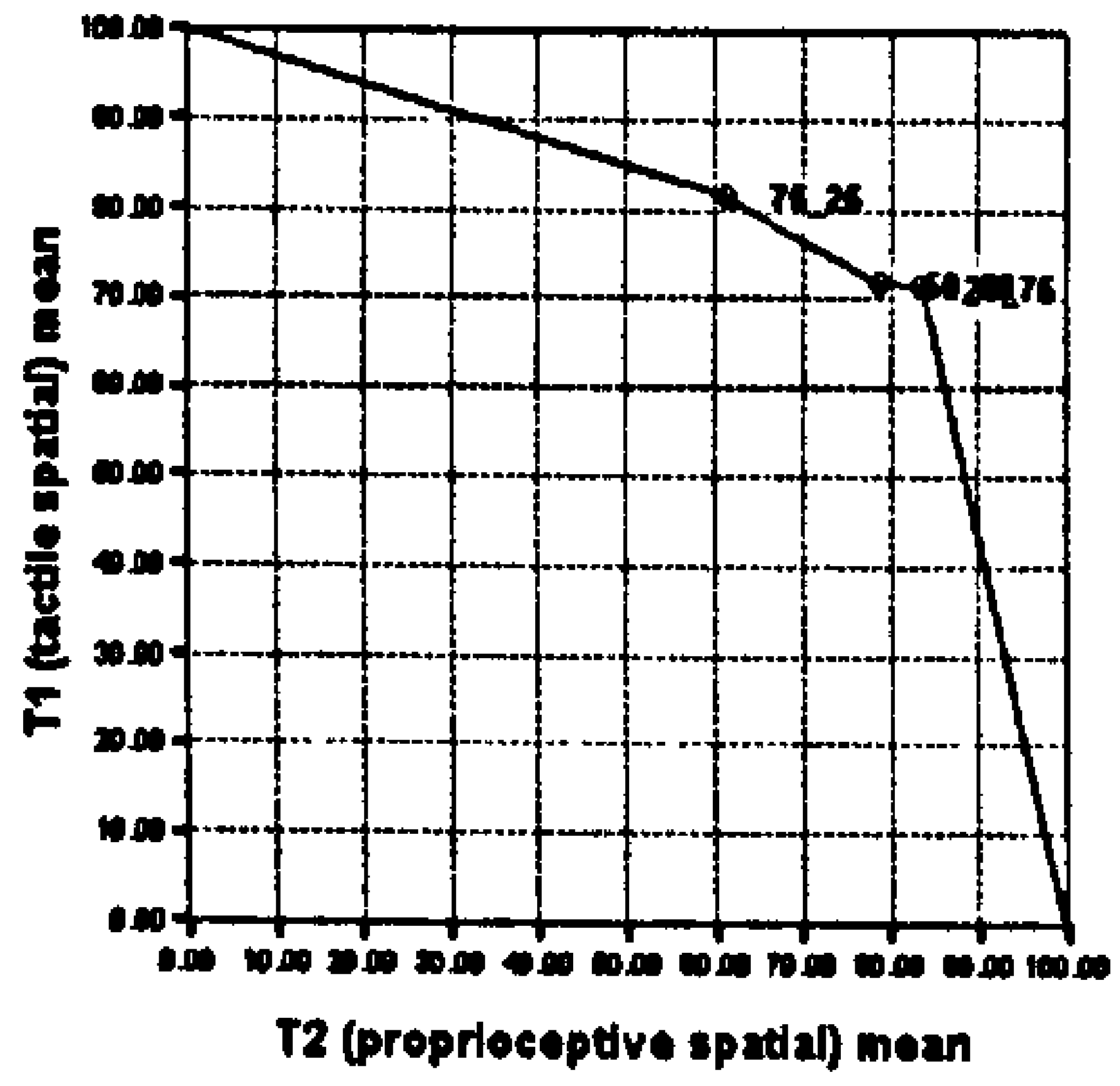


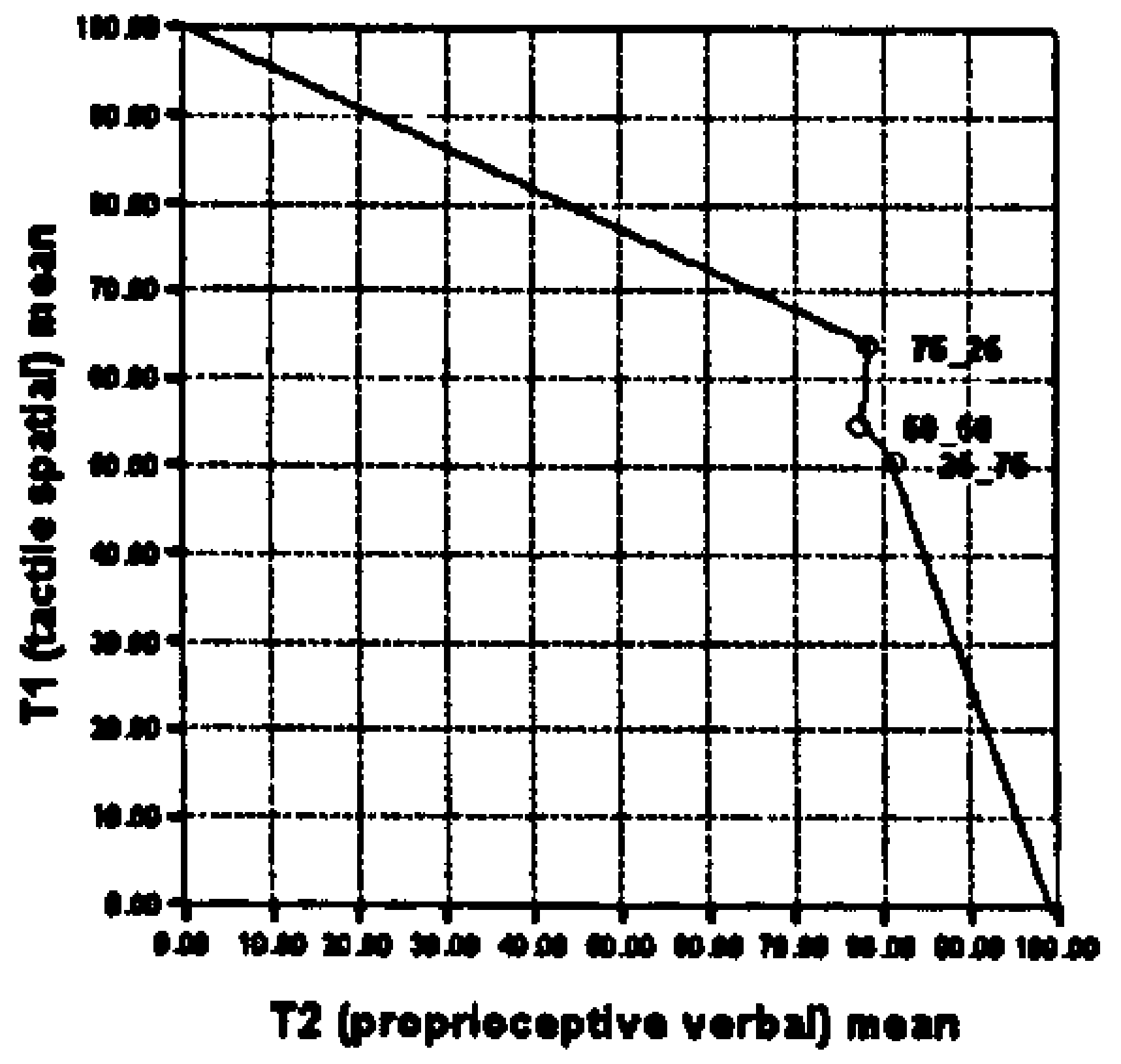
TSTV **TVPV** **Significant**



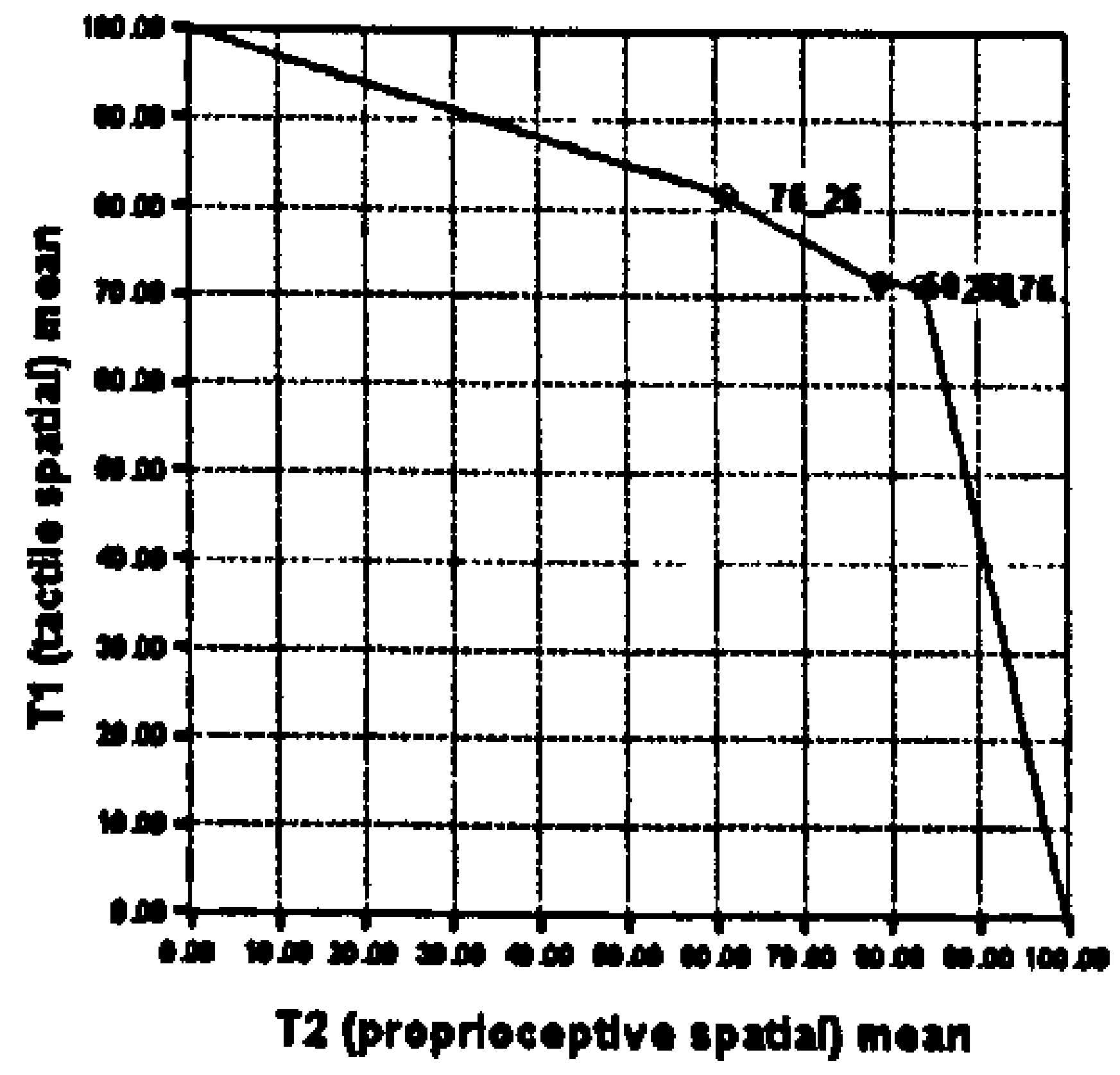


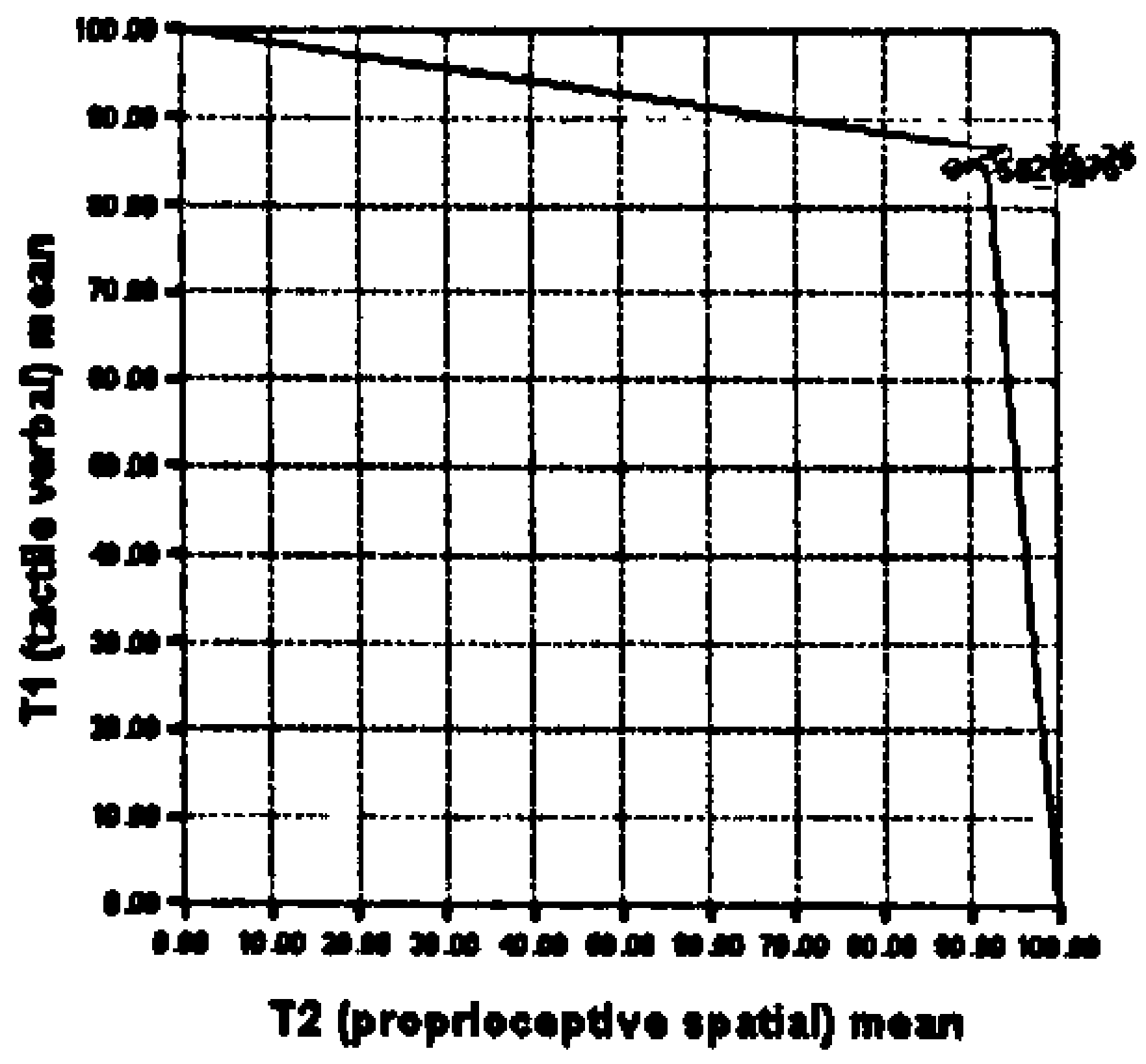
TSPS **TSPV** **Not Significant**



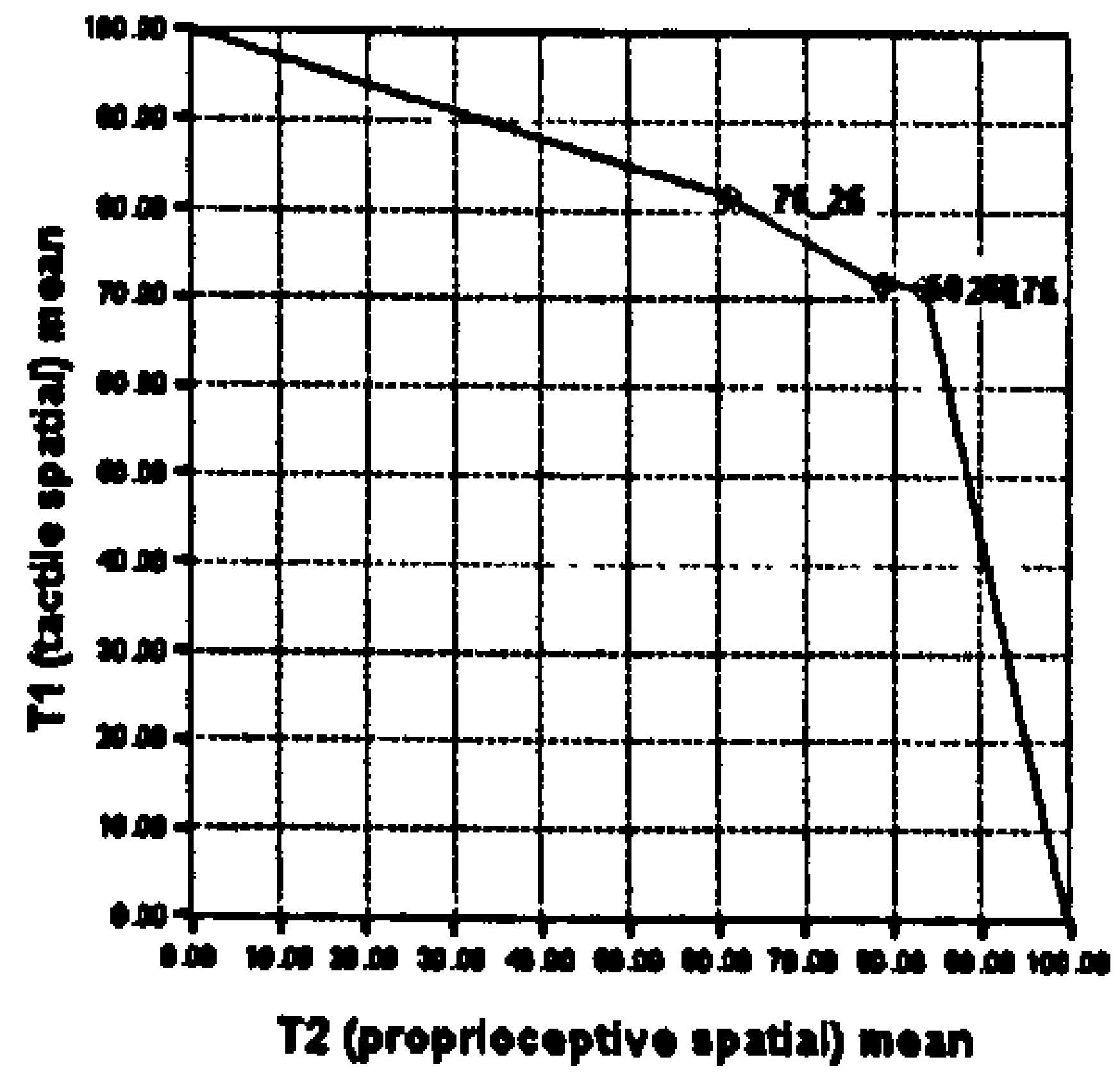


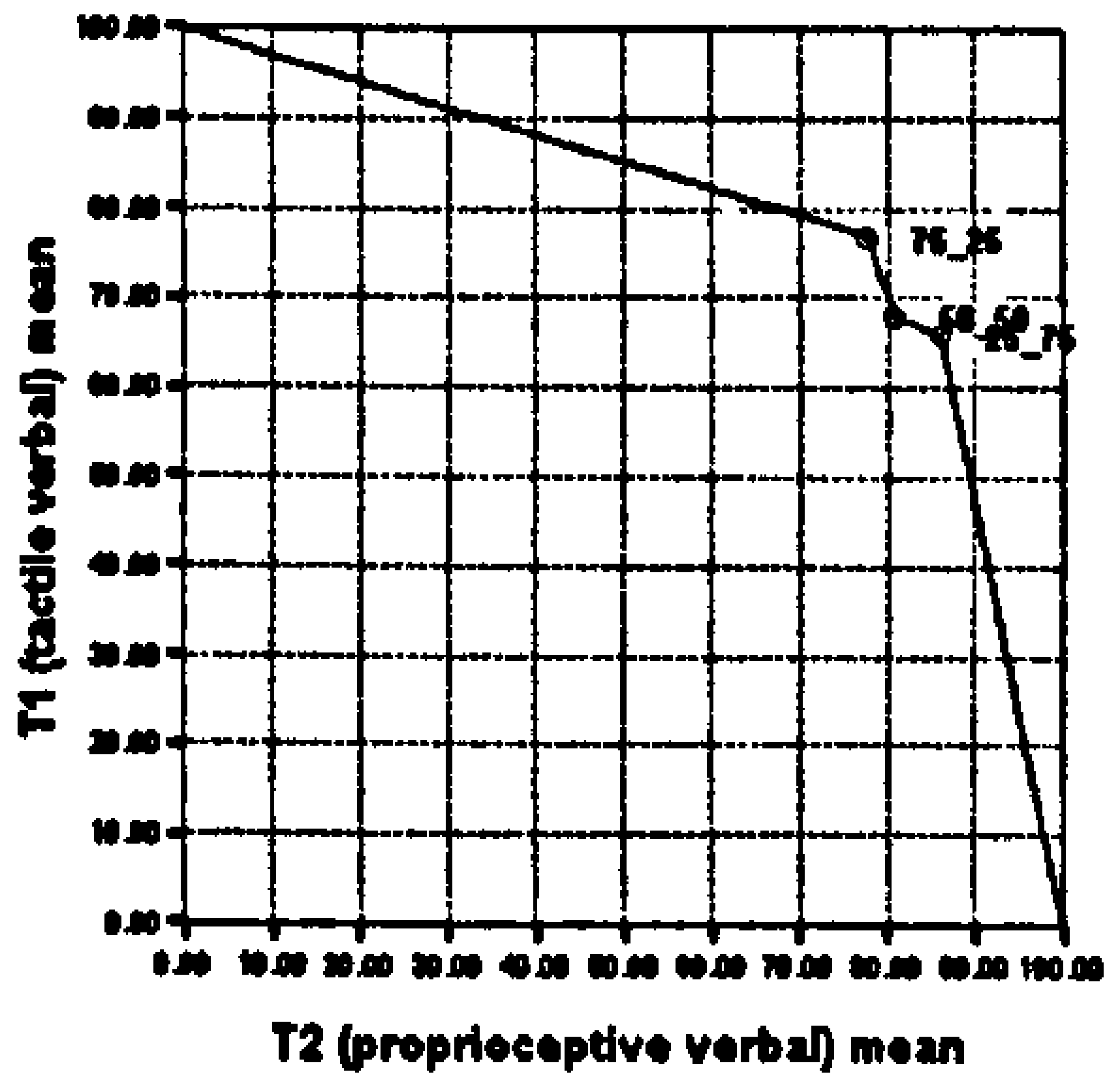
TSPS **TVPS** **Not Significant**



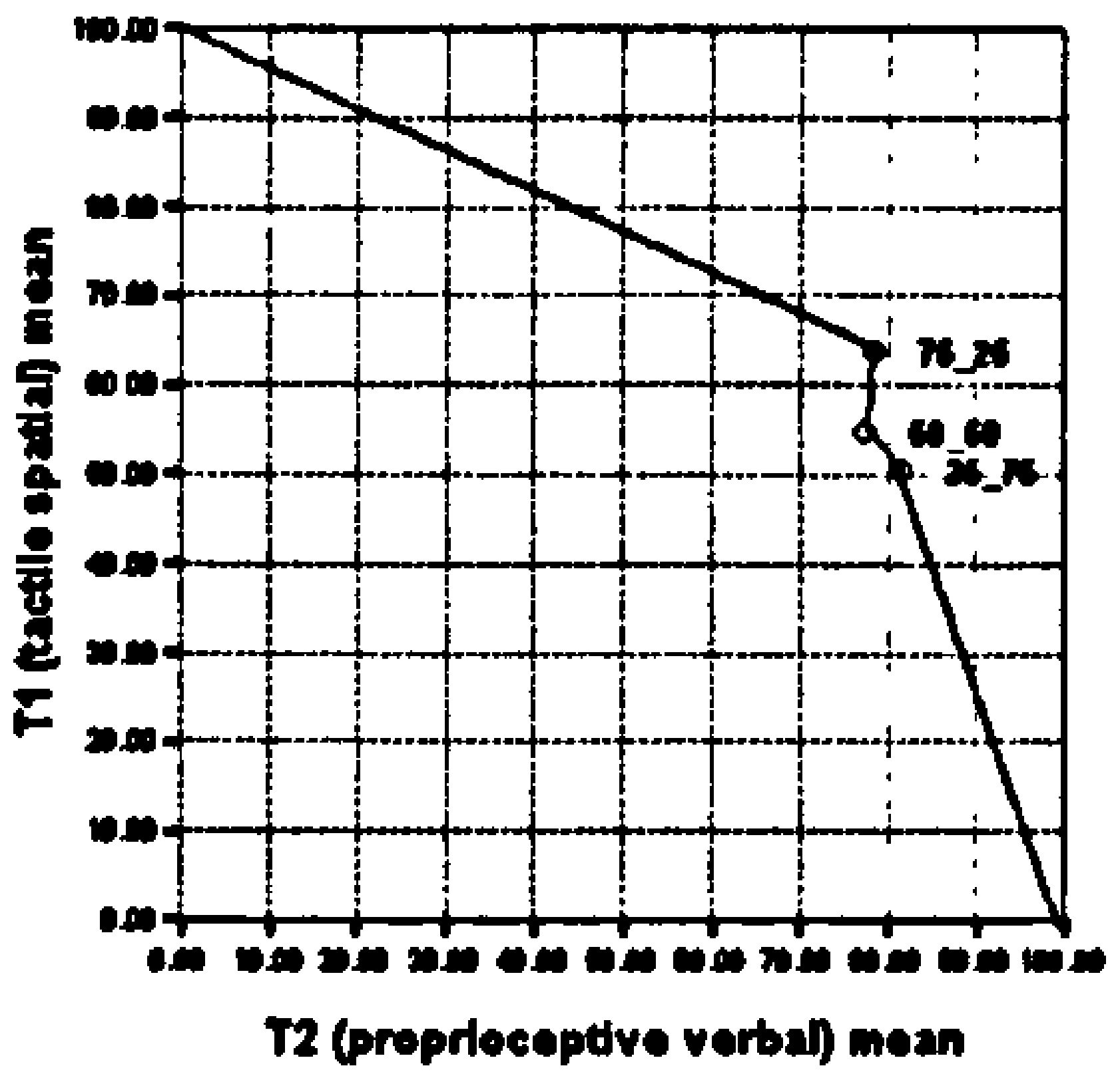


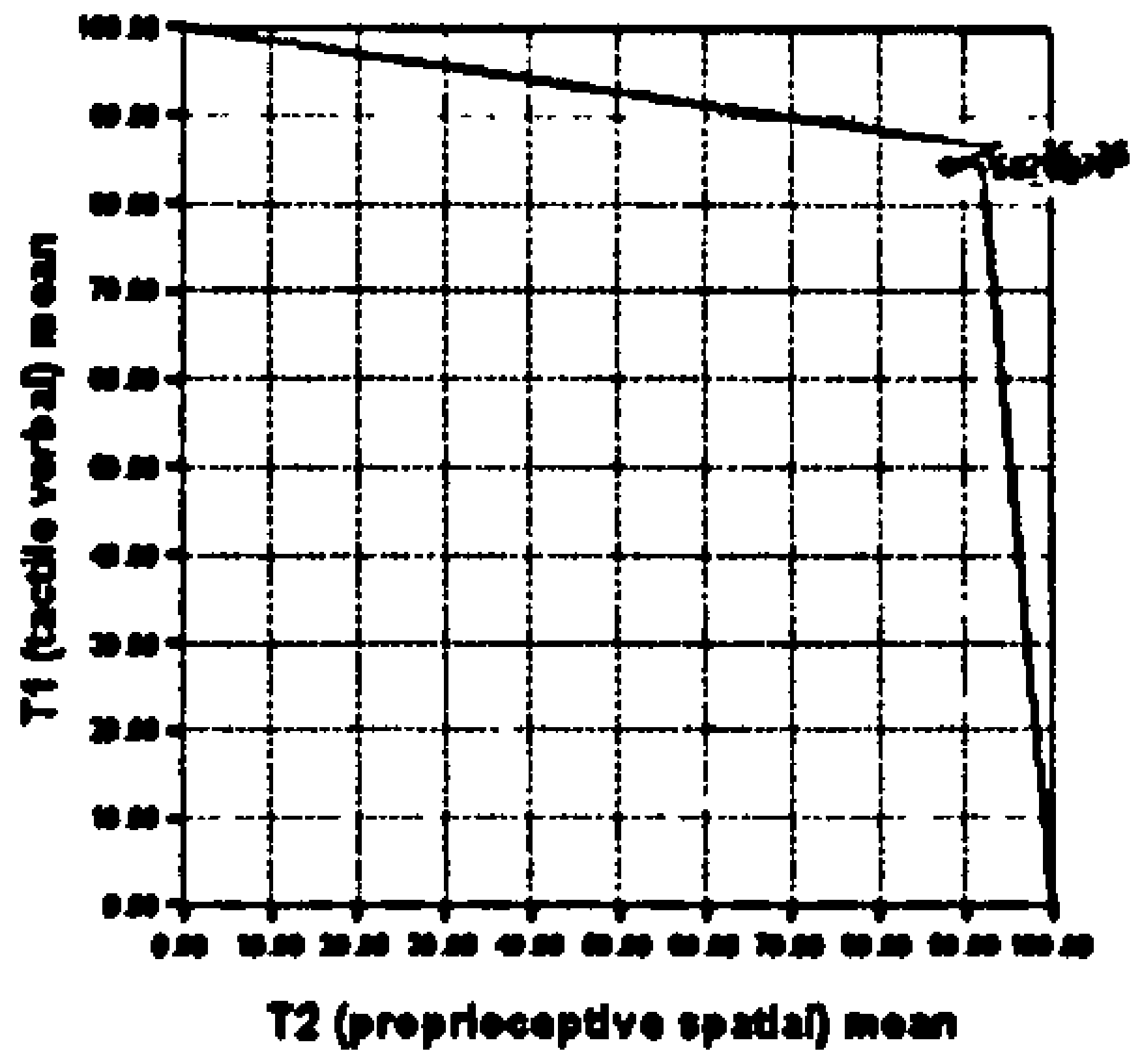
TSPS **TVPV** **Not Significant**



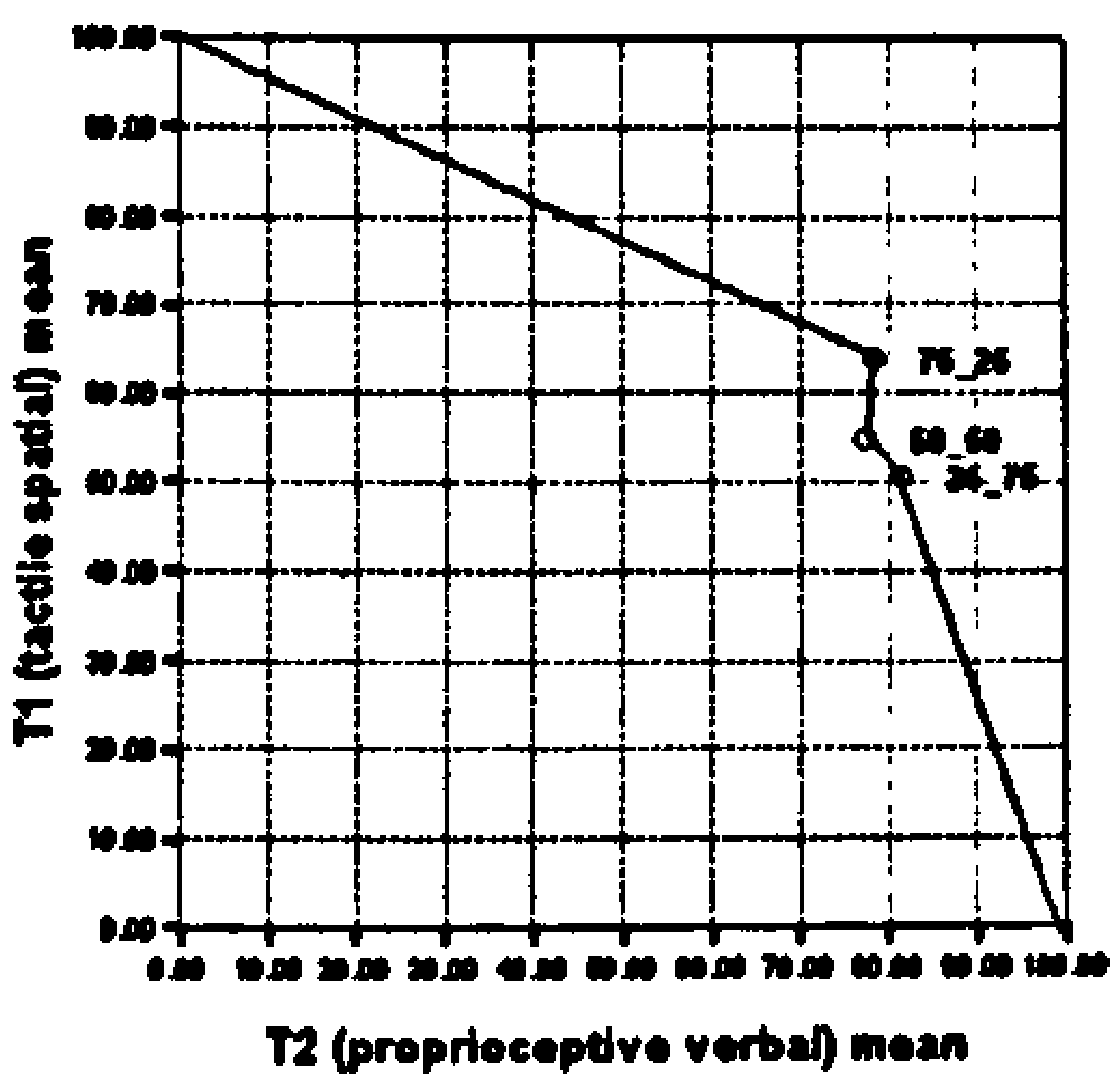


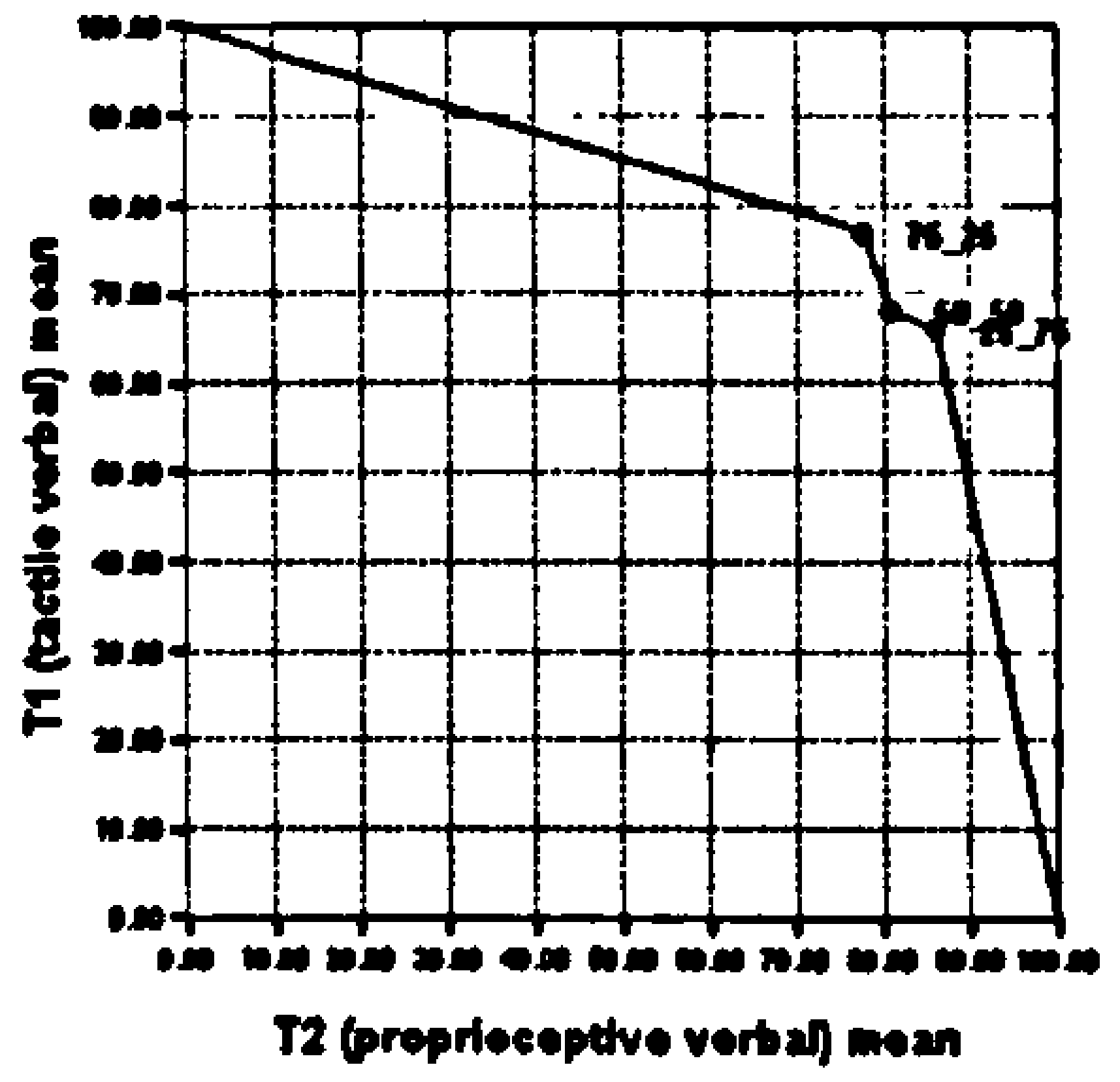
TSPV **TVPS** **Significant**



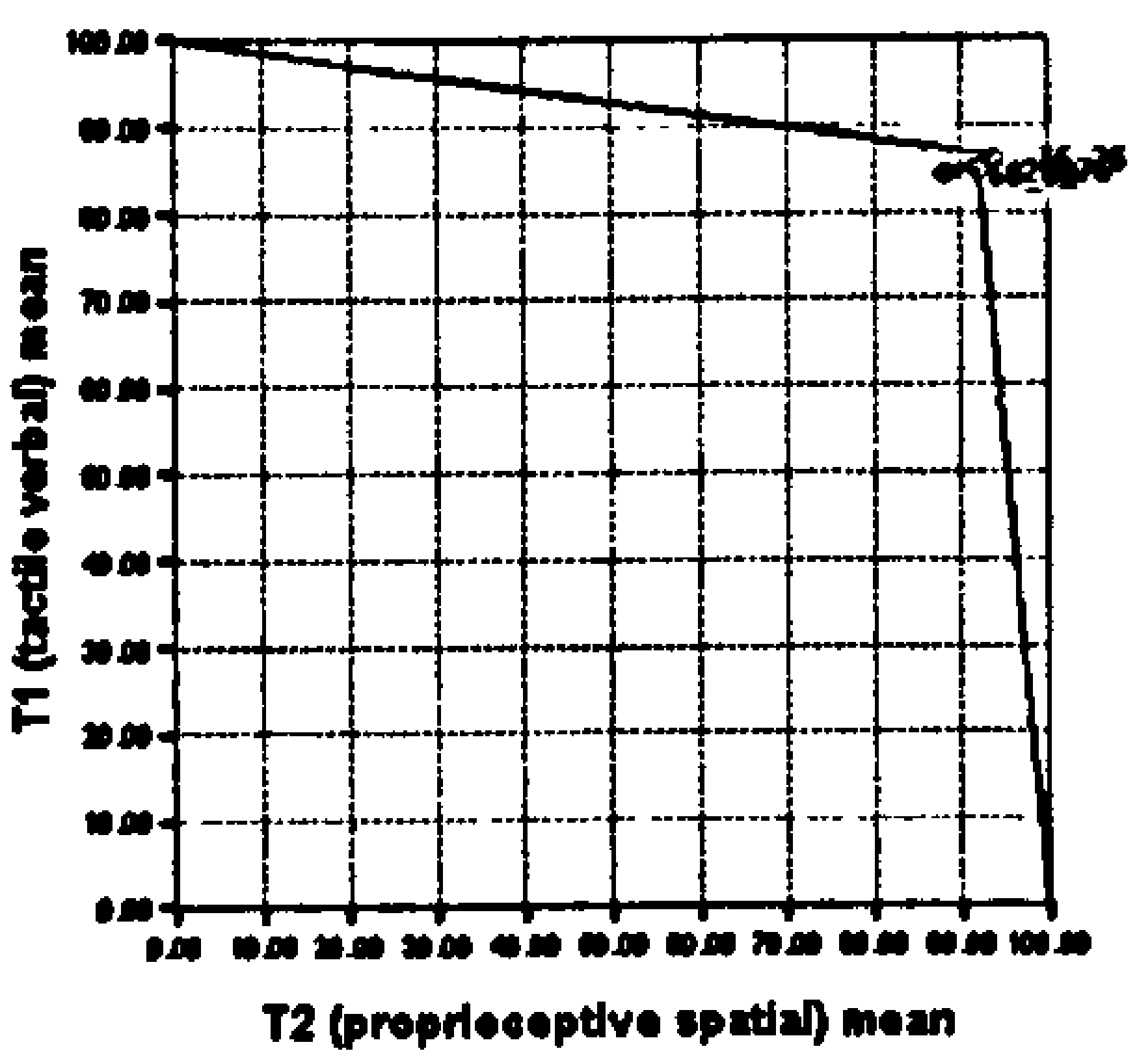


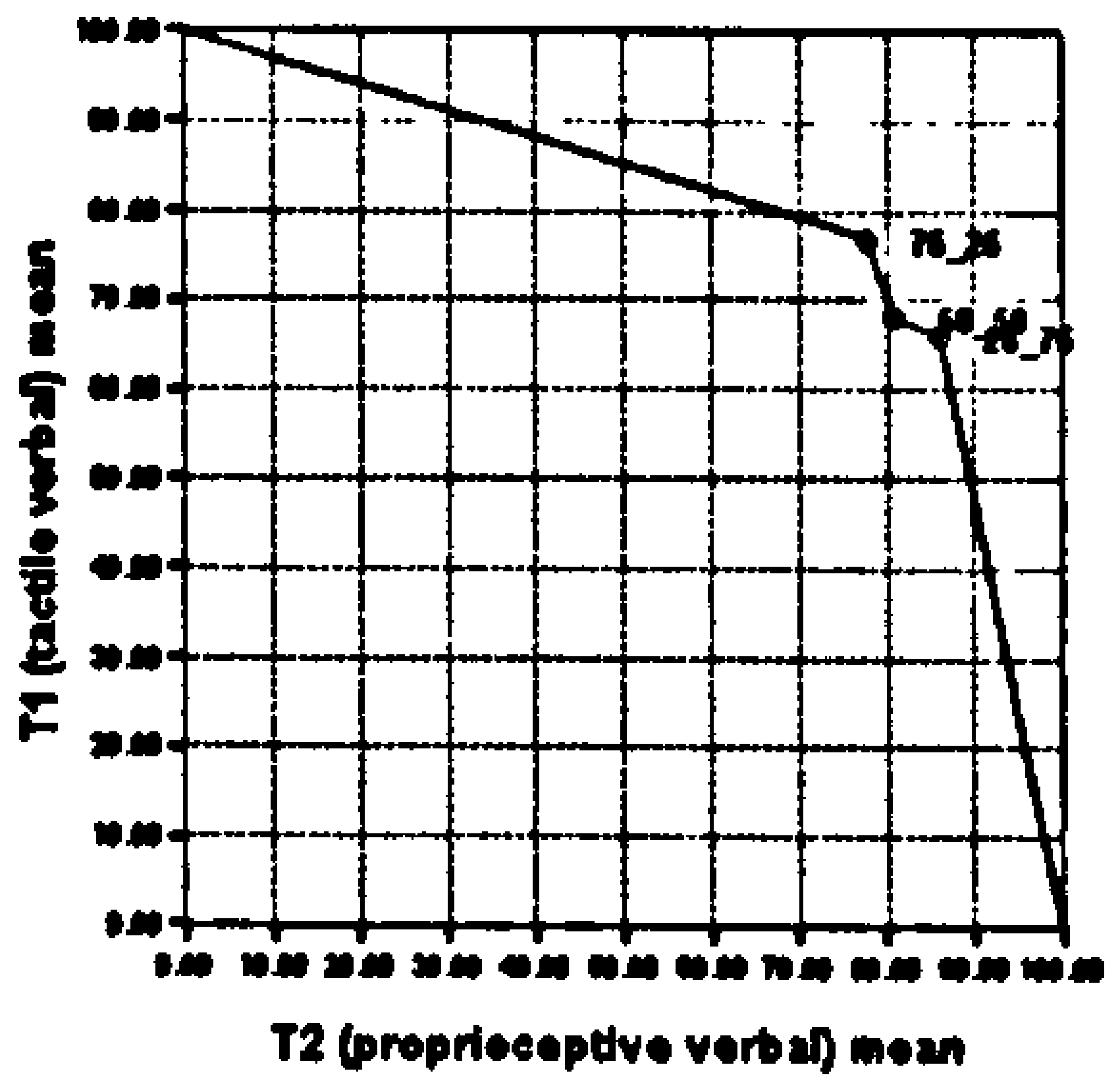
TSPV **TVPV** **Not Significant**





TVPS **TVPV** **Not Significant**





10 Discussion for Study One

A reminder of the dual–task conditions for Study One:

- PSPV — Proprioceptive Spatial (PS) & Proprioceptive Verbal (PV)
- TSTV — Tactile Spatial (TS) & Tactile Verbal (TV)
- TSPS — Tactile Spatial (TS) & Proprioceptive Spatial (PS)
- TSPV — Tactile Spatial (TS) & Proprioceptive Verbal (PV)
- TVPS — Tactile Verbal (TV) & Proprioceptive Spatial (PS)
- TVPV — Tactile Verbal (TV) & Proprioceptive Verbal (PV)

The results of Study One are summarised in Table 42.

Table 42: Summary of results for Study One

Dual–Task	*Dual–Task Score (%)*	*Significant Difference from Single–Tasks (in bold)*		*Significant Differences from the Other Dual–Tasks (in bold)*			
TSTV (tactile spatial & tactile verbal)	45	**TS**	**TV**		PSPV		
				TSPV	**TSPS**	**TVPV**	**TVPS**
PSPV (proprioceptive spatial & proprioceptive verbal)	60.5	**PS**	PV	TSTV			
				TSPV	**TSPS**	**TVPV**	**TVPS**
TSPV (tactile spatial & proprioceptive verbal)	70.3	**TS**	**PV**	**TSTV**	PSPV		
					TSPS	TVPV	**TVPS**
TSPS (tactile spatial & proprioceptive spatial)	78.5	**TS**	**PS**	**TSTV**	**PSPV**		
				TSPV		TVPV	TVPS
TVPV (tactile verbal & proprioceptive verbal)	79.8	**TV**	PV	**TSTV**	**PSPV**		
				TSPV	TSPS		TVPS
TVPS (tactile verbal & proprioceptive spatial)	89.5	**TV**	PS	**TSTV**	**PSPV**		
				TSPV	TSPS	TVPV	

Dual–task scores were first compared to the respective single task scores and differences tested for significance. This was a useful first step in understanding whether performance had suffered as a result of a particular dual–task combination, particularly for borderline results (where a small decrement had occurred but significance needed to be confirmed). These results show suggest that the difference between single and dual-task results becomes more significant as overall dual-task percentage score decreases (not surprisingly). It is worth noting though that, for the dual-task TSPS, significant single to dual-task differences, for the PS element, are only found at the 25% allocation policy and not at 50% or 75%. This is not surprising as one would expect worse results at the 25% allocation policy than at the other two policies. Figure 19 shows this to be the case and also shows that the results at the other two allocation policies are worse than at the single task condition even though these latter results were not significant.

However, despite attempts to control resource allocation, it was still possible that participants might have favoured one task over the other within the dual-task scenario. This could have a knock-on negative effect upon the non-favoured task. Therefore, it was also important to look at the dual-task as a whole. For example, where both tasks must share the same resource, then they will have access to 100% of that resource but that resource must be apportioned between the two tasks. Where one task is favoured then it may do very well and performance may not be significantly different from its single task score. The non-favoured task will do quite badly as a result, leading to performance that is significantly different from its single task score. An example of this is the PSPV dual-task where PV appears to have been favoured over PS, resulting in a significant result for PS but not for PV. Favouring of the PV task is suggested by looking at where the points on the PSPV POC curve fall (Figure 11); PV scores fall between 65% and 90%, whereas PS scores fall between 45% and 50% and are therefore not distributed equally. If resource allocation had been apportioned more equally, then performance on both tasks would hypothetically have been significantly below that of their single task scores.

Therefore an important next step was to consider the space below the POC curves to judge overall performance decrement related to a particular dual-task combination. This is because it is likely that, whereas resource allocation is variable, overall resource availability for a particular dual-task combination may be relatively fixed. Returning to the PSPV dual-task, overall space below the POC curve came to 60.5%. This is not only relatively low (signifying substantial performance decrement) but it makes the PSPV dual-task the second lowest scorer out of all the dual-task combinations — a lot lower than the TSPS dual-task for example (Figure 12), whose overall space came to 78.5% and yet both TSPS tasks were significantly different from their single task scores. A glance at the TSPS POC curve confirms that resources were apportioned relatively equally (70%–80% for one task and 60%–85% for the other task).

Finally, it was also important to look at the relative levels of decrement between different dual-tasks to try to understand and define how resources are divided and shared.

It is now possible to address each of the specific hypotheses for Study One.

10.1 H1: Dual-task performance will be significantly worse when input sense for both tasks is the same

The main hypothesis addresses the effect of input sense (tactile versus proprioceptive) on dual-task performance. Specifically: (a) two same-sense tasks will lead to a significant decrement in performance from the single-task to the dual–task condition and (b) two different–sense tasks will lead to less or no decrement in performance from the single–task to the dual–task condition. In Study One, same–sense conditions include two tactile tasks or two proprioceptive tasks, whereas, different–sense conditions include those with one tactile task and one proprioceptive task.

In Study One six dual–task combinations were tested for significant differences in performance (number of hits). Two of these combinations had the same input senses (TSTV and PSPV). The four other combinations had different input senses (TSPS, TSPV, TVPS and TVPV). Two of these combinations had same processing codes (TSPS and TVPV), whereas the other four combinations had different processing codes (TSTV, PSPV, TSPV and TVPS). Performance from poorest to best was as follows: TSTV; PSPV; TSPV; TSPS; TVPV; TVPS.

The TSTV dual–task combination yielded the poorest performance out of all the dual–task combinations. During this combination, the input sense was the same for both tasks (i.e. two tactile tasks were performed at the same time) but the processing code differed (i.e. one was a spatial task and the other a verbal-type* task). This result was significant: TSTV performance was found to be significantly poorer than single task performance and significantly poorer than all of the dual–task combinations where the input sense was not the same (i.e. a tactile task was performed at the same time as a proprioceptive task) regardless of processing code (i.e. processing codes could both be spatial, could both be verbal, or one spatial and one verbal in either direction). These combinations included: TSPS; TSPV; TVPS; TVPV.

The only dual–task from which TSTV was not found to be significantly different was PSPV; where processing code differed but input sense was the same (i.e. two proprioceptive tasks were performed at the same time). PSPV performance was the second poorest out of all the combinations and it was the only other dual–task combination in this study where the two input senses were the same.

As mentioned earlier, PSPV was found to be significantly different from single task scores only in part: PS was significantly different but PV was not. However, discussed in relation with this was the issue of task favouring and, as mentioned, the PSPV POC curve suggests that PV may have been favoured over PS. This is not surprising as participants often responded less positively to the PS task (finding this task more challenging and less enjoyable). It was suggested that had resources been allocated as per the policies then PS scores are likely to have improved and PV scores are likely to have worsened. This would have resulted significant difference from single task scores on both tasks.

In line with the TSTV results, the PSPV dual–task combination was found to be significantly poorer than the following dual–task combinations: TSPS; TVPS; TVPV (i.e. dual–tasks where input sense differed regardless of processing code). PSPV performance was also poorer than the other different–input–sense

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* See Section 6.2 for explanation of 'verbal-type' processing

combination (TSPV), although this difference was not found to be significant. Finally, as mentioned, PSPV performance was not significantly different from the other same–input–sense dual–task (TSTV). These results complement the TSTV results described in the previous paragraphs.

Overall, the results from Study One support the first hypothesis, that: (a) two same–sense tasks will lead to a significant decrement in performance from the single–task to the dual–task condition and (b) two different–sense tasks will lead to less or no decrement in performance from the single–task to the dual–task condition.

This is in line with dual–task studies (see Section Three) that indicate that when inputs are spread across the visual and auditory senses, performance is better than when all the inputs are visual or auditory in nature. This was explained in terms of separate sensory resources by MRT and Wickens's (1980) MRT model (see Section Three). In Section Four it was argued that the notion of separate sensory resources may be misleading due to recent neuroscientific findings indicating that multisensory integration occurs at early stages in information processing and within 'unisensory' areas of the brain. However, neuroscientific research into multisensory integration also reveals that multisensory inputs often result in better performance. According to the results of Study One, this appears to be the case for tactile versus proprioceptive inputs, suggesting that the brain treats these inputs as separate types of sensory inputs.

As far as introducing haptic displays into environments such as cockpit goes, these results suggest that the use of two tactile displays or two proprioceptive displays is likely to result in increased workload. The situation with one tactile and one proprioceptive display is a little less clear from these results. Overall, performance is significantly better under this condition but there was fairly wide variation in results ranging from 70% (of single task scores) for TSPV to 90% for TVPS. It is notable that at both of these extremes, processing codes as well as input senses are different. This suggests that there must be some other factor(s) relating to these tasks that has caused this variation. In Section Four, the importance of input congruency was mentioned and it may be that there was greater incongruency between the inputs presented in the TSPV condition than in the TVPS condition. However, the decrement associated with TSPV in particular may be simply due to the close relationship that the tactile and proprioceptive senses have to each other in information processing terms; perhaps it is not possible to treat them as completely separate. However, it is difficult to explain the other tactile & proprioceptive condition results using this argument, particularly TVPS, which resulted in good dual–task performance. Regardless, these results suggest that further research is required to confirm that tactile and proprioceptive displays can be used at the same time without significant increases in workload and what other factor(s) must be taken into consideration.

10.2 H2: Dual–task performance will be significantly worse when input processing code for both tasks is the same

The second hypothesis addresses the effect of information processing code, referred to simply as code (spatial versus verbal) on dual–task performance. Remember that haptic tasks cannot be verbal as such and therefore the word verbal is a synonym for the haptic equivalent of verbal[*]). Specifically: (a) two same–code tasks will lead to a significant decrement in performance from the single–task to the dual–task condition and (b) two different–code tasks will lead to less or no decrement in performance from the single–task to the dual–task condition. In both studies, same–code conditions include two spatial tasks or two verbal tasks, whereas, different–code conditions include those with one spatial task and one verbal task.

According to Wickens (1980), the same argument (that same inputs are associated with worse performance than different inputs) could be applied to processing codes as well as senses. In line with this, performance of the dual–task combination TVPV was not found to be significantly different from that of TSPS, and indeed their scores are very similar — TVPV and TSPS dual–task performances were roughly 80% of single task performance (Figure 16 and Figure 12 respectively). TSPS was significantly different from single task scores but TVPV was only significantly different from single task scores in part; PV was not found to significantly different, whereas TV was. The POC curves suggest that the dispersion of TSPS scores would result in very similar averages (72% for TS and 74% for PS, roughly), whereas the dispersion of TVPV scores would result in differing averages (70% for TV and 82% for PV, roughly). It is clear to see that slight task favouring may have occurred in TVPV.

What is not in line with Wickens's model is the fact that TVPV and TSPS were not found to be significantly different from TVPS nor TSPV. In the former two, there is processing code sharing, whereas in the latter two, there is no sharing at all, therefore, a significant difference would have been expected but this is not the case. The POC curves show that whereas the highest scoring dual–task is TVPS, its 'equivalent', TSPV, is the lowest scoring dual–task, apart from PSPV and TSTV and in fact was not found to be significantly different from PSPV. In addition, performance on TVPS was found to be significantly better than on TSPV, which one would not have expected within the framework of Wickens's MRT model.

However, although the highest scoring dual–task (TVPS) had different processing codes, performance was by no means perfect (89.5% of single task scores). Indeed comparison to single task scores found that one task from this dual–task was significantly different. This cannot easily be explained by suggesting that one task was favoured over the other as scores seem to be distributed evenly.

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[*] See Section 6.2 for explanation of the haptic equivalent of verbal

The decrements found in the top four dual–tasks could be due to partial resource sharing between tactile and proprioceptive inputs but then one would have expected all of the TSPS, TVPV, TSPV, and TVPS dual–tasks to have more similar results than they do and certainly not the significant difference between TSPV and TVPS dual–tasks. Another possibility is that this is a processing code–related decrement but that this is occurring due to some other factor not accommodated for by the Wickens's MRT model. This last suggestion is discussed further in the Final Discussion section of the thesis.

The results relating to processing code are not clear–cut and on balance, do not support Wickens's model.

10.3 Summary

The results of Study One strongly support the first hypothesis regarding input sense; same–sense tasks (two tactile or two proprioceptive) are associated with significantly greater decrements in dual–task performance than different–sense tasks (one tactile and one proprioceptive). However, there were too many inconsistencies to confidently support the second hypothesis, regarding processing code; same–code tasks (two spatial or two verbal) were not consistently associated with greater decrements in dual–task performance than different–code tasks (one spatial and one verbal).

These results so far suggest that (a) dual–task performance decrements are significantly greater where the input senses are the same as opposed to different; (b) within the context of Wickens's MRT model, tactile and proprioceptive sense can be tentatively treated as two different senses but because these results are not clear–cut, a dashed rather than hard line separates the two in Figure 31 below, and (c) processing code seems to have a secondary impact upon dual–task performance compared with input sense (hence the dashed line between tactile and proprioceptive processing codes in Figure 31 below).

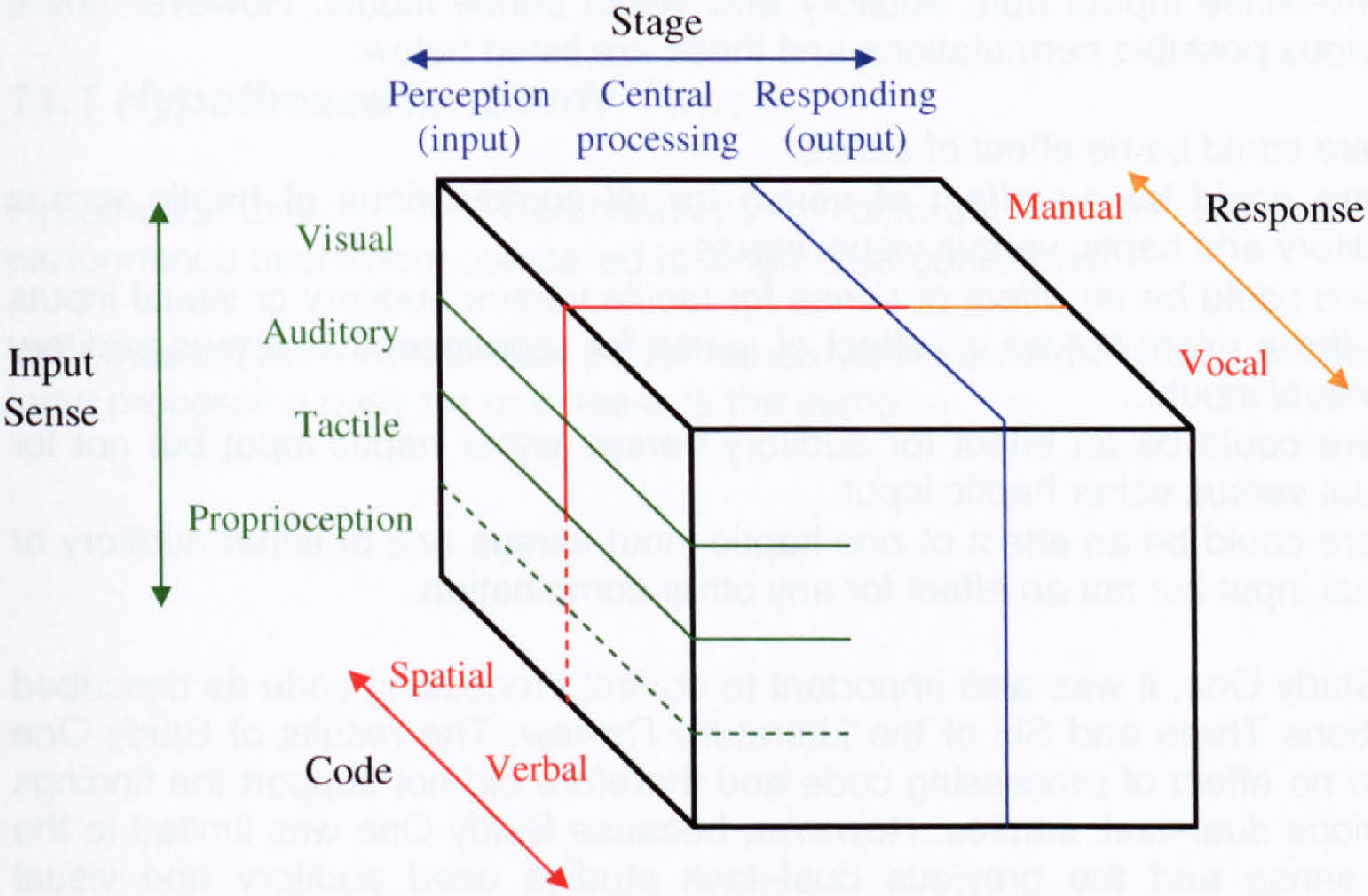


Figure 31: Suggested changes to Wickens's MRT Model (1980) based on the results of Study One

IV: STUDY TWO

11 Introduction to Study Two

The purpose of Study Two was to examine whether tactile tasks and proprioceptive tasks can be performed at the same time as auditory and visual tasks without performance decrement.

This would have implications for the introduction of haptic displays into environments such as the cockpit, which, as mentioned, it has been suggested would benefit from haptic displays if this had the effect of reducing overall workload.

It was expected that there would be an effect of sense on performance (that different–sense tasks would be associated with significantly better performance than same–sense tasks), which is suggested by previous dual–task studies and by the neuroscientific findings of multisensory summation.

In Study Two an effect of sense would indicate that tactile and proprioceptive sub–senses are treated as different–sense inputs from auditory and visual sense inputs by the brain. However, if no effect of sense occurred in Study Two, this would indicate that tactile and proprioceptive sub–senses are not treated as different–sense inputs from auditory and visual sense inputs. However, there are various possible permutations and these are listed below:

- There could be no effect of sense.
- There could be an effect of sense for all combinations of haptic versus auditory and haptic versus visual inputs.
- There could be an effect of sense for tactile versus auditory or visual inputs but there might not be an effect of sense for proprioceptive versus auditory or visual inputs.
- There could be an effect for auditory versus either haptic input but not for visual versus either haptic input.
- There could be an effect of *one* haptic input versus *one* of either auditory or visual input but not an effect for any other combination.

As in Study One, it was also important to control processing code as described in Sections Three and Six of the Literature Review. The results of Study One showed no effect of processing code and therefore did not support the findings of previous dual–task studies. However, because Study One was limited to the haptic sense and the previous dual–task studies used auditory and visual inputs, a different outcome may result in Study Two. Therefore a secondary expectation was that there would also be an effect of processing code on performance (different processing code inputs would be associated with better performance than same processing code inputs).

The methodological approach that was adopted was the same as for Study One: the dual–task technique, coupled with the on–screen effort allocation controls described, both of which were described in Section Five of the Literature Review. The methodological design, controls, equipment, participants and procedure are described in the section entitled Method for Study Two, although to avoid repetition this section is limited to changes from Study One and so for full details, one should refer to the section entitled Method for Study One.

The results were represented using performance operating characteristic (POC) curves (see Section Five for more on this) and the differences between (a) dual–task performance and single task performance and (b) performance on one dual–task against that on another dual–task, were tested using the analysis of variance (ANOVA) statistical technique. The results are presented in the section entitled Results for Study Two.

Finally, the results are briefly discussed in the section entitled Discussion for Study Two, before moving on to the main discussion of results from both studies.

The hypotheses for Study Two are described below. Note that the first hypothesis has different wording from that in Study One, to reflect the fact that there were no same–sense conditions in Study Two.

11.1 Hypotheses for Study Two:

Hypothesis One — No Combinations of different senses will produce a performance decrement compared to single task conditions.

Hypothesis Two — Dual–task performance would be significantly worse when input processing code for both tasks is the same.

12 Method for Study Two

12.1 DESIGN

The design for Study Two was virtually identical to Study One.

12.1 1 INDEPENDENT VARIABLES

As in Study One, the four independent variables (IVs) included: Task, Policy, Input Sense, and Input Processing Code.

Independent Variable One — Task

As in Study One, the first IV was task, which included nominal labels for the two tasks presented within dual–task conditions, as follows:

- Task one
- Task two

Please refer to Study One for more details. Note that visual and auditory feedback was presented from the front and therefore, whether their on–screen feedback was presented on the left– or right–hand side of the screen depended upon the position of the other task within the dual–task.

Independent Variable Two — Policy

As in Study One, the second IV was policy or, more fully, resource allocation policy. The levels included:

- 25%
- 50%
- 75%

Please refer to Study One for more details.

Independent Variable Three — Input Sense

In Study One, the third IV was input sense (proprioceptive or tactile). However in Study Two, auditory and visual input senses were also included, as follows (with changes highlighted in bold):

- Proprioceptive
- Tactile
- **Auditory**
- **Visual**

Independent Variable Four — Input Processing Code

Identically to Study One, input processing code levels include:

- Spatial
- Verbal

Please refer to Study One for details.

Combining Independent Variables Three & Four — Creating the Input Condition

The change to IV three had a knock–on affect on the number of task conditions presented to the participant. Note that auditory and visual inputs were restricted to verbal processing code tasks (to limit design complexity). Study Two included the following task *conditions* (with changes highlighted in bold):

- Proprioceptive Spatial
- Proprioceptive Verbal
- Tactile Spatial
- Tactile Verbal
- **Auditory Verbal**
- **Visual Verbal**

Please refer to Study One for the first four tasks and associated equipment. Auditory feedback was provided using Microsoft Windows sounds presented via headphones. Visual feedback was provided using coloured lights displayed on the monitor in front of the participant. Please refer to the Equipment section for more details.

The additional two tasks are as follows:

Auditory Verbal

The participant wore headphones for this task. The aim of this task was to respond to information coded into musical instrument sounds produced by the PC. Responses were made using the joystick by pressing the button that corresponded to that sound. Sounds were discrete but repeated every few seconds until cancelled. The two sounds comprised a 'piano chord' or a 'bell'.

One sound only was presented at a time but this sound was played to both ears in synchrony. The participants were told that the sounds represented different types of collision risk alerts.

Visual Verbal

The aim of this task was to respond to information coded into coloured lights visible on the screen in front of the participant. Responses were made using the joystick by pressing the button that corresponded to that light. Because of the automatic association participants made during the pilot trials between the location of the lights on the screen and the corresponding button, this task was made a little more difficult by removing the spatial association between the lights and the buttons. Difficulty was also increased by asking participants to respond only when the green light went out or when the red light came on. Participants were told that the lights represent engine alerts.

12.1.2 DEPENDENT VARIABLE — DUAL–TASK PERFORMANCE

As in Study One, the dependent variable (DV) was dual–task performance i.e. number of hits per minute on each task being performed within the dual–task combination. The following table (Table 43) indicates the DV for each task; changes from Study One to Study Two are highlighted in bold):

Table 43: The dependent variables for Study Two

Task Condition (IV 3 & IV 4)	**Dependent Variable**
Proprioceptive Spatial	Number of targets correctly positioned (referred to as hits) using force feedback
Proprioceptive Verbal	Number of correct responses (referred to as hits) to warning–related information pertaining to aircraft flying handling, presented through force feedback
Tactile Spatial	Number of times the aircraft is correctly oriented (referred to as hits) towards a target, using vibration feedback
Tactile Verbal	Number of correct responses (referred to as hits) to target–related information presented using vibration feedback
Auditory Verbal	**Number of correct responses (referred to as hits) to collision–related warnings presented using auditory feedback (in the form of musical instrument sounds)**
Visual Verbal	**Number of correct responses (referred to as hits) to engine– related warnings presented using visual feedback (in the form of coloured lights)**

The DV levels included:

- Number of hits for Task one at 25%
- Number of hits for Task one at 50%
- Number of hits for Task one at 75%
- Number of hits for Task two at 25%
- Number of hits for Task two at 50%
- Number of hits for Task two at 75%

Again, the DV results always came in pairs (as there were two tasks in the dual–task condition). Because resource allocation policies for each dual–task condition had to add up to 100%, the DV pairs for each dual–task condition were as follows:

- Task one 25% & Task two 75% (e.g. TSTV 25_75)
- Task one 50% & Task two 50% (e.g. TSTV 50_50)
- Task one 75% & Task two 25% (e.g. TSTV 75_25)

See Table 44 below for more details.

12.1.3 CONDITIONS IN DETAIL

The changes in Study Two meant that the number of single task conditions was increased. Dual–task conditions were also increased, although none of the dual–task conditions from Study One were repeated in Study Two. The single and dual–task conditions for Study Two are listed in full below:

Single Task Conditions

The single task conditions now included:

1. Proprioceptive Spatial (PS)
2. Proprioceptive Verbal (PV)
3. Tactile Spatial (TS)
4. Tactile Verbal (TV)
5. Auditory Verbal (AV)
6. Visual Verbal (VV)

Dual–Task Conditions

The eight dual–task conditions included:

1. Auditory Verbal & Proprioceptive Spatial (AVPS)
2. Auditory Verbal & Proprioceptive Verbal (AVPV)

3. Auditory Verbal & Tactile Spatial (AVTS)
4. Auditory Verbal & Tactile Verbal (AVTV)
5. Visual Verbal & Proprioceptive Spatial (VVPS)
6. Visual Verbal & Proprioceptive Verbal (VVPV)
7. Visual Verbal & Tactile Spatial (VVTS)
8. Visual Verbal & Tactile Verbal (VVTV)

The following table shows the eight dual–task conditions that make up one experiment, presented with the three policy levels per condition as in Study One.

Table 44: The dual–tasks for Study Two in more detail

Independent Variables					Dependent Variables
1.	Task One	Auditory	Verbal	25%	Hits as % of single task hits
AVPS	Task Two	Proprioceptive	Spatial	75%	Hits as % of single task hits
	Task One	Auditory	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	50%	Hits as % of single task hits
	Task One	Auditory	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	25%	Hits as % of single task hits
2.	Task One	Auditory	Verbal	25%	Hits as % of single task hits
AVPV	Task Two	Proprioceptive	Verbal	75%	Hits as % of single task hits
	Task One	Auditory	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	50%	Hits as % of single task hits
	Task One	Auditory	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	25%	Hits as % of single task hits
3.	Task One	Auditory	Verbal	25%	Hits as % of single task hits
AVTS	Task Two	Tactile	Spatial	75%	Hits as % of single task hits
	Task One	Auditory	Verbal	50%	Hits as % of single task hits
	Task Two	Tactile	Spatial	50%	Hits as % of single task hits
	Task One	Auditory	Verbal	75%	Hits as % of single task hits
	Task Two	Tactile	Spatial	25%	Hits as % of single task hits
4.	Task One	Auditory	Verbal	25%	Hits as % of single task hits
AVTV	Task Two	Tactile	Verbal	75%	Hits as % of single task hits
	Task One	Auditory	Verbal	50%	Hits as % of single task hits
	Task Two	Tactile	Verbal	50%	Hits as % of single task hits
	Task One	Auditory	Verbal	75%	Hits as % of single task hits
	Task Two	Tactile	Verbal	25%	Hits as % of single task hits
5.	Task One	Visual	Verbal	25%	Hits as % of single task hits
VVPS	Task Two	Proprioceptive	Spatial	75%	Hits as % of single task hits
	Task One	Visual	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	50%	Hits as % of single task hits
	Task One	Visual	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Spatial	25%	Hits as % of single task hits

6.	Task One	Visual	Verbal	25%	Hits as % of single task hits
VVPV	Task Two	Proprioceptive	Verbal	75%	Hits as % of single task hits
	Task One	Visual	Verbal	50%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	50%	Hits as % of single task hits
	Task One	Visual	Verbal	75%	Hits as % of single task hits
	Task Two	Proprioceptive	Verbal	25%	Hits as % of single task hits
7.	Task One	Visual	Verbal	25%	Hits as % of single task hits
VVTS	Task Two	Tactile	Spatial	75%	Hits as % of single task hits
	Task One	Visual	Verbal	50%	Hits as % of single task hits
	Task Two	Tactile	Spatial	50%	Hits as % of single task hits
	Task One	Visual	Verbal	75%	Hits as % of single task hits
	Task Two	Tactile	Spatial	25%	Hits as % of single task hits
8.	Task One	Visual	Verbal	25%	Hits as % of single task hits
VVTV	Task Two	Tactile	Verbal	75%	Hits as % of single task hits
	Task One	Visual	Verbal	50%	Hits as % of single task hits
	Task Two	Tactile	Verbal	50%	Hits as % of single task hits
	Task One	Visual	Verbal	75%	Hits as % of single task hits
	Task Two	Tactile	Verbal	25%	Hits as % of single task hits

12.1.4 CONTROLS

The controls for Study Two were identical to those of Study One. Therefore, please refer to Study One for these details.

12.2 PARTICIPANTS

Participants comprised an opportunity sample of forty three participants. Most of the participants for Study Two were different from those for Study One, although there were a handful of participants who volunteered for both studies.

Of these, twelve were female and thirty one were male, four were left–handed and thirty nine were right–handed. The youngest participant was fourteen and the oldest was sixty. Age breakdown was as follows:

10–19 yr olds — four
20–29 yr olds — twenty seven
30–39 yr olds — eight
40–49 yr olds — one
50–59 yr olds — two
60–69 yr olds — one

Note again that only six participants were used in a more complex version of this design devised by Gopher, Brickner and Navon (1982).

Note that, as before, although age, gender and handedness were recorded, these details were not relevant to test the effect of condition on dual–task performance, because participants acted as their own controls. Each participant's dual–task score was standardised into percentages of his/her single task (100%) score and it was the percentage of *change* from that participant's single to dual–task condition that was of interest.

12.3 EQUIPMENT

12.3.1 OVERVIEW

The equipment, which was the same for both studies, included the following:

- One x *CyberGlove*
- Two x *Sidewinder Force–Feedback two* joysticks
- One x *Haptic Tester* software controlling the equipment on two PCs.
- Two PCs plus two monitors.

However, during Study Two, headphones were connected so that the auditory inputs could be heard in a controlled manner by the participant. Also during Study Two, visual task inputs were displayed on the monitor screen in front of the participant (immediately next to the resource allocation feedback).

12.3.2 TASK INPUT INFORMATION

For tactile and proprioceptive task input information see Study One.

Visual alerts were delivered through two strips of colour (one red and one green) situated in the space on either side of the resource allocation window. Responses were required when the green light went out and when the red light came on. These were made by pressing the buttons on a joystick (the button positions deliberately did not correspond to the position of the visual alerts). Alerts were located around the resource allocation window such that they were within 5–degrees from the centre of the resource allocation window whilst in the seated position. This position has been associated with fastest accurate response time, whilst associated with minimum interference from and to a concurrent central tracking task (Watanabe et al, 1999; Yoo, 1999).

The auditory alerts consisted of two distinct Microsoft Windows sound events delivered through headphones and responses were made using buttons on a joystick. The two alerts were markedly different in terms of their tone: one was a clear–sounding bell; the other was more abrupt and alarming–sounding keyboard chord. The two sounds were at the same mid–range pitch and were set at a level of intensity that was roughly at the same level as normal speech (i.e. 40 to 60 dB). One sound only was presented at a time and that sound, though discrete, repeated every few seconds until cancelled by the participant's response. The sound was always delivered to both ears in synchrony.

As in Study One, all responses were made manually, using the joystick; please refer to Study One for more information.

12.4 PROCEDURE

The procedure for Study Two was identical to that of Study One. However, because there were additional single and dual–task conditions in Study Two, this altered the time breakdown. A time breakdown for Study Two (not including time for reading instructions) can be seen in the following table (Table 45):

Table 45: The time breakdown per participant for Study Two

Time Breakdown per Participant for Study Two	
Practise sessions (six tasks, five practise sessions per task)	Thirty minutes
Single Task conditions (six tasks)	Six minutes
Dual Task conditions (eight task pairs, three resource allocation policies per pair)	Twenty four minutes
TOTAL	**Sixty minutes**

13 Results of Study Two

13.1 Overview

As in Study One, participants first performed each task on its own (single task condition) and then performed two different tasks at the same time (dual–task condition). However, in Study Two there were six different tasks (auditory verbal (AV); proprioceptive verbal (PV); proprioceptive spatial (PS); tactile spatial (TS); tactile verbal (TV); and visual verbal (VV)), therefore the total number of dual–task conditions was eight (AVPS; AVPV; AVTS; AVTV; VVPS; VVPV; VVTS; and VVTV). As before, performance on each task was measured in terms of number of hits and this figure was converted to a percentage of the corresponding single task score, which served to standardize the results.

Again, in the same way as for Study One, participants were also asked to vary the proportion of effort they allocated to each task within each combination (25% (T1) and 75% (T2); 50% (T1) & 50% (T2); and 75% (T1) & 25% (T2)). As before, it was assumed that effort requires some kind of cognitive resource and that when performing a task by itself (single task condition) a participant is able to allocate 100% of that resource to that task. A sample mean was calculated for each task (T1 and T2) at each allocation policy (25%_75%, 50%_50% and 75%_25%), amounting to three means per task and therefore six means for each dual–task condition (or three pairs of means). As mentioned, because the scores were percentages of single task scores, the means were averages of the percentages not averages of the absolute number of hits.

Identically to Study One, the three pairs of means for each dual–task were again plotted in a scatterplot (one scatterplot per dual–task condition) to produce three points and a reference line connects each point to produce the POC curve. Note again that the points at 100% for each task were the corresponding single task results. As dual–task hits sometimes exceeded single task hits then the scale was extended beyond 100% to 150%. However, a box is drawn in black to indicate the 100% points. The position of the curve in relation to the 100% points represents the performance decrement as a function of resource sharing. The further away the points on the curve are from 100%, the greater the performance decrement. When the curve sits about the 50% position or less then total sharing of resources is indicated, as each task will have suffered at least a 50% decrement in performance. As before, a blue reference line has been drawn on each scatterplot at the 50% position.

As in Study One, these results are split into two sections; the first section contains the POC curves and the second section contains the statistical analyses. For the latter section, repeated measures ANOVA was used to test whether there were any significant differences firstly between dual–task conditions and single task conditions, then secondly between dual–task conditions themselves.

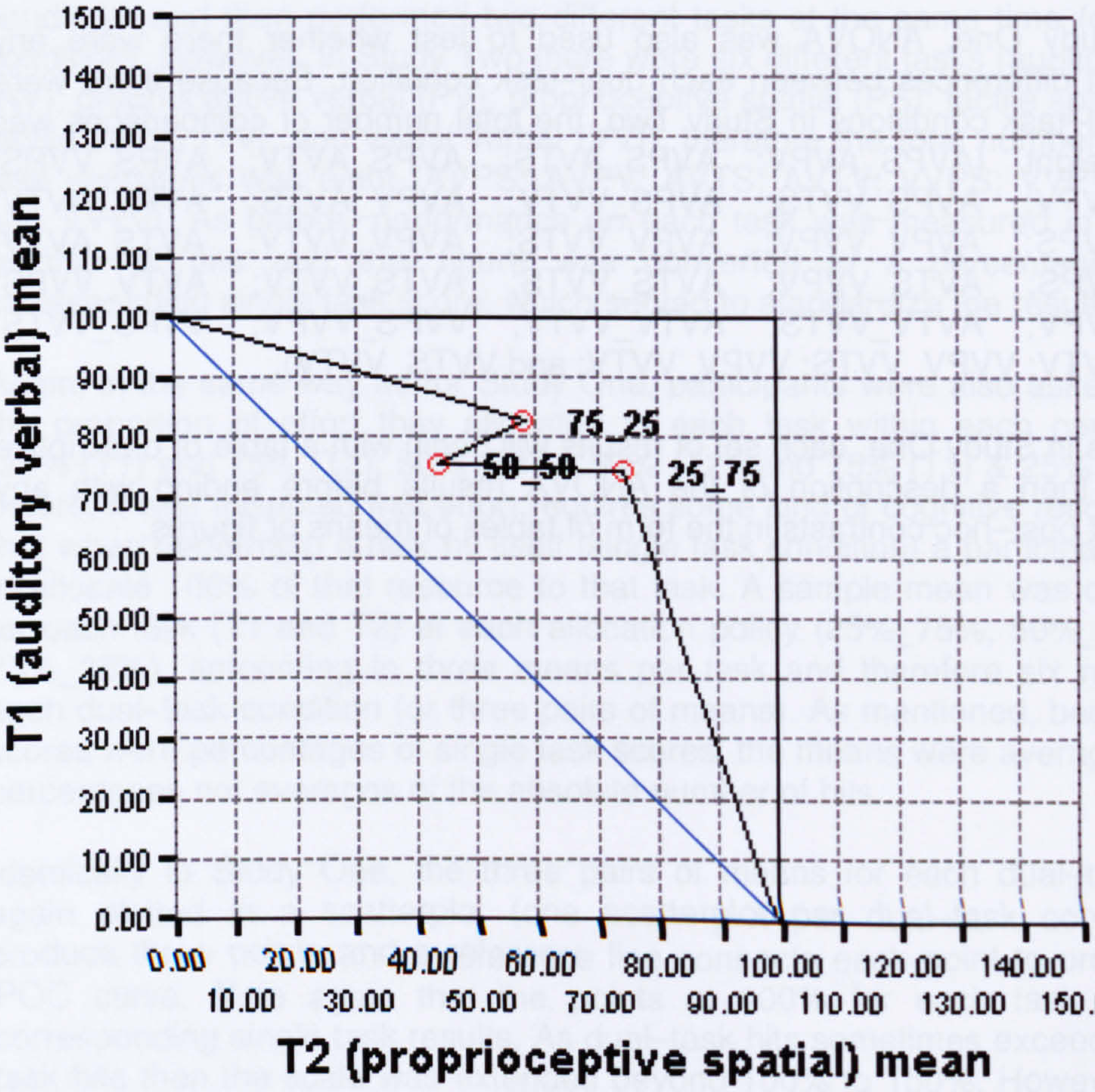
There were eight dual–tasks in Study Two and as each dual–task contained two tasks, both of these tasks had to be compared to their respective single task scores, amounting to twelve comparisons. For example, in the AVPS dual–task, the AV and PS scores were separated and then AV was compared to the AV single task score, while PS was compared to the PS single task score. The significance of these differences was tested using Within–Subjects ANOVA.

As in Study One, ANOVA was also used to test whether there were any significant differences between each dual–task condition. Because there were eight dual–task conditions in Study Two, the total number of comparisons was twenty eight (AVPS_AVPV; AVPS_AVTS; AVPS_AVTV; AVPS_VVPS; AVPS_VVPV; AVPS_VVTS; AVPS_VVTV; AVPV_AVTS; AVPV_AVTV; AVPV_VVPS; AVPV_VVPV; AVPV_VVTS; AVPV_VVTV; AVTS_AVTV; AVTS_VVPS; AVTS_VVPV; AVTS_VVTS; AVTS_VVTV; AVTV_VVPS; AVTV_VVPV; AVTV_VVTS; AVTV_VVTV; VVPS_VVPV; VVPS_VVTS; VVPS_VVTV; VVPV_VVTS; VVPV_VVTV; and VVTS_VVTV).

Finally, as in Study One, each set of results will begin with a table of descriptive statistics then a description of the ANOVA results before ending with any significant post–hoc contrasts in the form of tables of means or figures.

13.2 Individual Performance Operating Characteristic (POC) Curves

Auditory Verbal & Proprioceptive Spatial (AVPS)

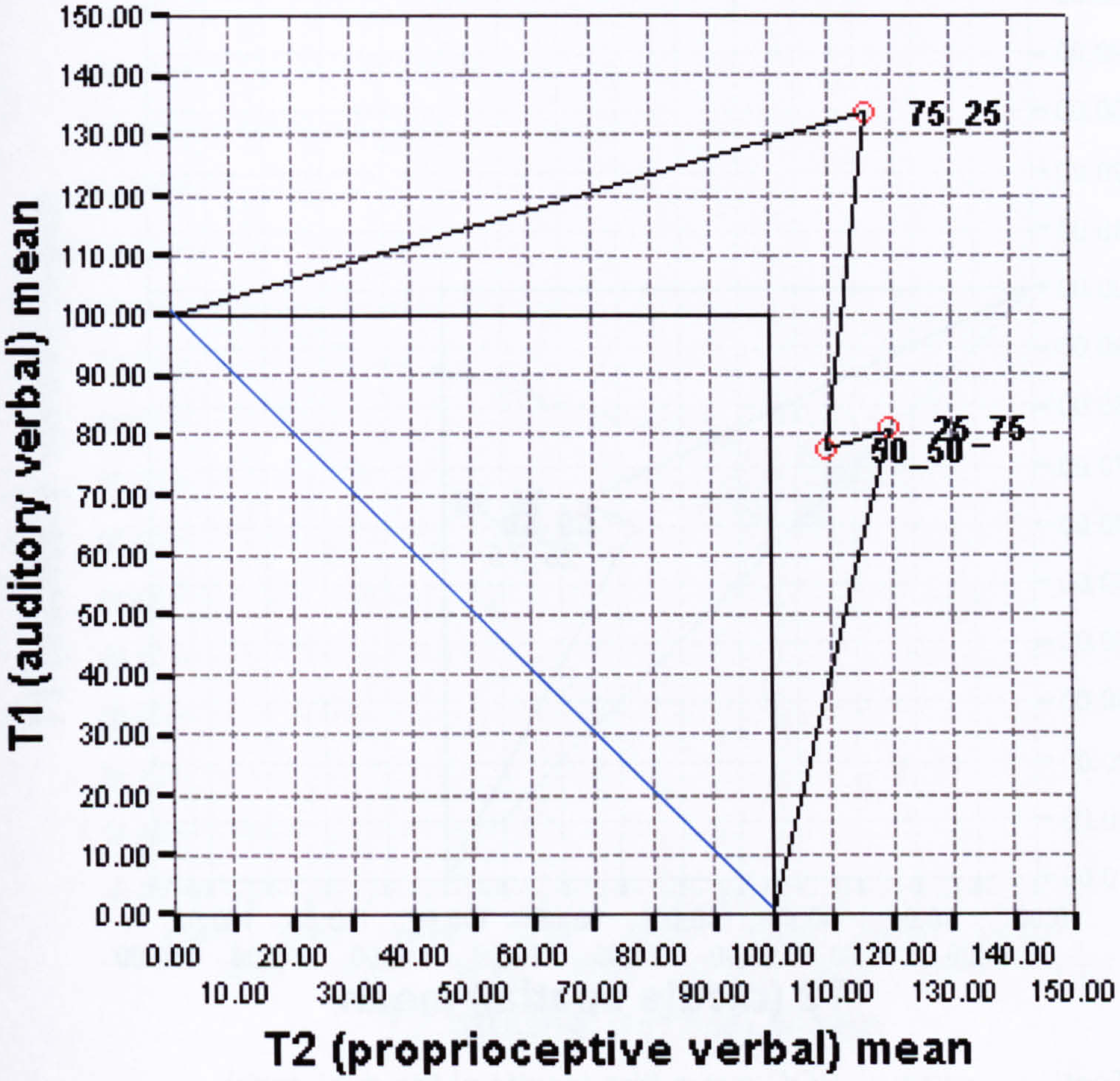


T1 = Task One
—— = POC curve (the results of the dual–task)
—— = 50% reference line (theoretical point of complete resource sharing)

Figure 32: Auditory Verbal (task one) performed at the same time as Proprioceptive Spatial (task two): mean percentage hits

The results of the auditory verbal (task one) and proprioceptive spatial (task two) dual task condition (AVPS) are depicted in Figure 32. The curve sits at approximately 75.5% of single task scores, as each task suffered a decrement in performance of about 25%. This suggests partial sharing of resources.

Auditory Verbal & Proprioceptive Verbal (AVPV)



T1 = Task One

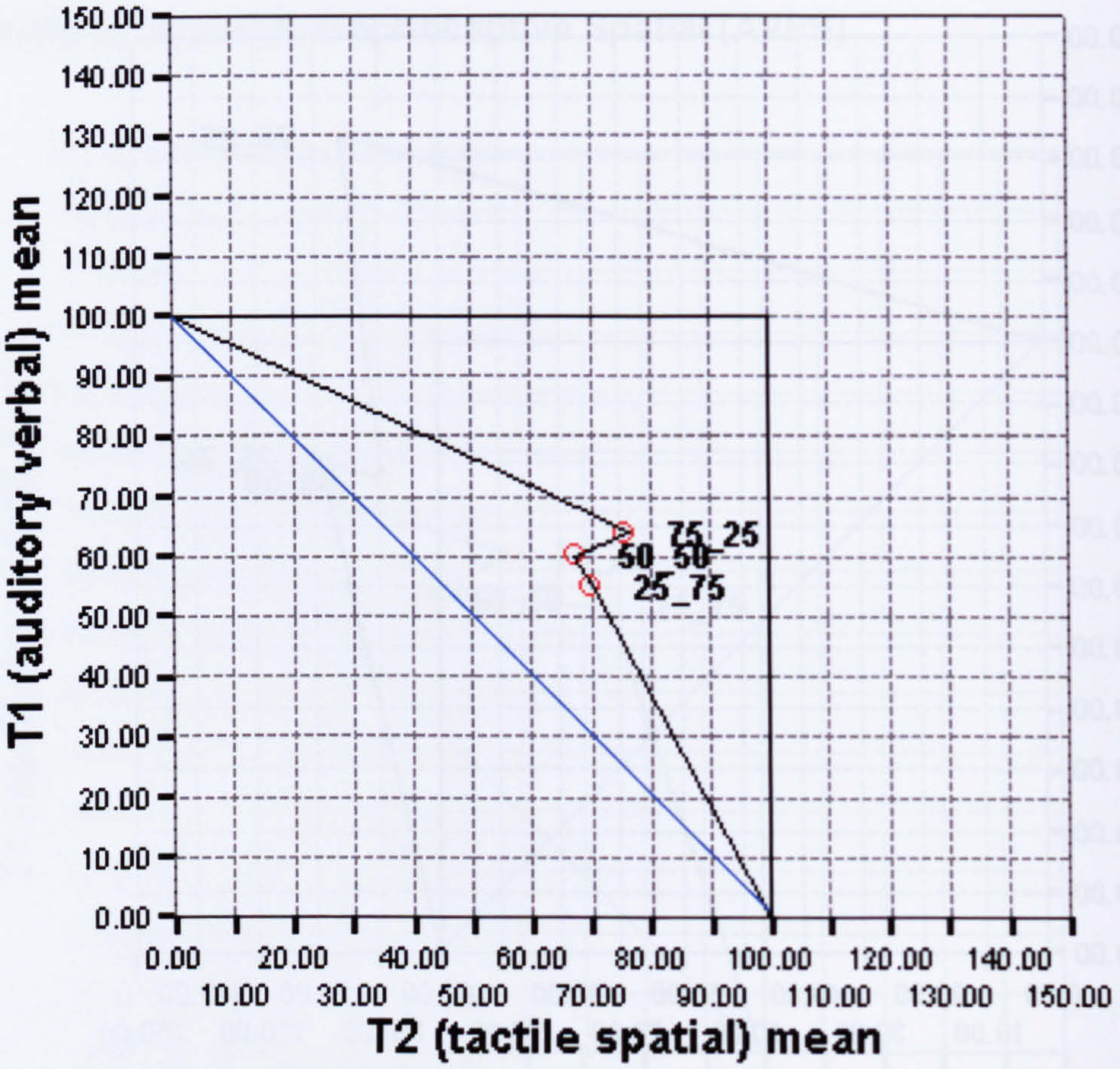
— = POC curve (the results of the dual–task)

— = 50% reference line (theoretical point of complete resource sharing)

Figure 33: Auditory Verbal (task one) performed at the same time as Proprioceptive Verbal (task two): mean percentage hits

The results of the auditory verbal (task one) and proprioceptive verbal (task two) dual task condition (AVPV) are depicted in Figure 33. The curve extends beyond 100% to approximately 129% of the single task scores, as performance on each task improved by about 30%. This suggests minimal sharing of resources and that performance is enhanced if these tasks are performed together rather than separately.

Auditory Verbal & Tactile Spatial (AVTS)



T1 = Task One

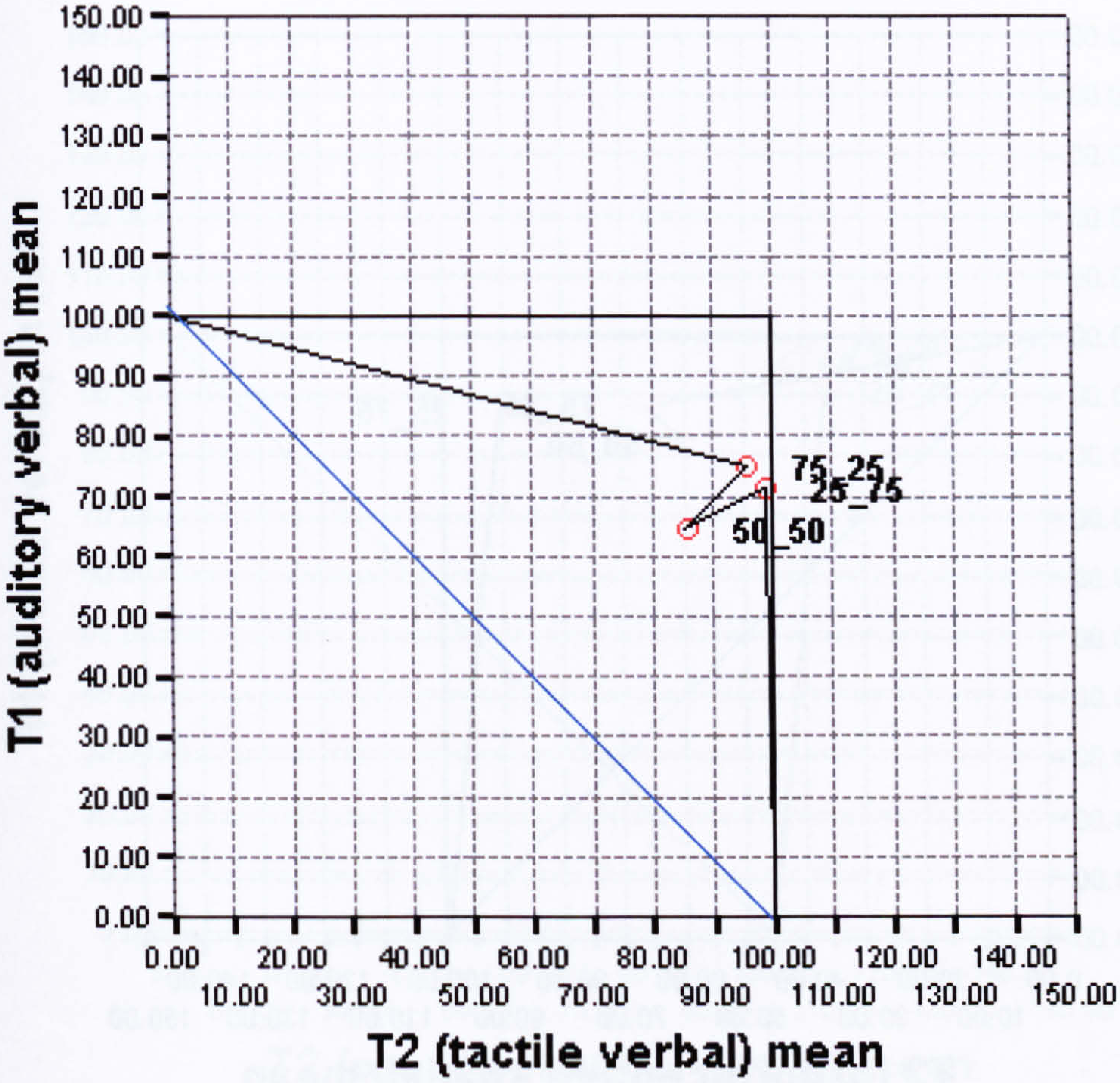
—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 34: Auditory Verbal (task one) performed at the same time as Tactile Spatial (task two): mean percentage hits

The results of the auditory verbal (task one) and tactile spatial (task two) dual task condition (AVTS) are depicted in Figure 34. The curve sits at approximately 66% of single task scores, as each task suffered a decrement in performance of about 35%. This suggests fairly substantial sharing of resources.

Auditory Verbal & Tactile Verbal (AVTV)



T1 = Task One

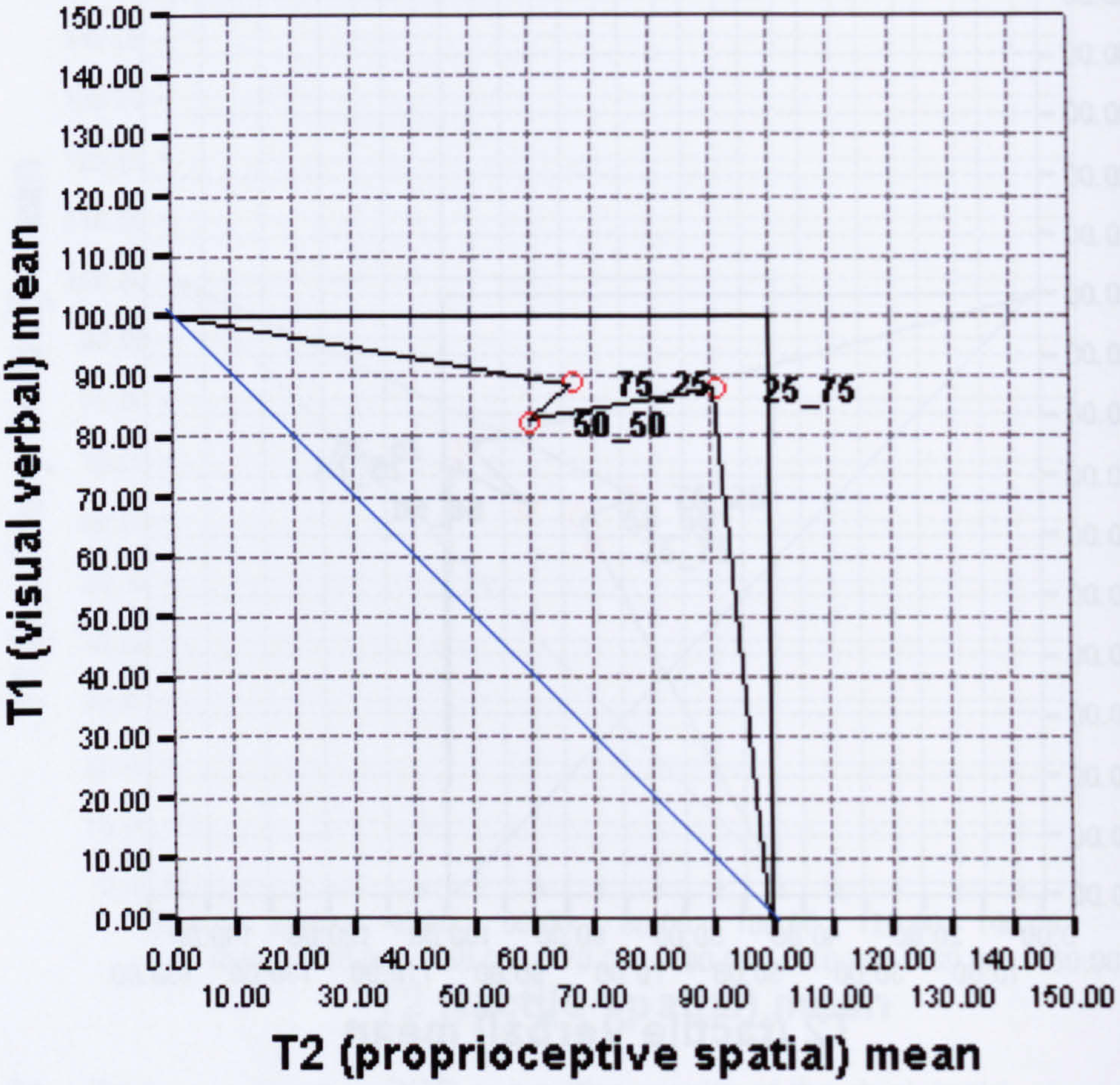
—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 35: Auditory Verbal (task one) performed at the same time as Tactile Verbal (task two): mean percentage hits

The results of the auditory verbal (task one) and tactile verbal (task two) dual task condition (AVTV) are depicted in Figure 35. The curve sits at 87.5% of single task scores, as each task suffered a decrement in performance of only 10–15%. This indicates minimal sharing of resources.

Visual Verbal & Proprioceptive Spatial (VVPS)



T1 = Task One

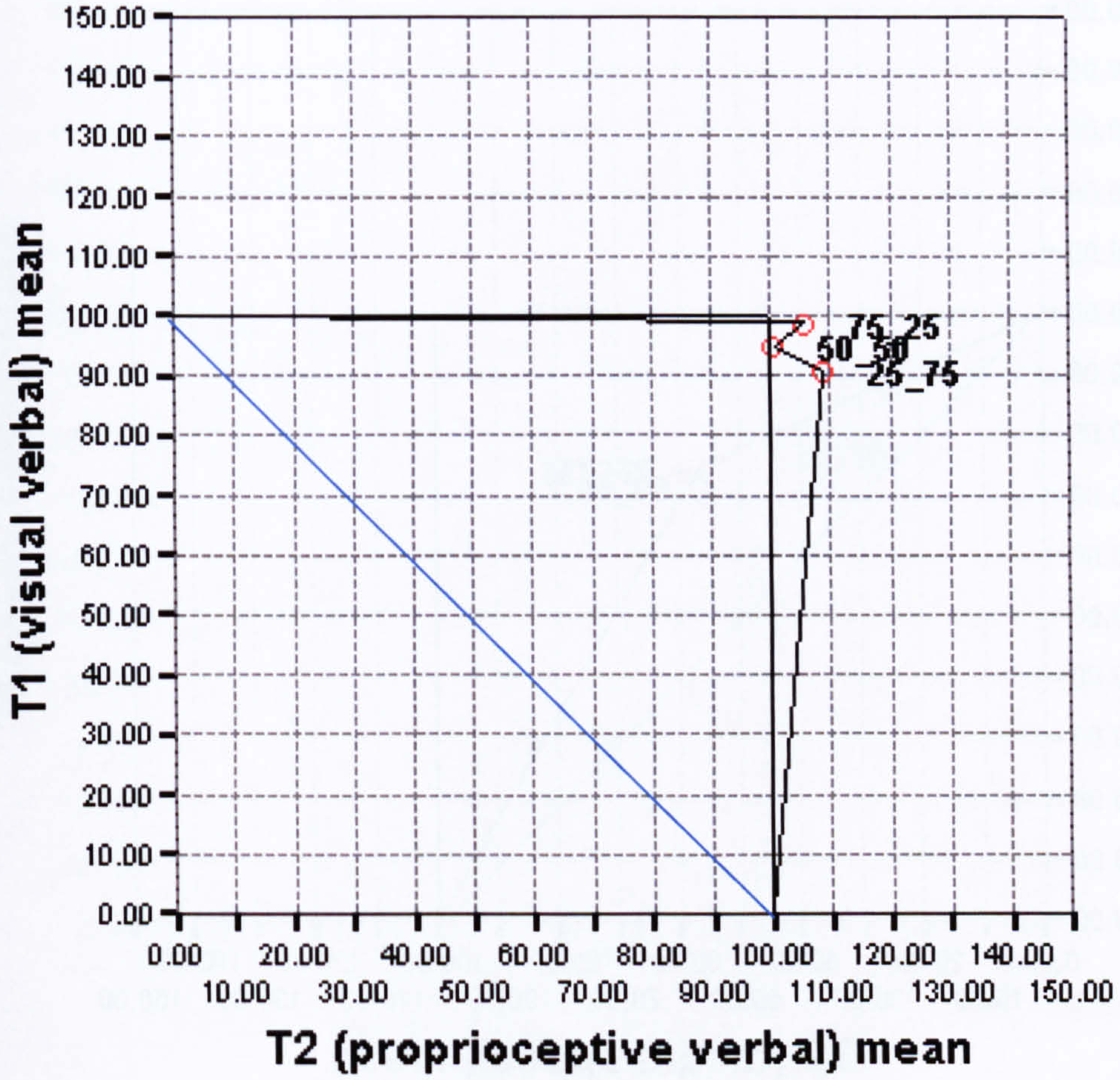
—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 36: Visual Verbal (task one) performed at the same time as Proprioceptive Spatial (task two): mean percentage hits

The results of the visual verbal (task one) and proprioceptive verbal (task two) dual task condition (VVPV) are depicted in Figure 36. The curve sits at 87.25% of single task scores, as each task suffered a decrement in performance of only 10–15%. This indicates minimal sharing of resources.

Visual Verbal & Proprioceptive Verbal (VVPV)



T1 = Task One

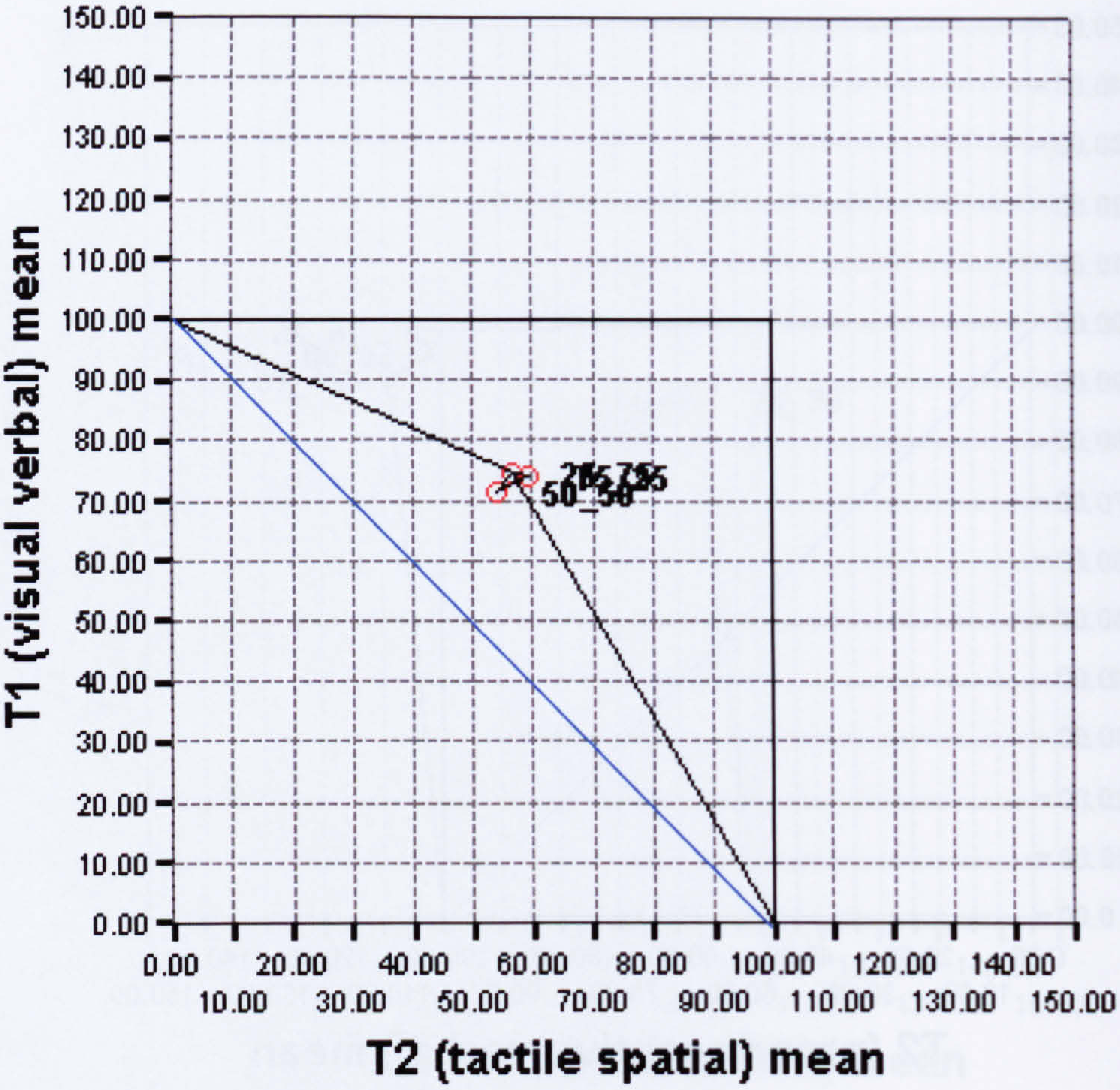
—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 37: Visual Verbal (task one) performed at the same time as Proprioceptive Verbal (task two): mean percentage hits

The results of the visual verbal (task one) and proprioceptive verbal (task two) dual task condition (VVPV) are depicted in Figure 37. The curve extends beyond 100% to approximately 105% of single task scores, as performance on each task improved by about 5%. This suggests minimal sharing of resources and that performance is enhanced if these tasks are performed together rather than separately.

Visual Verbal & Tactile Spatial (VVTS)



T1 = Task One

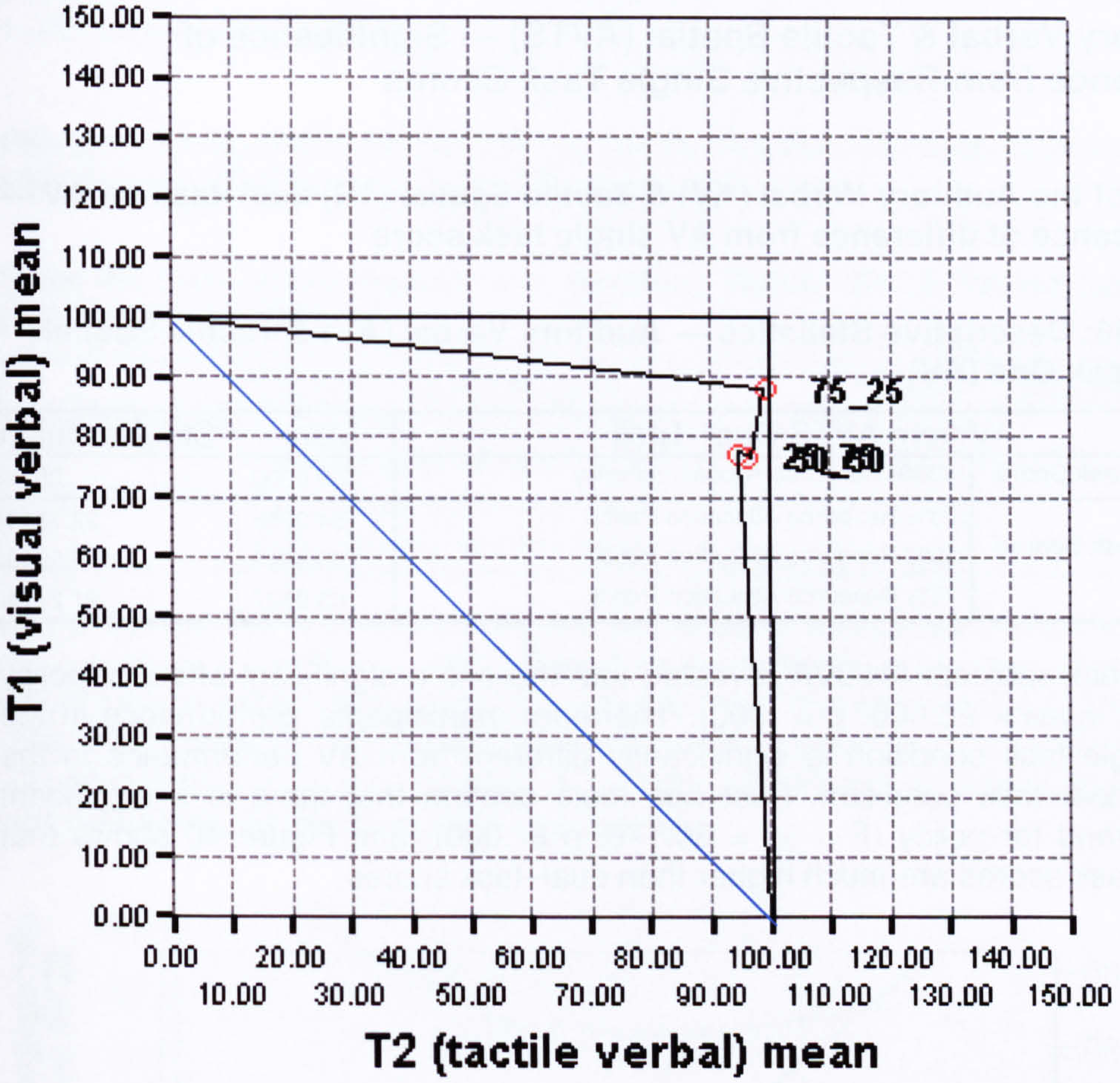
—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 38: Visual Verbal (task one) performed at the same time as Tactile Spatial (task two): mean percentage hits

The results of the visual verbal (task one) and tactile spatial (task two) dual task condition (VVTS) are depicted in Figure 38. The curve sits at approximately 65.25% of single task scores, as each task suffered a decrement in performance of about 35%. This suggests fairly substantial sharing of resources.

Visual Verbal & Tactile Verbal (VVTV)



T1 = Task One

—— = POC curve (the results of the dual–task)

—— = 50% reference line (theoretical point of complete resource sharing)

Figure 39: Visual Verbal (task one) performed at the same time as Tactile Verbal (task two): mean percentage hits

The results of the visual verbal (task one) and tactile verbal (task two) dual task condition (VVTV) are depicted in Figure 39. The curve sits at 91.5% of single task scores, as each task suffered a decrement in performance of only 10%. This indicates minimal sharing of resources.

13.3 Significance of Differences between Dual–Tasks and Single Tasks

Auditory Verbal & Tactile Spatial (AVTS) — Significance of Difference from Respective Single Task Scores

Effect of the Auditory Verbal (AV) & Tactile Spatial (TS) dual–task on AV — significance of difference from AV single task score

Table 46: Descriptive Statistics — Auditory Verbal (AV) & Tactile Spatial (TS), Task One (AV)

AV from AVTS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	54.9255	22.78434
	50% Resource Allocation Policy	60.5645	37.56481
	75% Resource Allocation Policy	63.9527	21.27140

The within–subjects ANOVA revealed that there is a significant effect of policy ($F_{(1.819,\ 65.479)} = 28.000$, $p = .000$). Therefore, participants' performance in the AV single task condition is significantly different from AV performance in the AVTS dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy ($F_{(1,\ 36)} = 80.176$, $p = .000$), and Figure 40 shows that single task scores are much higher than dual–task scores.

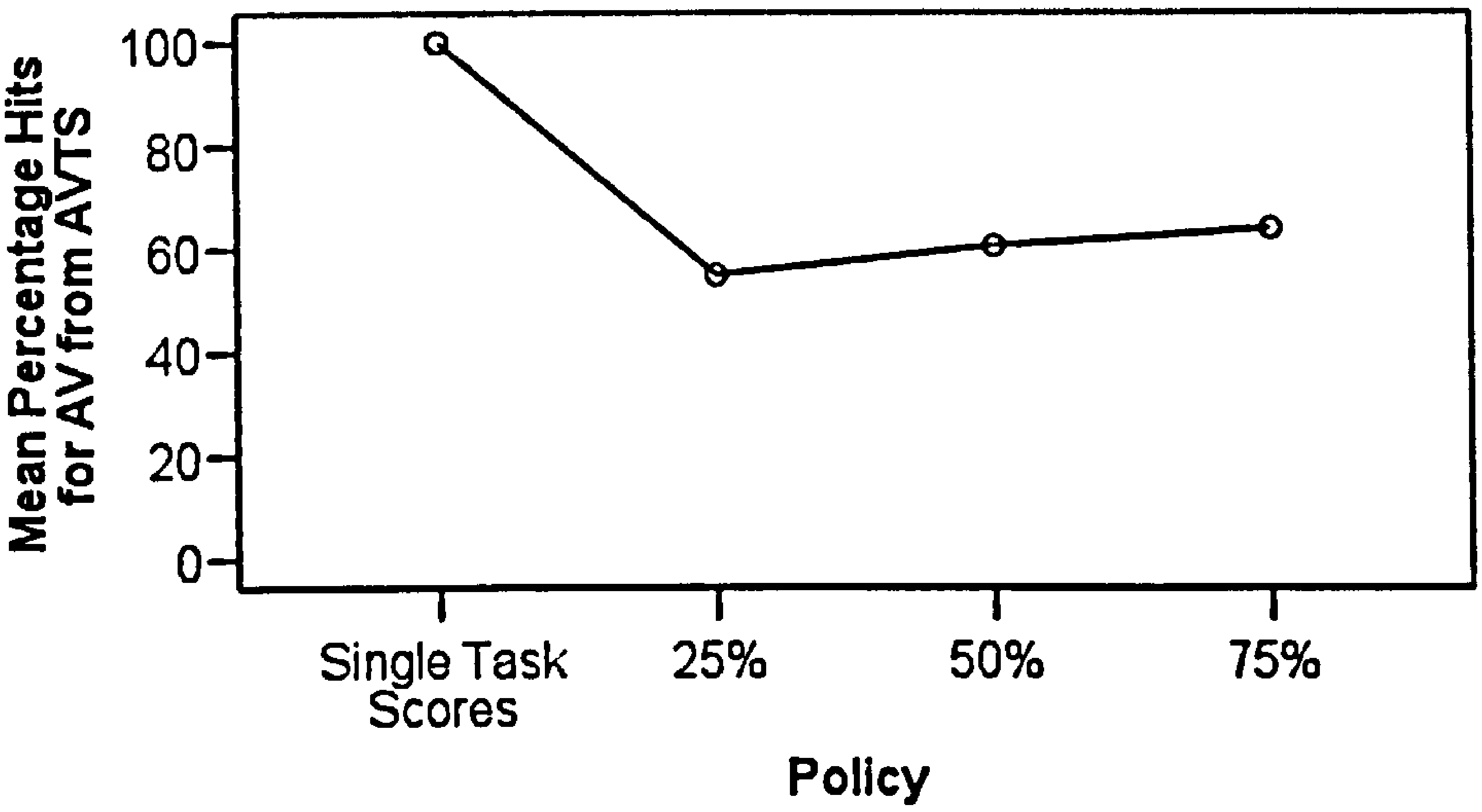


Figure 40: Mean Percentage Hits for Auditory Verbal (AV) from Auditory Verbal & Tactile Spatial (AVTS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 36) = 144.807, p = .000), at 50% (F (1, 36) = 40.777, p = .000) and at 75% (F (1, 36) = 106.256, p = .000) resource allocation.

Effect of the Auditory Verbal (AV) & Tactile Spatial (TS) dual–task on TS — significance of difference from TS single task score

Table 47: Descriptive Statistics — Auditory Verbal (AV) & Tactile Spatial (TS), Task Two (TS)

TS from AVTS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	69.8185	37.14094
	50% Resource Allocation Policy	67.1947	52.90059
	25% Resource Allocation Policy	75.1535	39.66322

The within–subjects ANOVA revealed that there is a significant effect of policy (F $_{(2.294,\,82.580)}$ = 7.949, p = .000). Therefore, participants' performance in the TS single task condition is significantly different from TS performance in the AVTS dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy (F $_{(1,\,36)}$ = 11.114, p = .002), and Figure 41 shows that single task scores are higher than dual–task scores.

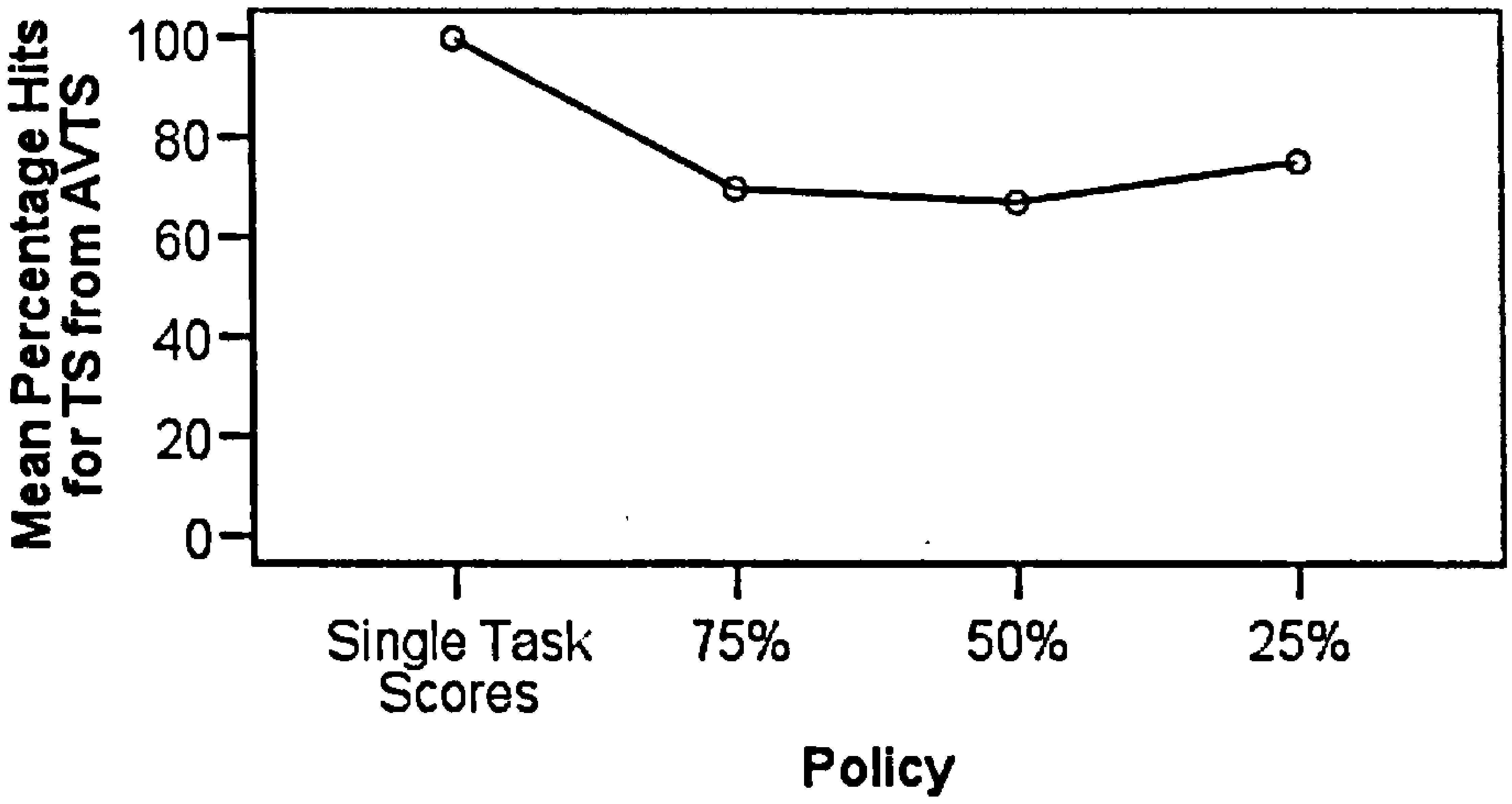


Figure 41: Mean Percentage Hits for Tactile Spatial (TS) from Auditory Verbal & Tactile Spatial (AVTS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 36) = 4.520, p = .001),

at 50% (F (1, 36) = 14.229, p = .001) and at 75% (F (1, 36) = 24.433, p = .000) resource allocation.

Auditory Verbal & Tactile Verbal (AVTV) — Significance of Difference from Respective Single Task Scores

Effect of the Auditory Verbal (AV) & Tactile Verbal (TV) dual-task on AV — significance of difference from AV single task score

Table 48: Descriptive Statistics — Auditory Verbal (AV) & Tactile Verbal (TV), Task One (AV)

AV from AVTV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	71.4579	20.80568
	50% Resource Allocation Policy	64.3381	22.37532
	75% Resource Allocation Policy	74.9150	16.66810

The within-subjects ANOVA revealed that there is a significant effect of policy (F $_{(2.245,\ 89.808)}$ = 62.198, p = .000). Therefore, participants' performance in the AV single task condition is significantly different from AV performance in the AVTV dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy (F $_{(1,\ 40)}$ = 96.792, p = .000), and Figure 42 shows that single task scores are higher than dual-task scores.

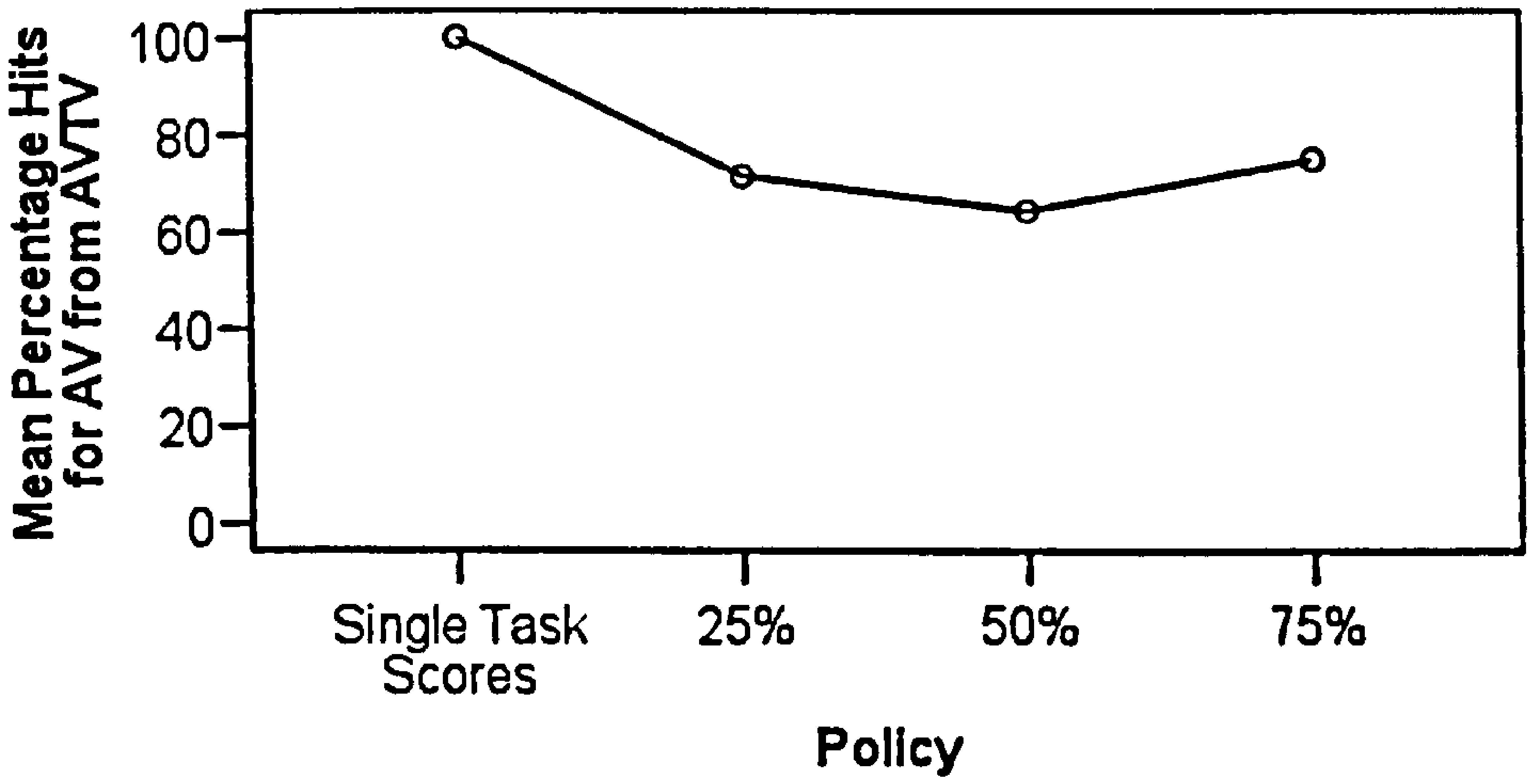


Figure 42: Mean Percentage Hits for Auditory Verbal (AV) from Auditory Verbal & Tactile Verbal (AVTV) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 40) = 77.160, p = .000), at 50% (F (1, 40) = 104.149, p = .000) and at 75% (F (1, 40) = 92.863, p = .000) resource allocation.

Effect of the Auditory Verbal (AV) & Tactile Verbal (TV) dual–task on TV — significance of difference from TV single task score

Table 49: Descriptive Statistics — Auditory Verbal (AV) & Tactile Verbal (TV), Task Two (TV)

TV from AVTV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	98.7366	52.91432
	50% Resource Allocation Policy	85.7615	44.68919
	25% Resource Allocation Policy	95.8024	56.43347

The within–subjects ANOVA revealed that there is no effect of policy ($F_{(1.202, 48.097)}$ = 2.322, p = .129). Therefore, participants' performance in the TV single task condition is not significantly different from TV performance in the AVTV dual–task condition.

Visual Verbal & Tactile Spatial (VVTS) — Significance of Difference from Respective Single Task Scores

Effect of the Visual Verbal (VV) & Tactile Spatial (TS) dual–task on VV — significance of difference from VV single task score

Table 50: Descriptive Statistics — Visual Verbal (VV) & Tactile Spatial (TS), Task One (VV)

VV from VVTS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	74.4583	58.23468
	50% Resource Allocation Policy	71.0864	49.44642
	75% Resource Allocation Policy	73.8517	68.43309

The within–subjects ANOVA revealed that there is a significant effect of policy ($F_{(3, 54)}$ = 3.529, p = .021). Therefore, participants' performance in the VV single task condition is significantly different from VV performance in the VVTS dual–task condition. Post–hoc tests confirm that there is a significant quadratic trend for policy ($F_{(1, 18)}$ = 8.449, p = .009), and Figure 43 shows that single task scores are higher than dual–task scores.

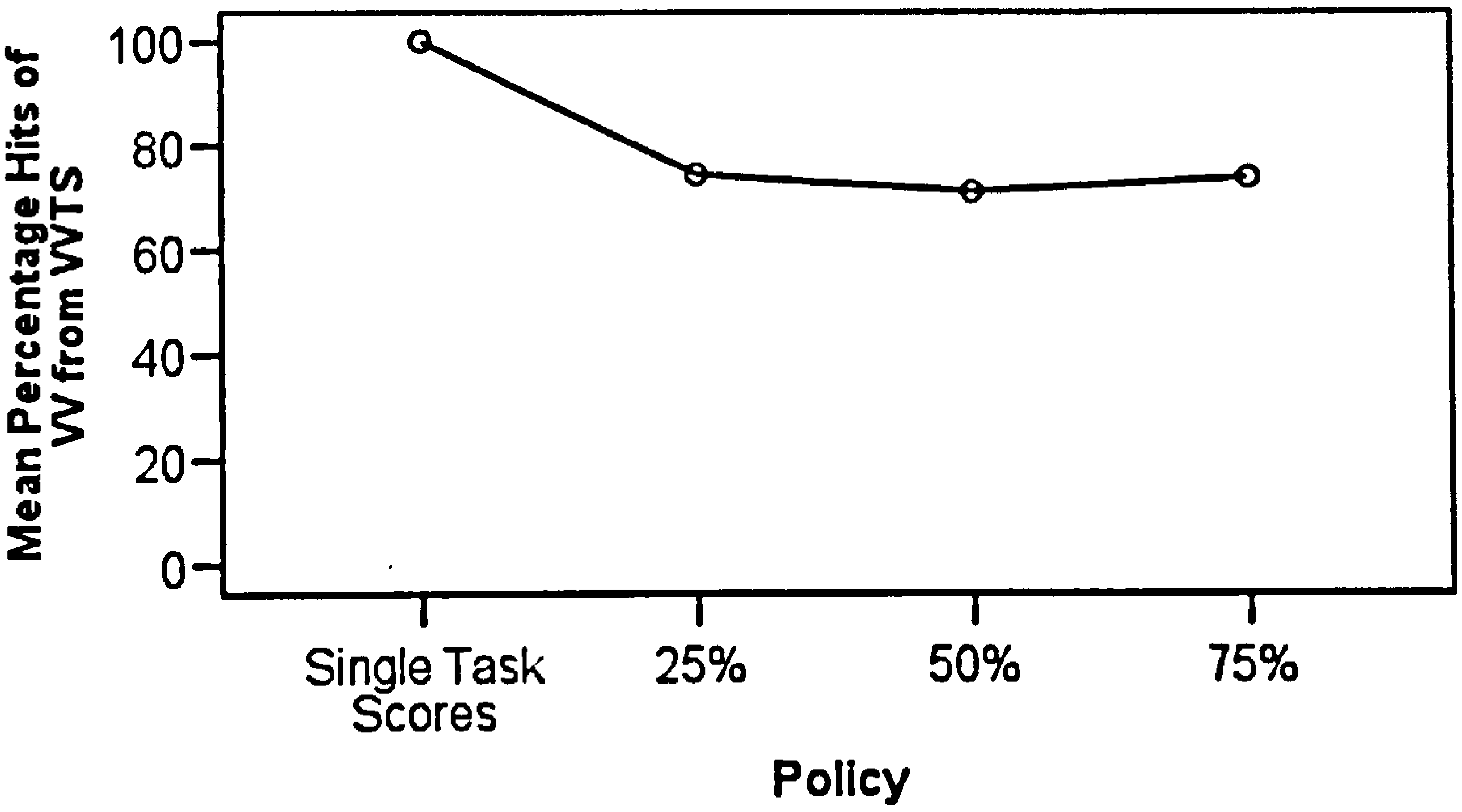


Figure 43: **Mean Percentage Hits for Visual Verbal (VV) from Visual Verbal & Tactile Spatial (VVTS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)**

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was no significant difference between the single task result and the dual-task results at 25% (F (1, 18) = 3.655, p = .072) nor at 75% (F (1, 18) = 2.774, p = .113) but there was at 50% (F (1, 18) = 6.497, p = .020) resource allocation.

Effect of the Visual Verbal (VV) & Tactile Spatial (TS) dual–task on TS — significance of difference from TS single task score

Table 51: Descriptive Statistics — Visual Verbal (VV) & Tactile Spatial (TS), Task Two (TS)

TS from VVTS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	56.9128	28.96065
	50% Resource Allocation Policy	53.9576	31.43137
	25% Resource Allocation Policy	59.5118	38.97374

The within–subjects ANOVA revealed that there is a significant effect of policy ($F_{(2.482, 44.670)}$ = 16.508, p = .000). Therefore, participants' performance in the TS single task condition is significantly different from TS performance in the VVTS dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy ($F_{(1, 18)}$ = 22.924, p = .00), and Figure 44 shows that single task scores are higher than dual–task scores.

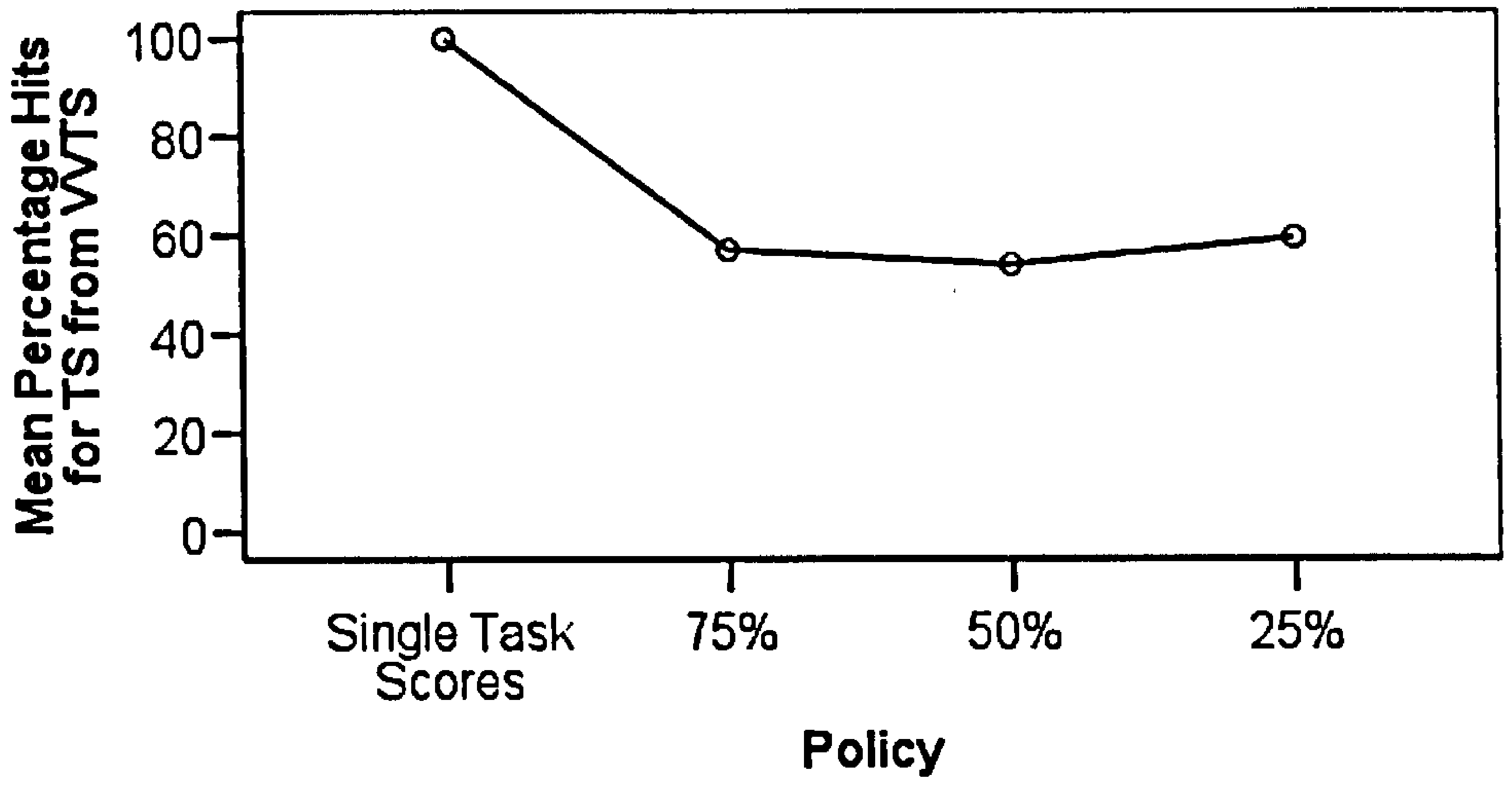


Figure 44: Mean Percentage Hits for Tactile Spatial (TS) from Visual Verbal & Tactile Spatial (VVTS) — Single Task Scores (100% resource allocation policy) and Dual–Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 18) = 20.505, p = .000), at 50% (F (1, 18) = 40.770, p = .000) and at 75% (F (1, 18) = 42.057, p = .000) resource allocation.

Visual Verbal & Tactile Verbal (VVTV) — Significance of Difference from Respective Single Task Scores

Effect of the Visual Verbal (VV) & Tactile Verbal (TV) dual–task on VV — significance of difference from VV single task score

Table 52: Descriptive Statistics — Visual Verbal (VV) & Tactile Verbal (TV), Task One (VV)

VV from VVTV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	77.0334	33.49992
	50% Resource Allocation Policy	76.4298	28.84940
	75% Resource Allocation Policy	88.0872	28.49981

The within–subjects ANOVA revealed that there is a significant effect of policy ($F_{(1.574, 34.624)} = 9.971$, p = .001). Therefore, participants' performance in the VV single task condition is significantly different from VV performance in the VVTV dual–task condition. Post–hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 22)}$ = 4.564, p = .044), and Figure 45 shows that single task scores are higher than dual-task scores.

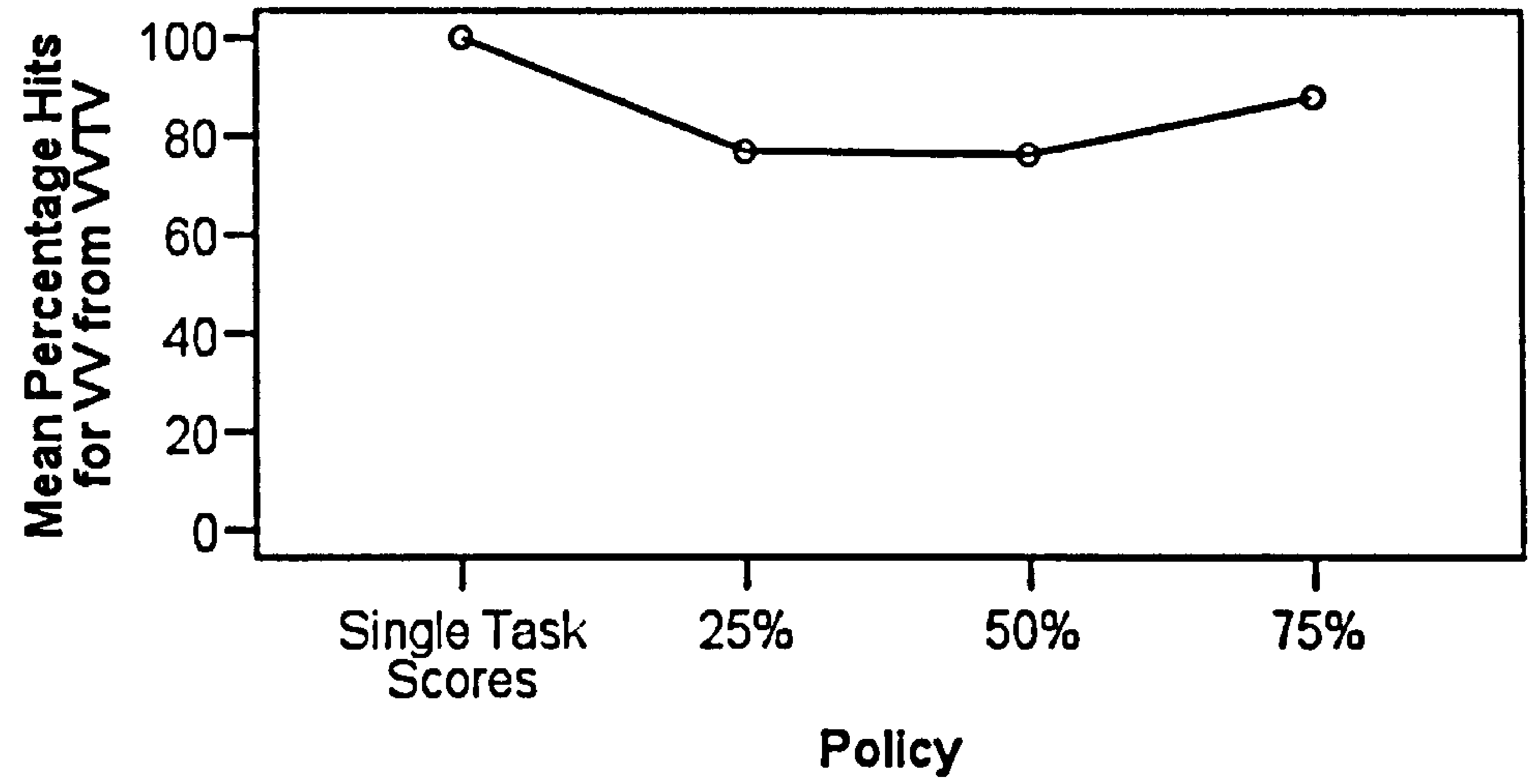


Figure 45: Mean Percentage Hits for Visual Verbal (VV) from Visual Verbal & Tactile Verbal (VVTV) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 22) = 10.810, p = .003) and at 50% (F (1, 22) = 15.353, p = .001) but only borderline significance at 75% (F (1, 22) = 4.019, p = .057) resource allocation.

Effect of the Visual Verbal (VV) & Tactile Verbal (TV) dual-task on TV — significance of difference from TV single task score

Table 53: Descriptive Statistics — Visual Verbal (VV) & Tactile Verbal (TV), Task Two (TV)

TV from VVTV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	75% Resource Allocation Policy	94.8823	56.41883
	50% Resource Allocation Policy	96.3196	57.00203
	25% Resource Allocation Policy	99.3027	61.04741

The within-subjects ANOVA revealed that there no significant effect of policy (F $_{(1.486, 32.701)}$ = .136, p = .812). Therefore, participants' performance in the TV single task condition is not significantly different from TV performance in the VVTV dual-task condition.

Auditory Verbal & Proprioceptive Spatial (AVPS) — Significance of Difference from Respective Single Task Scores

Effect of the Auditory Verbal (AV) & Proprioceptive Spatial (PS) dual-task on AV — significance of difference from AV single task score

Table 54: Descriptive Statistics — Auditory Verbal (AV) & Proprioceptive Spatial (PS), Task One (AV)

AV from AVPS Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	73.6729	17.82813
	50% Resource Allocation Policy	74.2128	16.81836
	75% Resource Allocation Policy	81.7618	14.93882

The within-subjects ANOVA revealed that there is a significant effect of policy (F $_{(3, 54)}$ = 25.802, p = .000). Therefore, participants' performance in the AV single task condition is significantly different from AV performance in the AVPS dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy (F $_{(1, 18)}$ = 28.458, p = .000), and Figure 46 shows that single task scores are higher than dual-task scores.

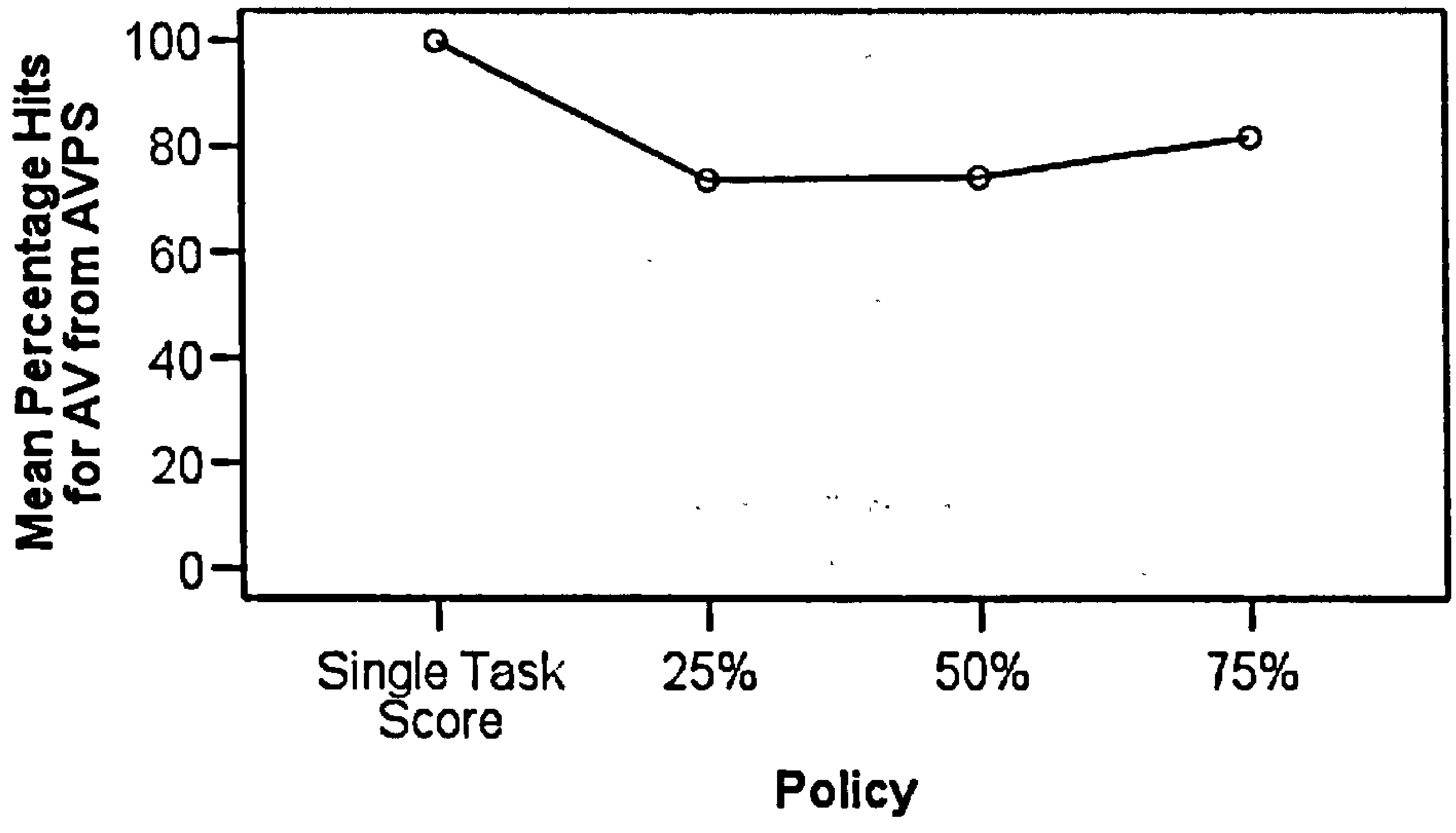


Figure 46: Mean Percentage Hits for Auditory Verbal (AV) from Auditory Verbal & Proprioceptive Spatial (AVPS) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 18) = 41.433, p = .000),

at 50% (F (1, 18) = 44.668, p = .000) and at 75% (F (1, 18) = 28.319, p = .000) resource allocation.

Effect of the Auditory Verbal (AV) & Proprioceptive Spatial (PS) dual-task on PS — significance of difference from PS single task score

Table 55: Descriptive Statistics — Auditory Verbal (AV) & Proprioceptive Spatial (PS), Task Two (PS)

PS from AVPS Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	75% Resource Allocation Policy	74.1374	63.02345
	50% Resource Allocation Policy	42.6901	42.43621
	25% Resource Allocation Policy	54.7515	58.19641

The within-subjects ANOVA revealed that there a significant effect of policy ($F_{(3, 54)}$ = 8.011, p = .000). Therefore, participants' performance in the PS single task condition is significantly different from PS performance in the AVPS dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy ($F_{(1, 18)}$ = 16.127, p = .001), and Figure 47 shows that single task scores are higher than dual-task scores.

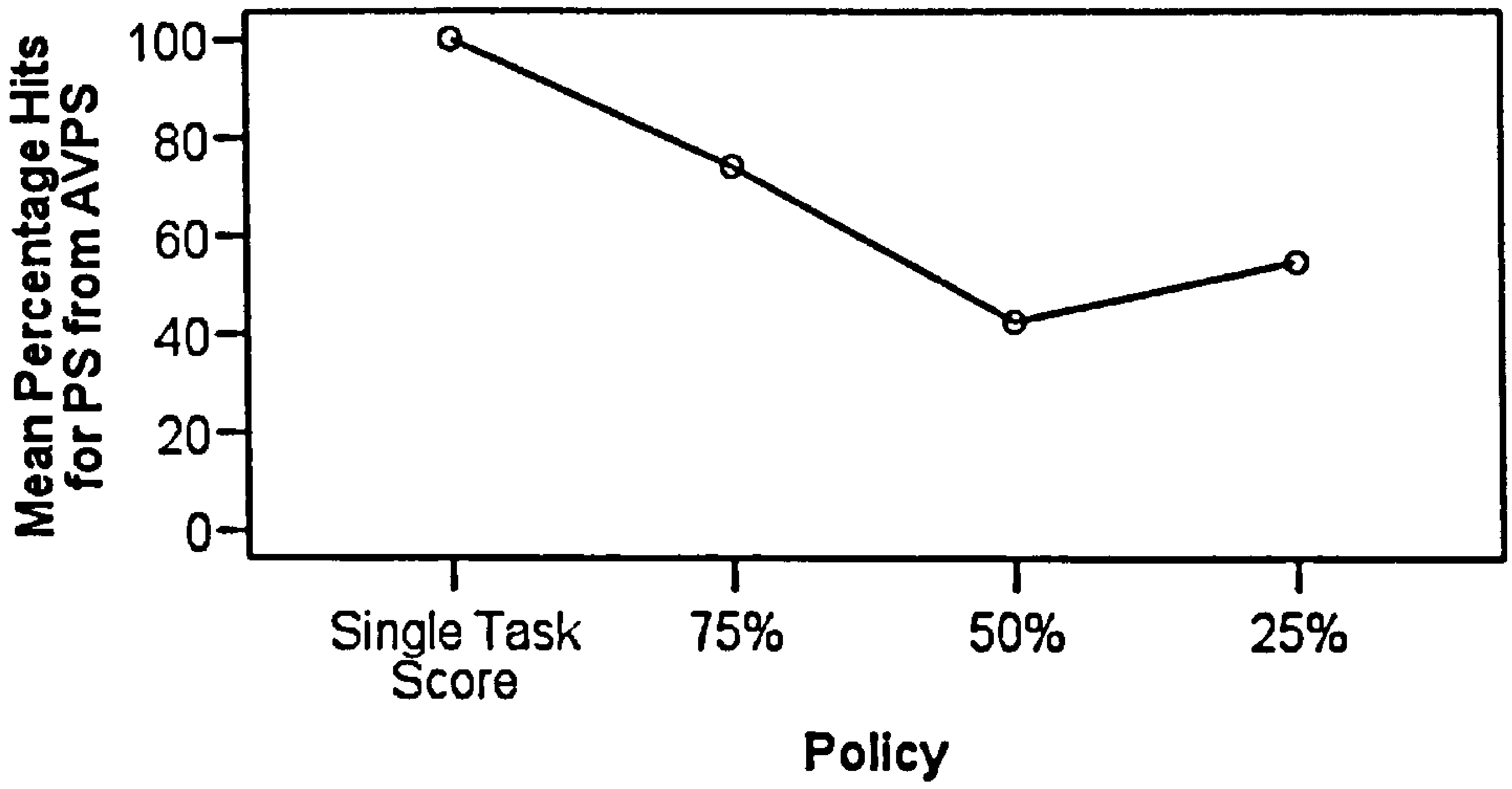


Figure 47: Mean Percentage Hits for Proprioceptive Spatial (PS) from Auditory Verbal & Proprioceptive Spatial (AVPS) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 18) = 11.486, p = .003) and at 50% (F (1, 18) = 34.653, p = .000) but not at 75% (F (1, 18) = 3.200, p = .091) resource allocation.

Auditory Verbal & Proprioceptive Verbal (AVPV) — Significance of Difference from Respective Single Task Scores

Effect of the Auditory Verbal (AV) & Proprioceptive Verbal (PV) dual-task on AV — significance of difference from AV single task score

Table 56: Descriptive Statistics — Auditory Verbal (AV) & Proprioceptive Verbal (PV), Task One (AV)

AV from AVPV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	81.7495	16.72829
	50% Resource Allocation Policy	77.9498	19.26468
	75% Resource Allocation Policy	135.7993	306.72272

The within-subjects ANOVA revealed that there is no effect of policy (F $_{(3, 54)}$ = 25.802, p = .000). Therefore, participants' performance in the AV single task condition is not significantly different from AV performance in the AVPS dual-task condition.

Effect of the Auditory Verbal (AV) & Proprioceptive Verbal (PV) dual-task on PV — significance of difference from PV single task score

Table 57: Descriptive Statistics — Auditory Verbal (AV) & Proprioceptive Verbal (PV), Task Two (PV)

PV from AVPV Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	75% Resource Allocation Policy	121.0161	68.58274
	50% Resource Allocation Policy	111.4169	50.55847
	25% Resource Allocation Policy	118.9385	58.41239

The within-subjects ANOVA revealed that there is no effect of policy (F $_{(1.744, 66.289)}$ = 2.966, p = .065). Therefore, participants' performance in the PV single task condition is not significantly different from PV performance in the AVPV dual-task condition.

Visual Verbal & Proprioceptive Spatial (VVPS) — Significance of Difference from Respective Single Task Scores

Effect of the Visual Verbal (VV) & Proprioceptive Spatial (PS) dual-task on VV — significance of difference from VV single task score

Table 58: Descriptive Statistics — Visual Verbal (VV) & Proprioceptive Spatial (PS), Task One (VV)

VV from VVPS Dual-Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual-Task Scores	25% Resource Allocation Policy	88.0177	17.39159
	50% Resource Allocation Policy	82.3413	13.98060
	75% Resource Allocation Policy	89.0224	16.45600

The within-subjects ANOVA revealed that there is a significant effect of policy ($F_{(1.594, 17.539)} = 8.213$, $p = .005$). Therefore, participants' performance in the VV single task condition is significantly different from VV performance in the VVPS dual-task condition. Post-hoc tests confirm that there is a significant linear trend for policy ($F_{(1, 11)} = 8.489$, $p = .014$), and Figure 48 shows that single task scores are higher than dual-task scores.

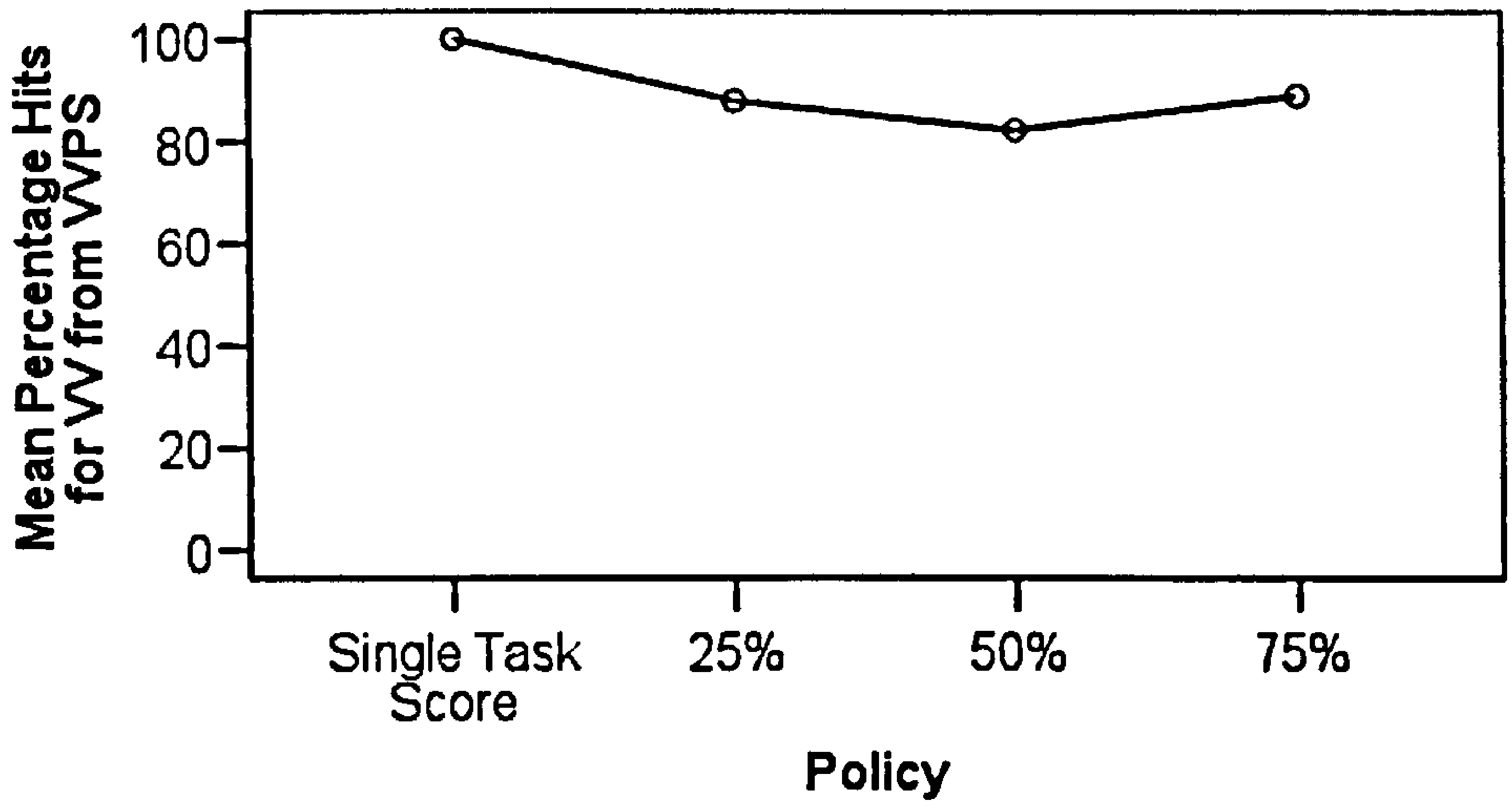


Figure 48: Mean Percentage Hits for Visual Verbal (VV) from Visual Verbal & Proprioceptive Spatial (VVPS) — Single Task Scores (100% resource allocation policy) and Dual-Task Scores (25%, 50% and 75% resource allocation policies)

Simple contrasts of the dual-task results against the single task result were conducted. These revealed that there was a significant difference between the single task result and the dual-task results at 25% (F (1, 11) = 5.696, p = .036),

at 50% (F (1, 11) = 19.145, p = .001) and at 75% (F (1, 11) = 5.340, p = .041) resource allocation.

Effect of the Visual Verbal (VV) & Proprioceptive Spatial (PS) dual–task on PS — significance of difference from PS single task score

Table 59: Descriptive Statistics — Visual Verbal (VV) & Proprioceptive Spatial (PS), Task Two (PS)

PS from VVPS Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	91.2831	110.14807
	50% Resource Allocation Policy	59.5304	74.48719
	25% Resource Allocation Policy	67.0701	95.58322

The within–subjects ANOVA revealed that there is no effect of policy ($F_{(3, 33)}$ = 1.072, p = .374). Therefore, participants' performance in the PS single task condition is not significantly different from PS performance in the VVPS dual–task condition.

Visual Verbal & Proprioceptive Verbal (VVPV) — Significance of Difference from Respective Single Task Scores

Effect of the Visual Verbal (VV) & Proprioceptive Verbal (PV) dual–task on VV — significance of difference from VV single task score

Table 60: Descriptive Statistics — Visual Verbal (VV) & Proprioceptive Verbal (PV), Task One (VV)

VV from VVPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	25% Resource Allocation Policy	90.8537	23.63604
	50% Resource Allocation Policy	94.5700	39.38110
	75% Resource Allocation Policy	98.5266	47.49754

The within–subjects ANOVA revealed that there is no effect of policy ($F_{(1.231, 19.694)}$ = .583, p = .488). Therefore, participants' performance in the VV single task condition is not significantly different from VV performance in the VVPV dual–task condition.

Effect of the Visual Verbal (VV) & Proprioceptive Verbal (PV) dual–task on PV — significance of difference from PV single task score

Table 61: Descriptive Statistics — Visual Verbal (VV) & Proprioceptive Verbal (PV), Task Two (PV)

PV from VVPV Dual–Task		Mean	Std. Deviation
Single Task Score	100% Resource Allocation Policy	100.0000	.00000
Dual–Task Scores	75% Resource Allocation Policy	108.7637	37.37778
	50% Resource Allocation Policy	100.3648	30.61336
	25% Resource Allocation Policy	105.4935	30.25066

The within–subjects ANOVA revealed that there is no effect of policy ($F_{(1.879, 30.069)} = .797$, $p = .502$). Therefore, participants' performance in the PV single task condition is not significantly different from PV performance in the VVPV dual–task condition.

SUMMARY

A summary of the results is displayed in Table 62, which shows the significances of differences between scores on each task within the dual-task combinations and their single task scores. As in Study One, because each dual-task contains two tasks (task one and task two), two comparisons must be made per dual-task.

Three dual-tasks (AVPS, AVTS and VVTS) show a significant difference between both tasks and their respective single task scores. However, where AVPV, VVPS and VVTV are concerned, a significant difference was found between task one and its single task score but not for task two. Finally, both tasks in AVPV and VVPV were found to be not significantly different from their single task scores. These results are discussed in the Discussion to Study Two.

Table 62: Summary of Comparisons between Dual-Tasks and Single Tasks for Study Two — Significance of Differences

Dual-Tasks		*Single Tasks*	*Significance of Difference*
AVPS	AV (Auditory Verbal)	AV	Significant
	PS (Proprioceptive Spatial)	PS	Significant
AVPV	AV (Auditory Verbal)	AV	Not Significant
	PV (Proprioceptive Verbal)	PV	Not Significant
AVTS	AV (Auditory Verbal)	AV	Significant
	TS (Tactile Spatial)	TS	Significant
AVTV	AV (Auditory Verbal)	AV	Significant
	TV (Tactile Verbal)	TV	Not Significant
VVPS	VV (Visual Verbal)	VV	Significant
	PS (Proprioceptive Spatial)	PS	Not Significant
VVPV	VV (Visual Verbal)	VV	Not Significant
	PV (Proprioceptive Verbal)	PV	Not Significant
VVTS	VV (Visual Verbal)	VV	Significant
	TS (Tactile Spatial)	TS	Significant
VVTV	VV (Visual Verbal)	VV	Significant
	TV (Tactile Verbal)	TV	Not Significant

13.4 Significance of Differences between Dual–Tasks

Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Proprioceptive Verbal (AVPV)

Table 63 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Proprioceptive Verbal (AVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	74.5320	19.14150
AVPS 25_75 Task Two (PS at 75%)	79.7049	66.02589
AVPS 50_50 Task One (AV at 50%)	73.9516	17.15445
AVPS 50_50 Task Two (PS at 50%)	49.3056	42.93478
AVPS 75_25 Task One (AV at 75%)	83.1717	14.97143
AVPS 75_25 Task Two (PS at 25%)	65.0174	57.89842
AVPV 25_75 Task One (AV at 25%)	80.6761	18.39359
AVPV 25_75 Task Two (PV at 75%)	116.0238	78.19414
AVPV 50_50 Task One (AV at 50%)	78.5971	16.10636
AVPV 50_50 Task Two (PV at 50%)	96.8911	28.91851
AVPV 75_25 Task One (AV at 75%)	206.1786	478.56008
AVPV 75_25 Task Two (PV at 25%)	99.0988	38.87433

The ANOVA revealed that there is no effect of condition ($F_{(1, 15)} = 3.372$, $p = .086$). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the AVPV condition. There is no significant two–way interaction effect of condition by policy ($F_{(1.041, 15.608)} = 1.296$, $p = .279$), nor of condition by task ($F_{(1, 15)} = 2.419$, $p = .127$), nor of policy by task by condition ($F_{(1.037, 15.557)} = 2.385$, $p = .115$).

Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Tactile Spatial (AVTS)

Table 64 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Tactile Spatial (AVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	74.2654	18.56624
AVPS 25_75 Task Two (PS at 75%)	78.9379	64.00746
AVPS 50_50 Task One (AV at 50%)	74.8956	17.05969
AVPS 50_50 Task Two (PS at 50%)	46.4052	43.25720
AVPS 75_25 Task One (AV at 75%)	83.5733	14.59032
AVPS 75_25 Task Two (PS at 25%)	61.1928	58.23551
AVTS 25_75 Task One (AV at 25%)	56.7291	22.10601
AVTS 25_75 Task Two (TS at 75%)	75.8303	39.17418
AVTS 50_50 Task One (AV at 50%)	68.0882	50.29837
AVTS 50_50 Task Two (TS at 50%)	66.3795	34.70756
AVTS 75_25 Task One (AV at 75%)	63.3885	21.46824
AVTS 75_25 Task Two (TS at 25%)	78.2353	31.75997

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 16)} = .050$, $p = .825$). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the AVTS condition. There is no two-way interaction effect of condition by policy ($F_{(2, 32)} = 2.199$, $p = .127$), nor of condition by task ($F_{(1, 16)} = 2.559$, $p = .129$). There is no three-way interaction effect of policy by task by condition ($F_{(2, 32)} = .487$, $p = .619$).

Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Proprioceptive Verbal (AVTV)

Table 65 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Auditory Verbal & Tactile Verbal (AVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	73.8769	18.32215
AVPS 25_75 Task Two (PS at 75%)	74.5525	64.82387
AVPS 50_50 Task One (AV at 50%)	73.3358	16.85291
AVPS 50_50 Task Two (PS at 50%)	45.0617	42.35098
AVPS 75_25 Task One (AV at 75%)	81.3041	15.23423
AVPS 75_25 Task Two (PS at 25%)	57.7932	58.30878
AVTV 25_75 Task One (AV at 25%)	66.9369	27.24861
AVTV 25_75 Task Two (TV at 75%)	94.8957	47.34972
AVTV 50_50 Task One (AV at 50%)	57.5628	24.94014
AVTV 50_50 Task Two (TV at 50%)	78.7237	32.86472
AVTV 75_25 Task One (AV at 75%)	71.2122	14.40338
AVTV 75_25 Task Two (TV at 25%)	87.2211	50.81712

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 17)}$ = .978, p = .336). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the AVTV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 34)}$ = .077, p = .926). However there is a significant two–way interaction effect of condition by task ($F_{(1, 17)}$ = 10.128, p = .005). Finally, there is no significant three–way interaction effect of policy by task by condition ($F_{(2, 34)}$ = 1.155, p = .327).

There is a significant interaction between condition and task ($F_{(1, 17)}$ = 10.128, p = .005). In AVPS, task one hits are greater than task two hits, whereas in AVTV, task two hits are greater than task one hits. This trend is illustrated in Figure 49.

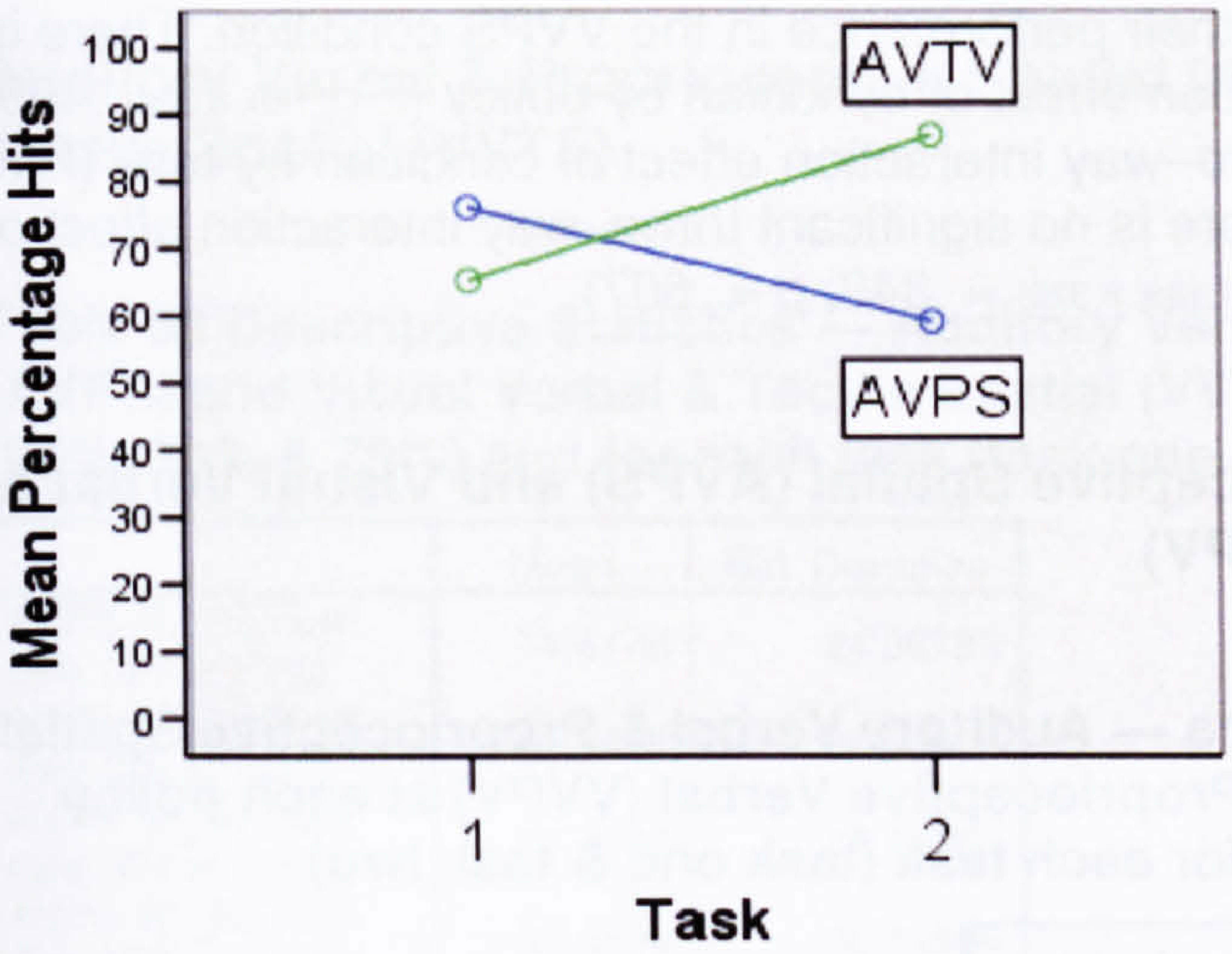


Figure 49: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTV & AVPS) by TASK (task one & task two)

Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Proprioceptive Spatial (VVPS)

Table 66 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Proprioceptive Spatial (VVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	77.9374	9.38609
AVPS 25_75 Task Two (PS at 75%)	80.4167	63.90562
AVPS 50_50 Task One (AV at 50%)	77.9996	11.21260
AVPS 50_50 Task Two (PS at 50%)	53.9583	55.06084
AVPS 75_25 Task One (AV at 75%)	86.1544	12.01662
AVPS 75_25 Task Two (PS at 25%)	75.2083	69.43901
VVPS 25_75 Task One (VV at 25%)	85.0027	20.23157
VVPS 25_75 Task Two (PS at 75%)	96.2500	134.58269
VVPS 50_50 Task One (VV at 50%)	79.4102	15.75506
VVPS 50_50 Task Two (PS at 50%)	60.6250	92.10043
VVPS 75_25 Task One (VV at 75%)	89.4318	19.22456
VVPS 75_25 Task Two (PS at 25%)	54.3750	103.21398

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 7)} = .013$, $p = .912$). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the VVPS condition. There is no significant two-way interaction effect of condition by policy ($F_{(1.189, 8.324)}$ .499, p = .531) and no significant two-way interaction effect of condition by task ($F_{(1, 7)}$ = .008, p = .931). Finally, there is no significant three-way interaction effect of policy by task by condition ($F_{(1.189, 8.323)}$ = .349, p = .607).

Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Proprioceptive Verbal (VVPV)

Table 67 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Proprioceptive Verbal (VVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	79.3711	10.40109
AVPS 25_75 Task Two (PS at 75%)	96.1111	63.95890
AVPS 50_50 Task One (AV at 50%)	75.3632	11.65985
AVPS 50_50 Task Two (PS at 50%)	71.9444	51.88038
AVPS 75_25 Task One (AV at 75%)	87.7513	12.65240
AVPS 75_25 Task Two (PS at 25%)	100.2778	61.10480
VVPV 25_75 Task One (VV at 25%)	90.6890	4.07019
VVPV 25_75 Task Two (PV at 75%)	106.4683	9.68953
VVPV 50_50 Task One (VV at 50%)	85.0469	9.22302
VVPV 50_50 Task Two (PV at 50%)	106.1905	24.18748
VVPV 75_25 Task One (VV at 75%)	89.0657	7.13433
VVPV 75_25 Task Two (PV at 25%)	102.2222	7.07374

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 5)}$ = 1.876, p = .229). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the VVPV condition. There is no significant two-way interaction effect of condition by policy ($F_{(2, 10)}$ = 1.295, p = .316), nor of condition by task ($F_{(1, 5)}$ = .154, p = .711). There is no significant three-way interaction effect of policy by task by condition ($F_{(2, 10)}$ = .791, p = .480).

Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Tactile Spatial (VVTS)

Table 68 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	74.5176	24.06783
AVPS 25_75 Task Two (PS at 75%)	81.5476	64.00309
AVPS 50_50 Task One (AV at 50%)	77.4428	20.16861
AVPS 50_50 Task Two (PS at 50%)	35.9524	35.11696
AVPS 75_25 Task One (AV at 75%)	76.7996	17.83053
AVPS 75_25 Task Two (PS at 25%)	47.9762	51.84971
VVTS 25_75 Task One (VV at 25%)	65.6586	20.93958
VVTS 25_75 Task Two (TS at 75%)	67.5037	16.40167
VVTS 50_50 Task One (VV at 50%)	53.3612	24.82395
VVTS 50_50 Task Two (TS at 50%)	77.5223	27.17372
VVTS 75_25 Task One (VV at 75%)	59.0198	31.10430
VVTS 75_25 Task Two (TS at 25%)	57.8992	36.86328

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1,6)} = .036$, $p = .857$). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the VVTS condition. There is no significant two-way interaction effect of condition by policy ($F_{(2,12)} = 1.071$, $p = .373$), nor of condition by task ($F_{(1,6)} = 3.469$, $p = .112$), and no significant three-way interaction effect of policy by task by condition ($F_{(2,12)} = 3.738$, $p = .055$).

There is a significant interaction between condition, policy and task ($F_{(1,6)} = 7.188$, $p = .036$). Task One hits are greater for AVPS than for VVTS for all three allocation policies. That means that the task one for AVPS (i.e. AV) does better than the task one for VVTS (i.e. VV). However, Task Two hits are greater for VVTS than for AVPS for allocation policies two and three. That means that, for policies two and three, the task two for VVTS (i.e. TS) does better than the task two for AVPS (i.e. PS). However, for policy one of task two, AVPS (i.e. PS) has more hits than VVTS (i.e. TS). These trends are illustrated in Figure 50 and Figure 51.

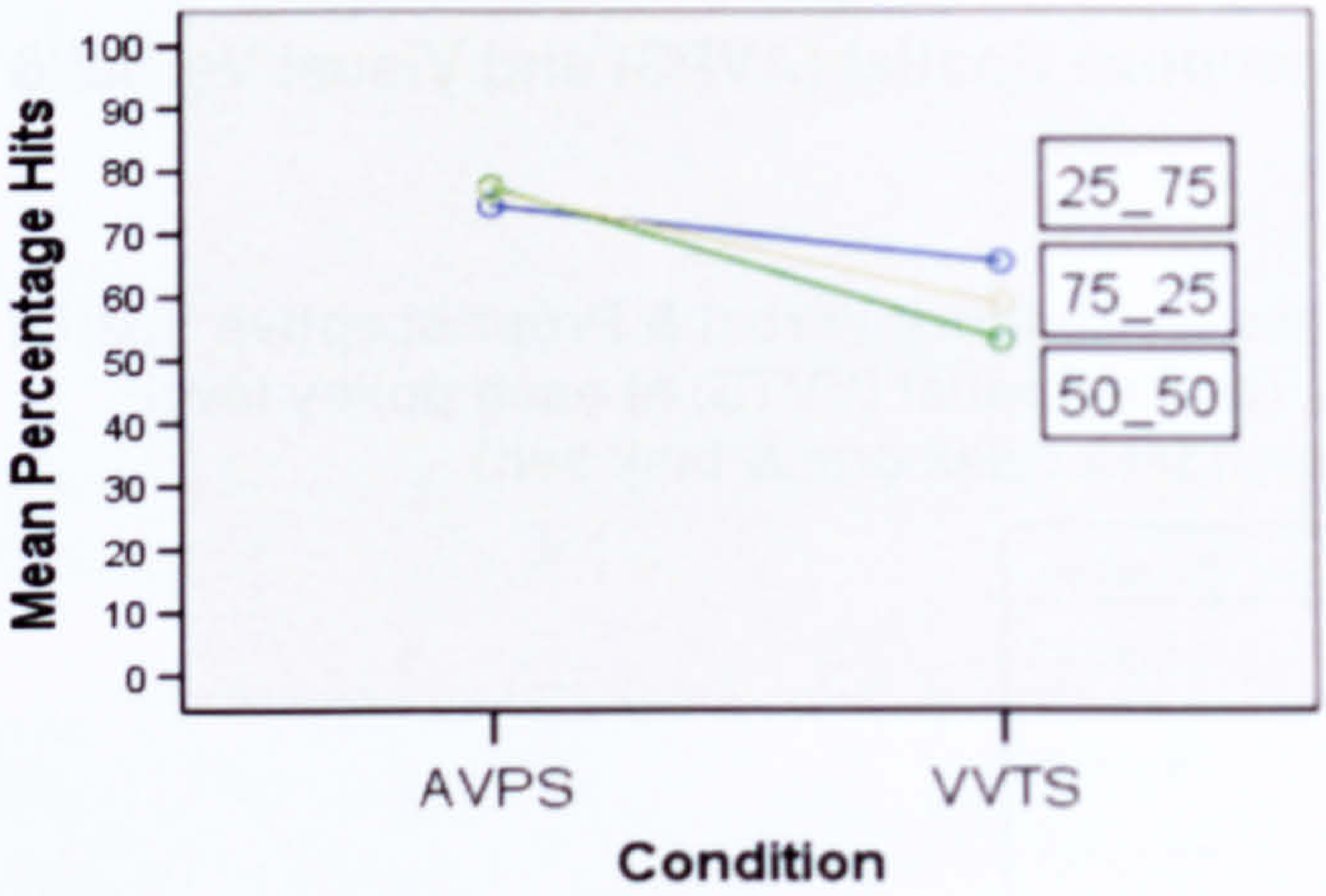


Figure 50: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVPS & VVTS) by POLICY (25_75%, 50_50% & 75–25%) by TASK (Task One)

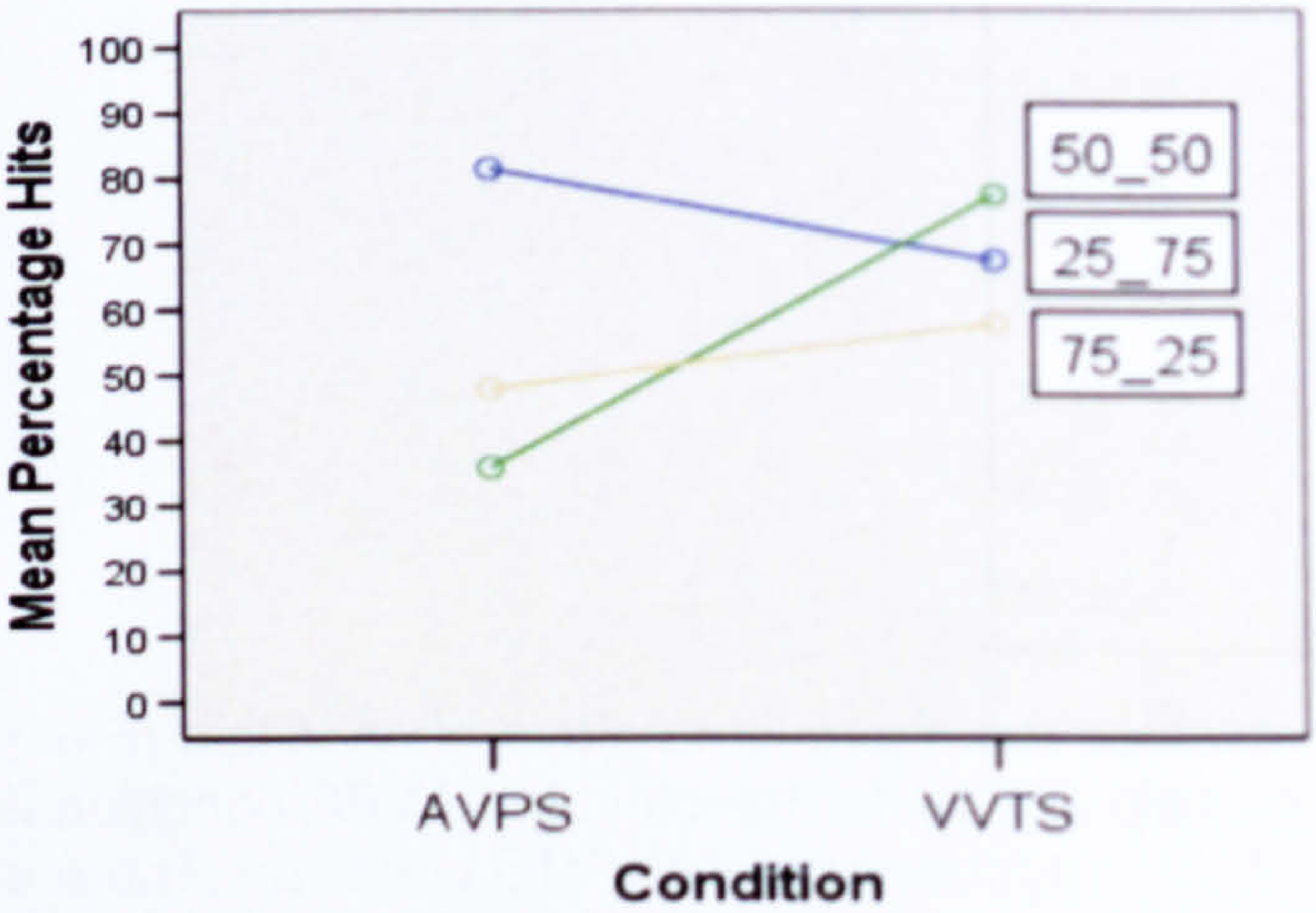


Figure 51: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVPS & VVTS) by POLICY (25_75%, 50_50% & 75–25%) by TASK (Task Two)

Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Tactile Verbal (VVTV)

Table 69 Descriptive Statistics — Auditory Verbal & Proprioceptive Spatial (AVPS) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPS 25_75 Task One (AV at 25%)	75.5566	23.99718
AVPS 25_75 Task Two (PS at 75%)	72.0238	71.14776
AVPS 50_50 Task One (AV at 50%)	76.2740	19.54710
AVPS 50_50 Task Two (PS at 50%)	35.9524	35.11696
AVPS 75_25 Task One (AV at 75%)	74.3321	16.86851
AVPS 75_25 Task Two (PS at 25%)	47.9762	51.84971
VVTV 25_75 Task One (VV at 25%)	69.7279	34.50315
VVTV 25_75 Task Two (TV at 75%)	76.8622	39.17515
VVTV 50_50 Task One (VV at 50%)	70.2907	25.46961
VVTV 50_50 Task Two (TV at 50%)	87.5240	30.36859
VVTV 75_25 Task One (VV at 75%)	79.7835	14.10173
VVTV 75_25 Task Two (TV at 25%)	81.4301	40.58006

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,\ 6)} = .836$, $p = .396$). Therefore, participants' performance in the AVPS condition is not significantly different from their performance in the VVTV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2,\ 12)} = 2.292$, $p = .144$), no significant two–way interaction effect of condition by task ($F_{(1,\ 6)} = 2.191$, $p = .189$), and no significant three–way interaction effect of policy by task by condition ($F_{(2,\ 12)} = 1.501$, $p = .262$).

Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Spatial (AVTS)

Table 70 Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Spatial (AVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	82.3440	17.52839
AVPV 25_75 Task Two (PV at 75%)	127.0692	69.79687
AVPV 50_50 Task One (AV at 50%)	80.5182	16.87319
AVPV 50_50 Task Two (PV at 50%)	115.1150	51.18812
AVPV 75_25 Task One (AV at 75%)	142.5029	323.54838
AVPV 75_25 Task Two (PV at 25%)	122.9124	60.14498
AVTS 25_75 Task One (AV at 25%)	55.5539	23.28251
AVTS 25_75 Task Two (TS at 75%)	72.3320	36.40794
AVTS 50_50 Task One (AV at 50%)	61.9505	38.07905
AVTS 50_50 Task Two (TS at 50%)	68.0820	53.75041
AVTS 75_25 Task One (AV at 75%)	64.4099	21.74912
AVTS 75_25 Task Two (TS at 25%)	76.5908	39.86981

The within–subjects ANOVA revealed that there is an effect of condition ($F_{(1, 34)} = 18.165$, $p = .000$). Therefore, participants' performance in the AVPV condition is significantly different from their performance in the AVTS condition. There is no significant two–way interaction effect of condition by policy ($F_{(1.082, 36.780)} = .865$, $p = .367$), nor of condition by task ($F_{(1, 34)} = .133$, $p = .717$), and no significant three–way interaction effect of policy by task by condition ($F_{(1.118, 38.005)} = 1.147$, $p = .298$). For these data there is a significant trend for condition ($F_{(1, 34)} = 18.165$, $p = .000$), and Table 71 shows a greater percentage of hits for AVPV than for AVTS.

Table 71 Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Proprioceptive Verbal (AVPV) compared to Auditory Verbal & Tactile Spatial (AVTS)

condition	Mean	Std. Error
AVPV	111.744	10.357
AVTS	66.487	3.289

Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Verbal (AVTV)

Table 72: Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Verbal (AVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	81.5324	16.89706
AVPV 25_75 Task Two (PV at 75%)	118.4990	67.65307
AVPV 50_50 Task One (AV at 50%)	77.8300	19.50857
AVPV 50_50 Task Two (PV at 50%)	109.9629	50.40408
AVPV 75_25 Task One (AV at 75%)	136.8730	310.76571
AVPV 75_25 Task Two (PV at 25%)	115.9281	56.04673
AVTV 25_75 Task One (AV at 25%)	71.9188	19.91885
AVTV 25_75 Task Two (TV at 75%)	100.3900	54.09346
AVTV 50_50 Task One (AV at 50%)	65.4905	21.47488
AVTV 50_50 Task Two (TV at 50%)	86.8755	45.62368
AVTV 75_25 Task One (AV at 75%)	74.8291	17.27309
AVTV 75_25 Task Two (TV at 25%)	97.4105	57.51748

The within-subjects ANOVA revealed that there is an effect of condition ($F_{(1, 37)} = 5.578$, $p = .024$). Therefore, participants' performance in the AVPV condition is significantly different from their performance in the AVTV condition. There is no two-way interaction effect of condition by policy ($F_{(1.039, 38.449)} = .964$, $p = .336$), nor of condition by task ($F_{(1, 37)} = .146$, $p = .704$), and no three-way interaction effect of policy by task by condition ($F_{(1.039, 38.461)} = 1.075$, $p = .309$). There is a significant trend for condition ($F_{(1, 37)} = 5.578$, $p = .024$), and Table 73 shows a greater percentage of hits for AVPV than for AVTV.

Table 73: Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Proprioceptive Verbal (AVPV) compared to Auditory Verbal & Tactile Verbal (AVTV)

condition	Mean	Std. Error
AVPV	106.771	9.679
AVTV	82.819	4.914

Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Proprioceptive Spatial (VVPS)

Table 74: Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Proprioceptive Spatial (VVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	86.8859	21.75391
AVPV 25_75 Task Two (PV at 75%)	110.9910	48.36957
AVPV 50_50 Task One (AV at 50%)	85.3223	20.33705
AVPV 50_50 Task Two (PV at 50%)	110.4660	46.99952
AVPV 75_25 Task One (AV at 75%)	284.8871	602.94750
AVPV 75_25 Task Two (PV at 25%)	108.3496	49.92611
VVPS 25_75 Task One (VV at 25%)	85.1212	17.67381
VVPS 25_75 Task Two (PS at 75%)	109.5397	112.27958
VVPS 50_50 Task One (VV at 50%)	80.2641	14.43864
VVPS 50_50 Task Two (PS at 50%)	64.7698	79.69556
VVPS 75_25 Task One (VV at 75%)	87.2814	17.59611
VVPS 75_25 Task Two (PS at 25%)	80.4841	99.83404

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1,9)} = 1.806$, $p = .212$). Therefore, participants' performance in the AVPV condition is not significantly different from their performance in the VVPS condition. There is no significant two-way interaction effect of condition by policy ($F_{(1.012,\ 9.105)} = .951$, $p = .356$), no significant two-way interaction effect of condition by task ($F_{(1,\ 9)} = .348$, $p = .570$), and no significant three-way interaction effect of policy by task by condition ($F_{(1.013,\ 9.114)} = 1.204$, $p = .302$).

Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Proprioceptive Verbal (VVPV)

Table 75: Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Proprioceptive Verbal (VVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	85.1440	18.46649
AVPV 25_75 Task Two (PV at 75%)	115.2121	49.87301
AVPV 50_50 Task One (AV at 50%)	80.5598	24.63046
AVPV 50_50 Task Two (PV at 50%)	115.1121	44.58291
AVPV 75_25 Task One (AV at 75%)	203.7207	463.21525
AVPV 75_25 Task Two (PV at 25%)	119.7750	48.32938
VVPV 25_75 Task One (VV at 25%)	90.8537	23.63604
VVPV 25_75 Task Two (PV at 75%)	108.7637	37.37778
VVPV 50_50 Task One (VV at 50%)	94.5700	39.38110
VVPV 50_50 Task Two (PV at 50%)	100.3648	30.61336
VVPV 75_25 Task One (VV at 75%)	98.5266	47.49754
VVPV 75_25 Task Two (PV at 25%)	105.4935	30.25066

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 16)} = .940$, $p = .347$). Therefore, participants' performance in the AVPV condition is not significantly different from their performance in the VVPV condition. There is no significant two-way interaction effect of condition by policy ($F_{(1.007, 16.105)} = 1.139$, $p = .302$), no significant two-way interaction effect of condition by task ($F_{(1, 16)} = .167$, $p = .688$), and no significant three-way interaction effect of policy by task by condition ($F_{(1.012, 16.189)} = .983$, $p = .337$).

Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Tactile Spatial (VVTS)

Table 76: Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	77.4661	16.15169
AVPV 25_75 Task Two (PV at 75%)	144.9587	85.50537
AVPV 50_50 Task One (AV at 50%)	74.4220	14.17487
AVPV 50_50 Task Two (PV at 50%)	119.7281	59.11179
AVPV 75_25 Task One (AV at 75%)	82.0656	12.18105
AVPV 75_25 Task Two (PV at 25%)	137.0265	71.23417
VVTS 25_75 Task One (VV at 25%)	75.8232	60.86291
VVTS 25_75 Task Two (TS at 75%)	58.9025	27.39475
VVTS 50_50 Task One (VV at 50%)	73.3571	51.29485
VVTS 50_50 Task Two (TS at 50%)	53.3448	28.38065
VVTS 75_25 Task One (VV at 75%)	75.8595	71.61201
VVTS 75_25 Task Two (TS at 25%)	66.5132	34.84296

The within–subjects ANOVA revealed that there is an effect of condition (F $_{(1,\ 16)}$ = 10.354, p = .005). Therefore, participants' performance in the AVPV condition is significantly different from their performance in the VVTS condition. There is no two–way interaction effect of condition by policy (F $_{(2,\ 32)}$ = 1.052, p = .361) but there is a two–way interaction effect of condition by task (F $_{(1,\ 16)}$ = 13.941, p = .002). Finally, there is no three–way interaction effect of policy by task by condition (F $_{(2,\ 32)}$ = 1.292, p = .289).

For these data there is a significant trend for condition (F $_{(1,\ 16)}$ = 10.354, p = .005). Table 77 shows a greater percentage of hits for AVPV than for VVTS.

Table 77: Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Proprioceptive Verbal (AVPV) compared to Visual Verbal & Tactile Spatial (VVTS)

condition	Mean	Std. Error
AVPV	105.944	8.877
VVTS	67.300	8.642

There is also a significant interaction between condition and task ($F_{(1, 16)} = 13.941$, $p = .002$). In AVPV, task two hits are greater than task one hits, whereas in VVTS, task one hits are greater than task two hits. This trend is illustrated in Figure 52.

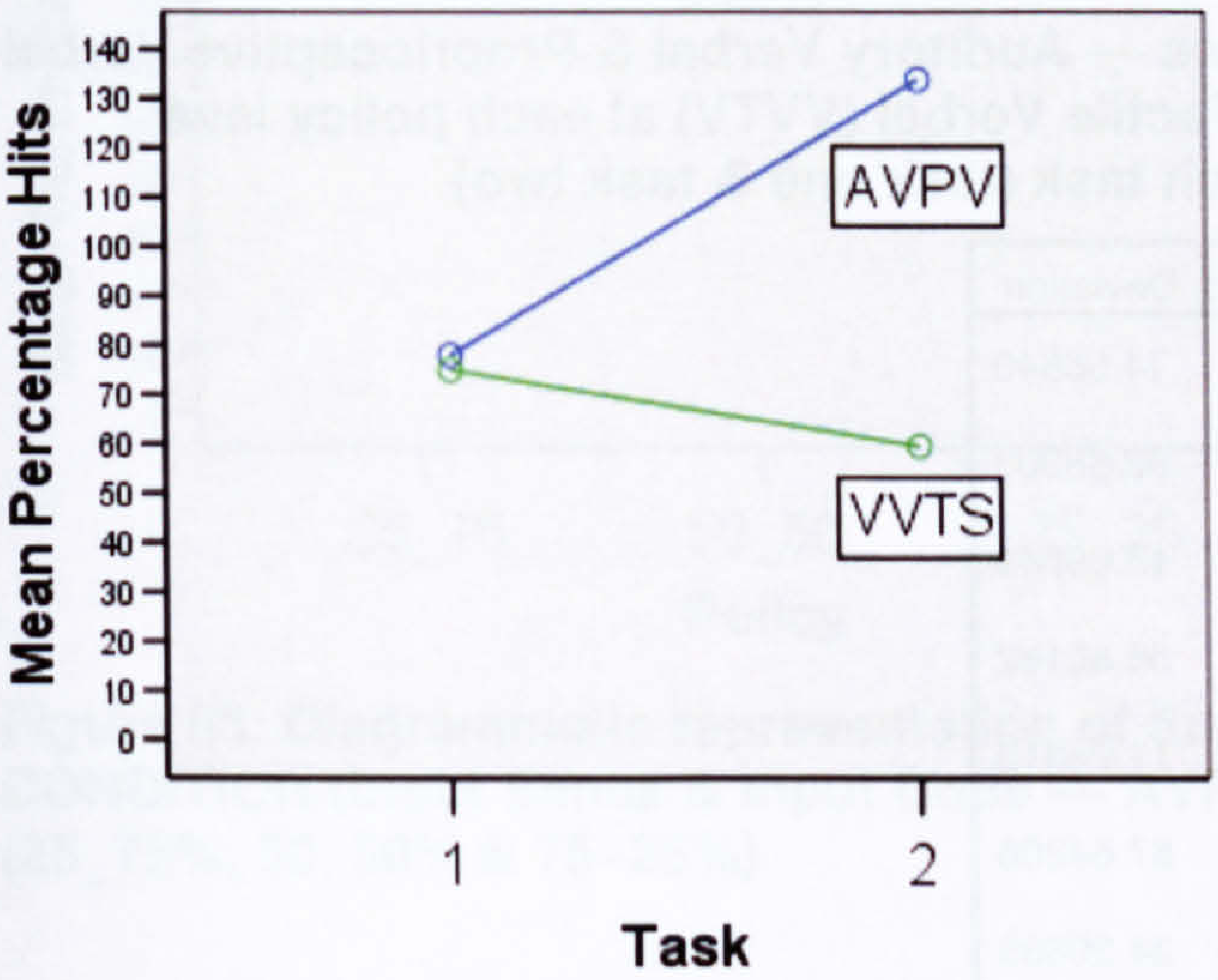


Figure 52: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVPV & VVTS) by TASK (task one & task two)

Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Tactile Verbal (VVTV)

Table 78: Descriptive Statistics — Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVPV 25_75 Task One (AV at 25%)	77.2911	14.56640
AVPV 25_75 Task Two (PV at 75%)	130.3098	82.68303
AVPV 50_50 Task One (AV at 50%)	70.8133	18.09543
AVPV 50_50 Task Two (PV at 50%)	111.9815	56.85182
AVPV 75_25 Task One (AV at 75%)	81.1280	11.98313
AVPV 75_25 Task Two (PV at 25%)	126.9580	67.64306
VVTV 25_75 Task One (VV at 25%)	78.2165	34.20885
VVTV 25_75 Task Two (TV at 75%)	96.4782	58.50459
VVTV 50_50 Task One (VV at 50%)	78.6686	28.20810
VVTV 50_50 Task Two (TV at 50%)	100.1358	56.62950
VVTV 75_25 Task One (VV at 75%)	87.9422	29.86896
VVTV 75_25 Task Two (TV at 25%)	102.1775	62.95335

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 20)} = .589$, $p = .452$). Therefore, participants' performance in the AVPV condition is not significantly different from their performance in the VVTV condition. There is no significant two–way interaction effect of condition by policy ($F_{(1.330, 2.593)} = 2.494$, $p = .118$), no significant two–way interaction effect of condition by task ($F_{(1, 20)} = 3.098$, $p = .094$), and no significant three–way interaction effect of policy by task by condition ($F_{(1.290, 25.797)} = .801$, $p = .409$).

There is a significant interaction between condition and policy ($F_{(1, 20)} = 5.149$, $p = .034$). AVPV hits are roughly the same at 25_75 and 75_25 but dip at 50_50. VVTV hits increase from 25_75, through 50_50, to 75_25. This trend is illustrated in Figure 53.

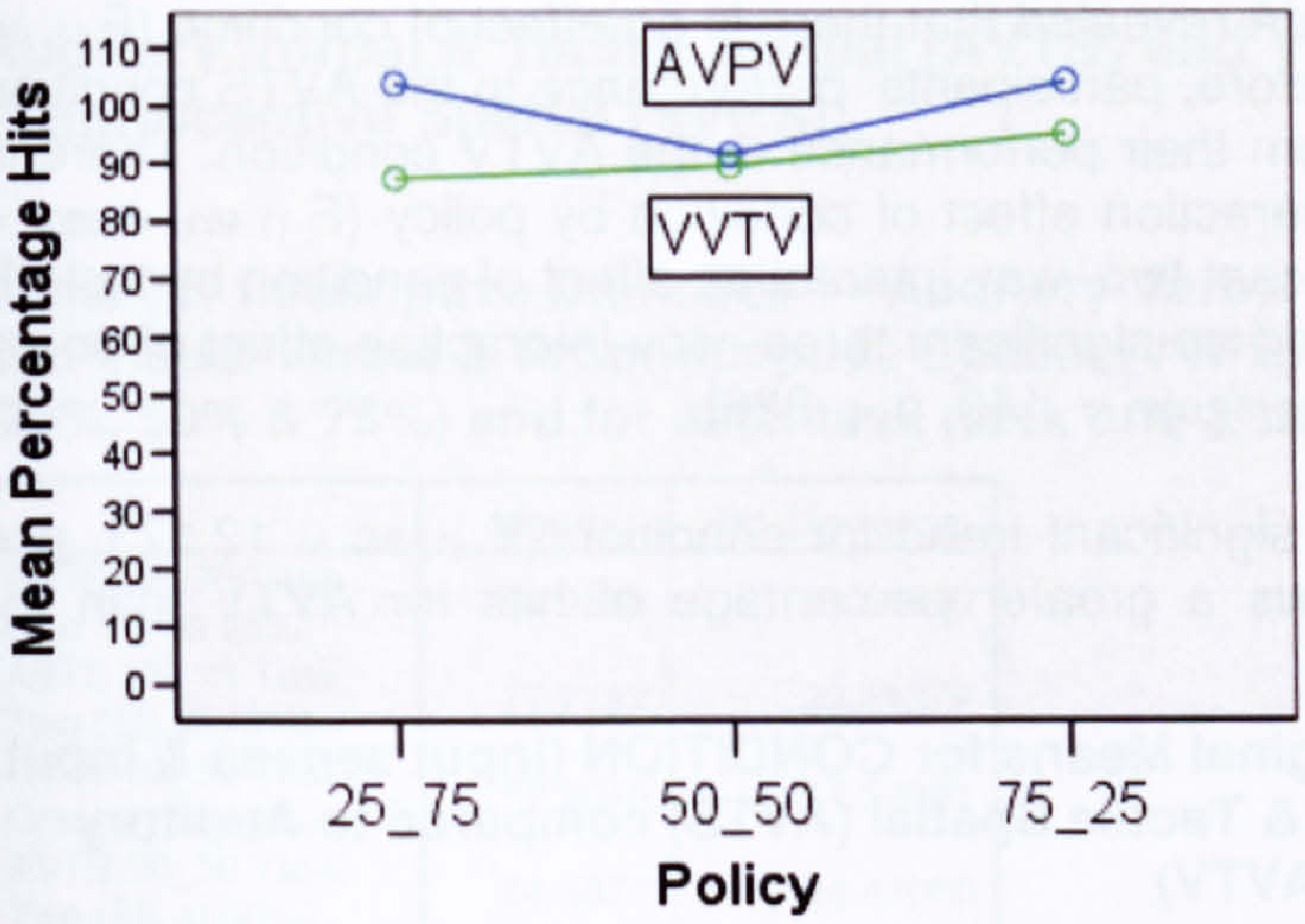


Figure 53: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVPV & VVTV) by POLICY (25_75%, 50_50% & 75–25%)

Auditory Verbal & Tactile Spatial (AVTS) and Auditory Verbal & Tactile Verbal (AVTV)

Table 79: Descriptive Statistics — Auditory Verbal & Tactile Spatial (AVTS) and Auditory Verbal & Tactile Verbal (AVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTS 25_75 Task One (AV at 25%)	56.7784	21.31904
AVTS 25_75 Task Two (TS at 75%)	69.7605	37.55647
AVTS 50_50 Task One (AV at 50%)	63.3111	36.62337
AVTS 50_50 Task Two (TS at 50%)	67.0208	54.33622
AVTS 75_25 Task One (AV at 75%)	66.1786	18.65395
AVTS 75_25 Task Two (TS at 25%)	75.4684	40.76928
AVTV 25_75 Task One (AV at 25%)	73.4982	19.63614
AVTV 25_75 Task Two (TV at 75%)	96.9710	37.26059
AVTV 50_50 Task One (AV at 50%)	66.0020	20.58789
AVTV 50_50 Task Two (TV at 50%)	83.1053	27.15692
AVTV 75_25 Task One (AV at 75%)	76.1070	16.55074
AVTV 75_25 Task Two (TV at 25%)	92.4459	38.40901

The within–subjects ANOVA revealed that there is an effect of condition (F $_{(1, 34)}$ = 12.173, p = .001). Therefore, participants' performance in the AVTS condition is significantly different from their performance in the AVTV condition. There is no significant two–way interaction effect of condition by policy (F $_{(1.461, 49.680)}$ = 2.974, p = .075), no significant two–way interaction effect of condition by task (F $_{(1, 34)}$ = 1.738, p = .196), and no significant three–way interaction effect of policy by task by condition (F $_{(1.619, 55.038)}$ = .140, p = .826).

For these data there is a significant trend for condition (F $_{(1, 34)}$ = 12.173, p = .001), and Table 80 shows a greater percentage of hits for AVTV than for AVTS.

Table 80: Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Tactile Spatial (AVTS) compared to Auditory Verbal & Tactile Verbal (AVTV)

condition	Mean	Std. Error
AVTS	66.420	3.307
AVTV	81.355	3.781

There is a significant interaction between condition and policy (F $_{(1, 34)}$ = 5.704, p = .023). AVTS hits are roughly the same at 25_75 and 75_25 but dip at 50_50. AVTV hits increase from 25_75, through 50_50, to 75_25. This is illustrated in Figure 54.

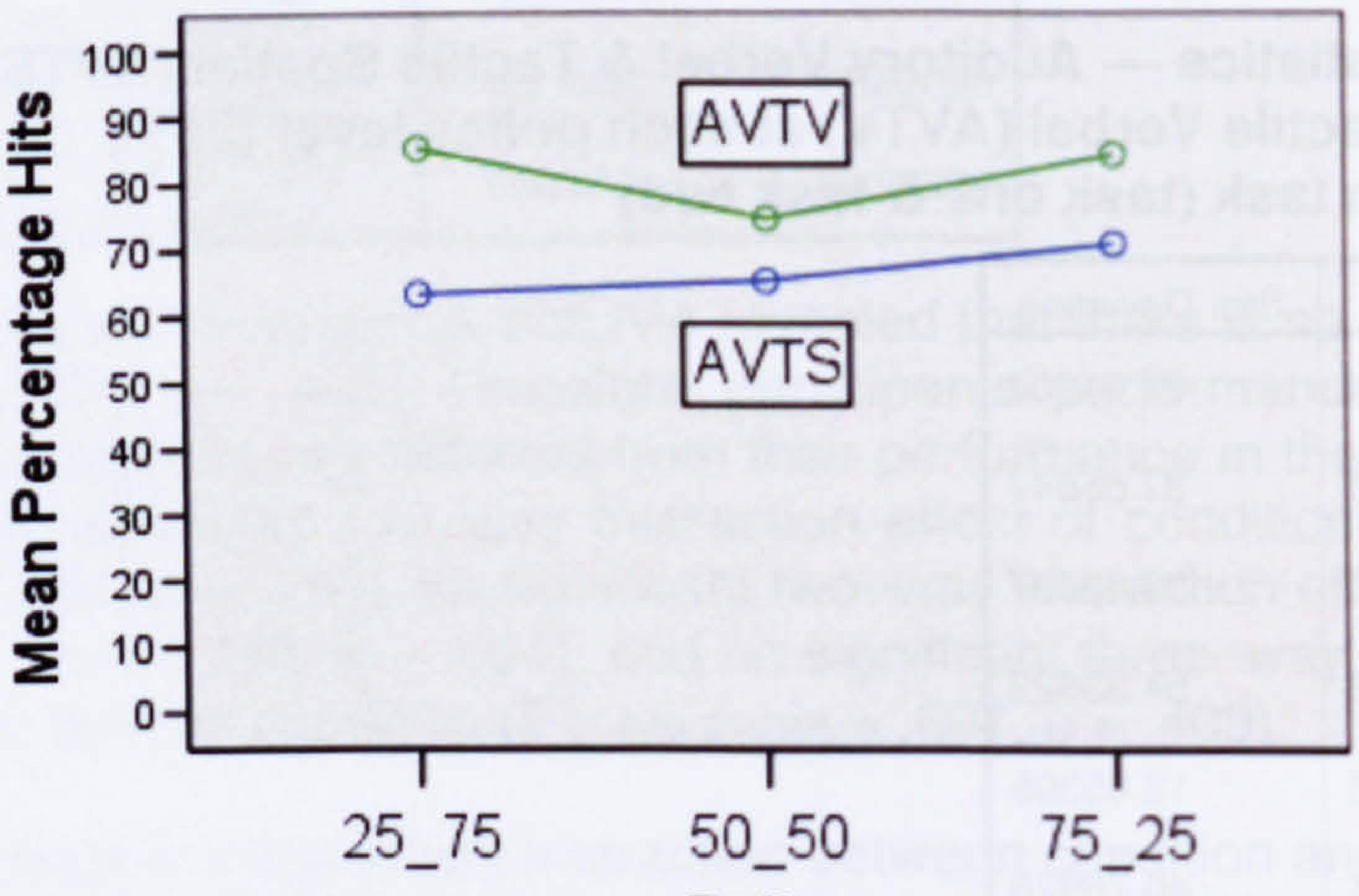


Figure 54 Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTV & AVTS) by POLICY (25_75%, 50_50% & 75–25%)

Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Proprioceptive Spatial (VVPS)

Table 81: Descriptive Statistics — Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Proprioceptive Spatial (VVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTS 25_75 Task One (AV at 25%)	64.0808	18.56870
AVTS 25_75 Task Two (TS at 75%)	77.2197	29.21379
AVTS 50_50 Task One (AV at 50%)	57.9078	17.52381
AVTS 50_50 Task Two (TS at 50%)	64.3877	24.43060
AVTS 75_25 Task One (AV at 75%)	74.4204	19.76420
AVTS 75_25 Task Two (TS at 25%)	83.6373	13.06642
VVPS 25_75 Task One (VV at 25%)	86.9284	17.80593
VVPS 25_75 Task Two (PS at 75%)	99.5815	111.52061
VVPS 50_50 Task One (VV at 50%)	81.1492	14.00871
VVPS 50_50 Task Two (PS at 50%)	64.9423	75.60801
VVPS 75_25 Task One (VV at 75%)	88.4376	17.12795
VVPS 75_25 Task Two (PS at 25%)	73.1674	97.77031

The within–subjects ANOVA revealed that there is no effect of condition (F $_{(1,\ 10)}$ = .904, p = .364). Therefore, participants' performance in the AVTS condition is not significantly different from their performance in the VVPS condition. There is no significant two–way interaction effect of condition by policy (F $_{(2,\ 20)}$ = 1.552, p = .236), no significant two–way interaction effect of condition by task (F $_{(1,\ 10)}$ = .318, p = .585), and no significant three–way interaction effect of policy by task by condition (F $_{(2,\ 20)}$ = .443, p = .648).

Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Proprioceptive Verbal (VVPV)

Table 82: Descriptive Statistics — Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Proprioceptive Verbal (VVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTS 25_75 Task One (AV at 25%)	63.5341	18.58132
AVTS 25_75 Task Two (TS at 75%)	70.7494	38.73454
AVTS 50_50 Task One (AV at 50%)	59.0407	16.63161
AVTS 50_50 Task Two (TS at 50%)	76.1594	74.56425
AVTS 75_25 Task One (AV at 75%)	72.5586	18.82275
AVTS 75_25 Task Two (TS at 25%)	87.6462	46.62549
VVPV 25_75 Task One (VV at 25%)	86.5264	17.44698
VVPV 25_75 Task Two (PV at 75%)	110.4084	39.62609
VVPV 50_50 Task One (VV at 50%)	85.0239	10.11357
VVPV 50_50 Task Two (PV at 50%)	99.0714	31.83591
VVPV 75_25 Task One (VV at 75%)	86.5507	16.91250
VVPV 75_25 Task Two (PV at 25%)	105.7498	32.30187

The within–subjects ANOVA revealed that there is an effect of condition ($F_{(1, 14)} = 9.460$, $p = .008$). Therefore, participants' performance in the AVTS condition is significantly different from their performance in the VVPV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 28)} = 1.510$, $p = .238$), no significant two–way interaction effect of condition by task ($F_{(1, 14)} = .162$, $p = .693$), and no significant three–way interaction effect of policy by task by condition ($F_{(1.319, 18.468)} = .445$, $p = .567$).

For these data there is a significant trend for condition ($F_{(1, 14)} = 9.460$, $p = .008$), and Table 83 shows a greater percentage of hits for VVPV than for AVTS.

Table 83: Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Tactile Spatial (AVTS) compared to Visual Verbal & Proprioceptive Verbal (VVPV)

condition	Mean	Std. Error
AVTS	71.615	5.011
VVPV	95.555	5.323

There is also a significant interaction between condition and policy ($F_{(1, 14)}$ = 5.787, p = .031). AVTS hits are roughly the same at 25_75 and 50_50 then increase at 75_25. VVPV hits are roughly the same at 25_75 and 75_25, but dip at 50_50. This trend is illustrated in Figure 55.

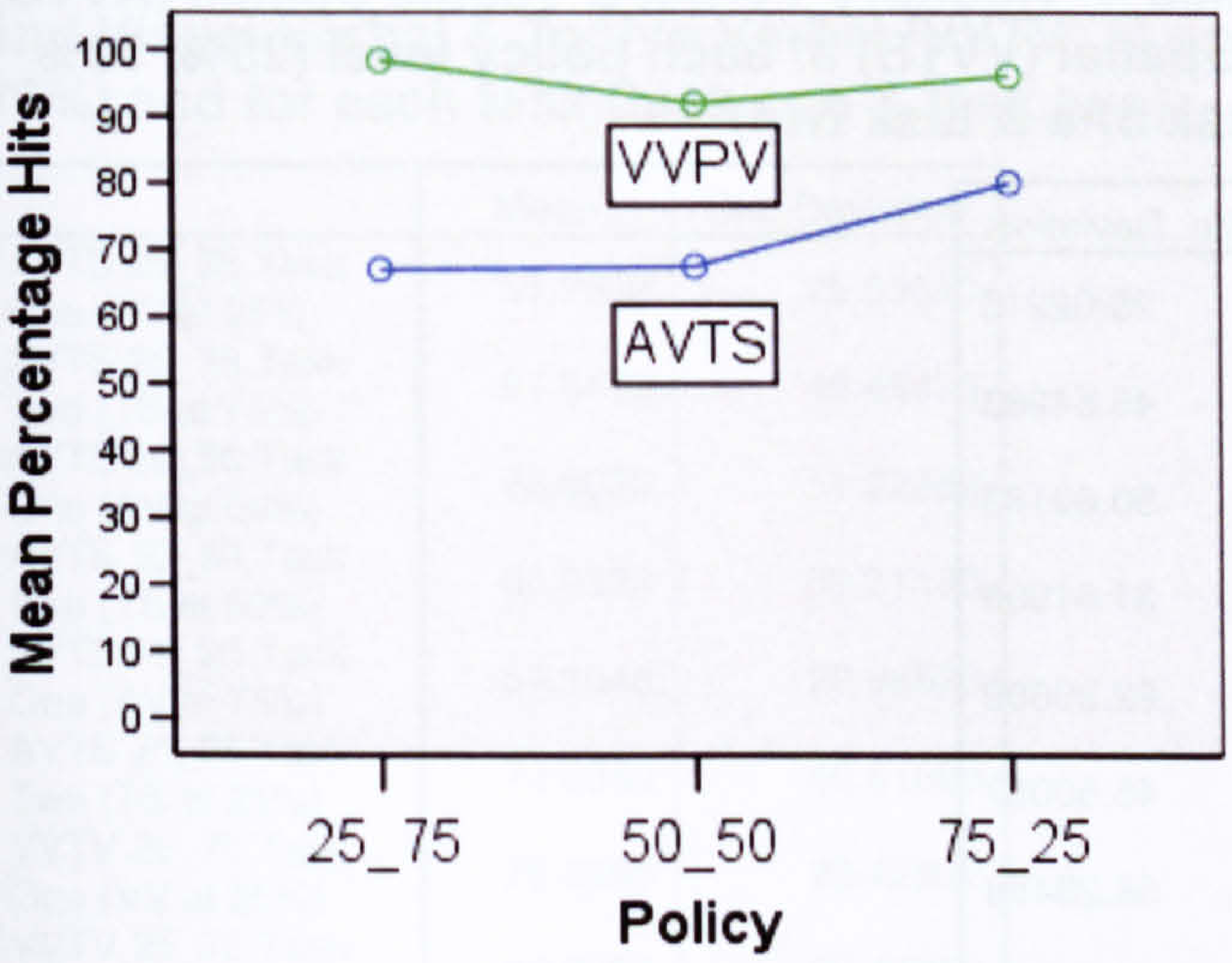


Figure 55: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTS & VVPV) by POLICY (25_75%, 50_50% & 75–25%)

Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Tactile Spatial (VVTS)

Table 84: Descriptive Statistics — Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTS 25_75 Task One (AV at 25%)	51.3984	25.02213
AVTS 25_75 Task Two (TS at 75%)	66.4415	45.54263
AVTS 50_50 Task One (AV at 50%)	64.4124	50.69183
AVTS 50_50 Task Two (TS at 50%)	62.1024	31.81906
AVTS 75_25 Task One (AV at 75%)	56.7307	22.39699
AVTS 75_25 Task Two (TS at 25%)	72.9764	45.50057
VVTS 25_75 Task One (VV at 25%)	74.4583	58.23468
VVTS 25_75 Task Two (TS at 75%)	56.9128	28.96065
VVTS 50_50 Task One (VV at 50%)	71.0864	49.44642
VVTS 50_50 Task Two (TS at 50%)	53.9576	31.43137
VVTS 75_25 Task One (VV at 75%)	73.8517	68.43309
VVTS 75_25 Task Two (TS at 25%)	59.5118	38.97374

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 18)} = .223$, $p = .642$). Therefore, participants' performance in the AVTS condition is not significantly different from their performance in the VVTS condition. There is no significant two-way interaction effect of condition by policy ($F_{(2, 36)} = .676$, $p = .515$), no significant two-way interaction effect of condition by task ($F_{(1, 18)} = 2.313$, $p = .146$), and no significant three-way interaction effect of policy by task by condition ($F_{(1.468, 26.420)} = .626$, $p = .495$).

Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Tactile Verbal (VVTV)

Table 85: Descriptive Statistics — Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTS 25_75 Task One (AV at 25%)	51.7539	25.69815
AVTS 25_75 Task Two (TS at 75%)	67.8179	46.45458
AVTS 50_50 Task One (AV at 50%)	66.6020	51.22859
AVTS 50_50 Task Two (TS at 50%)	60.9229	32.31130
AVTS 75_25 Task One (AV at 75%)	57.1046	22.98520
AVTS 75_25 Task Two (TS at 25%)	72.8640	46.81698
VVTV 25_75 Task One (VV at 25%)	72.3598	23.42532
VVTV 25_75 Task Two (TV at 75%)	82.3353	36.46369
VVTV 50_50 Task One (VV at 50%)	73.1452	19.85578
VVTV 50_50 Task Two (TV at 50%)	83.8325	30.48743
VVTV 75_25 Task One (VV at 75%)	84.1597	11.20194
VVTV 75_25 Task Two (TV at 25%)	87.0893	29.59681

The within–subjects ANOVA revealed that there is an effect of condition ($F_{(1, 17)} = 13.180$, $p = .002$). Therefore, participants' performance in the AVTS condition is significantly different from their performance in the VVTV condition. There is no two–way interaction effect of condition by policy ($F_{(2, 34)} = .396$, $p = .676$), nor of condition by task ($F_{(1, 17)} = .007$, $p = .935$), and no three–way interaction effect of policy by task by condition ($F_{(2, 34)} = 1.506$, $p = .236$).

For these data there is a significant trend for condition ($F_{(1, 17)} = 13.180$, $p = .002$), and Table 86 shows a greater percentage of hits for VVTV than for AVTS.

Table 86: Estimated Marginal Means for CONDITION (input senses & input code) — Auditory Visual & Tactile Spatial (AVTS) compared to Visual Verbal & Tactile Verbal (VVTV)

condition	Mean	Std. Error
AVTS	62.844	5.593
VVTV	80.487	4.991

Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Proprioceptive Spatial (VVPS)

Table 87: Descriptive Statistics — Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Proprioceptive Spatial (VVPS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTV 25_75 Task One (AV at 25%)	73.6731	27.72321
AVTV 25_75 Task Two (TV at 75%)	103.8832	54.65812
AVTV 50_50 Task One (AV at 50%)	64.1047	25.29186
AVTV 50_50 Task Two (TV at 50%)	85.0929	38.19156
AVTV 75_25 Task One (AV at 75%)	76.9393	20.86991
AVTV 75_25 Task Two (TV at 25%)	103.0080	51.65214
VVPS 25_75 Task One (VV at 25%)	86.4738	17.35662
VVPS 25_75 Task Two (PS at 75%)	99.5815	111.52061
VVPS 50_50 Task One (VV at 50%)	81.6450	14.44313
VVPS 50_50 Task Two (PS at 50%)	58.8817	78.08726
VVPS 75_25 Task One (VV at 75%)	88.0244	16.87405
VVPS 75_25 Task Two (PS at 25%)	73.1674	97.77031

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1,10)} = .032$, $p = .861$). Therefore, participants' performance in the AVTV condition is not significantly different from their performance in the VVPS condition. There is no significant two–way interaction effect of condition by policy ($F_{(2,206)} = .504$, $p = .611$), nor of condition by task ($F_{(1,10)} = 1.581$, $p = .237$), and no significant three–way interaction effect of policy by task by condition ($F_{(2,20)} = .535$, $p = .594$).

Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Proprioceptive Verbal (VVPV)

Table 88: Descriptive Statistics — Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Proprioceptive Verbal (VVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTV 25_75 Task One (AV at 25%)	72.6089	23.67066
AVTV 25_75 Task Two (TV at 75%)	114.2161	69.75200
AVTV 50_50 Task One (AV at 50%)	64.5636	21.56534
AVTV 50_50 Task Two (TV at 50%)	95.9064	60.86427
AVTV 75_25 Task One (AV at 75%)	75.5386	20.77300
AVTV 75_25 Task Two (TV at 25%)	113.8463	74.12964
VVPV 25_75 Task One (VV at 25%)	90.8537	23.63604
VVPV 25_75 Task Two (PV at 75%)	108.7637	37.37778
VVPV 50_50 Task One (VV at 50%)	94.5700	39.38110
VVPV 50_50 Task Two (PV at 50%)	100.3648	30.61336
VVPV 75_25 Task One (VV at 75%)	98.5266	47.49754
VVPV 75_25 Task Two (PV at 25%)	105.4935	30.25066

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 16)} = 1.892$, $p = .188$). Therefore, participants' performance in the AVTV condition is not significantly different from their performance in the VVPV condition. There is a two-way interaction effect of condition by policy ($F_{(2, 32)} = 3.548$, $p = .041$) but not of condition by task ($F_{(1, 16)} = 1.269$, $p = .277$). Finally, there is no three-way interaction effect of policy by task by condition ($F_{(2, 32)} = .296$, $p = .746$). There is a significant interaction between condition and policy ($F_{(1, 16)} = 6.022$, $p = .026$). AVTV hits are roughly the same at 25_75 and 75_25 but dip at 50_50. VVPV hits are roughly the same at 25_75 and 50_50, then increase at 75_25. This trend is illustrated in Figure 56.

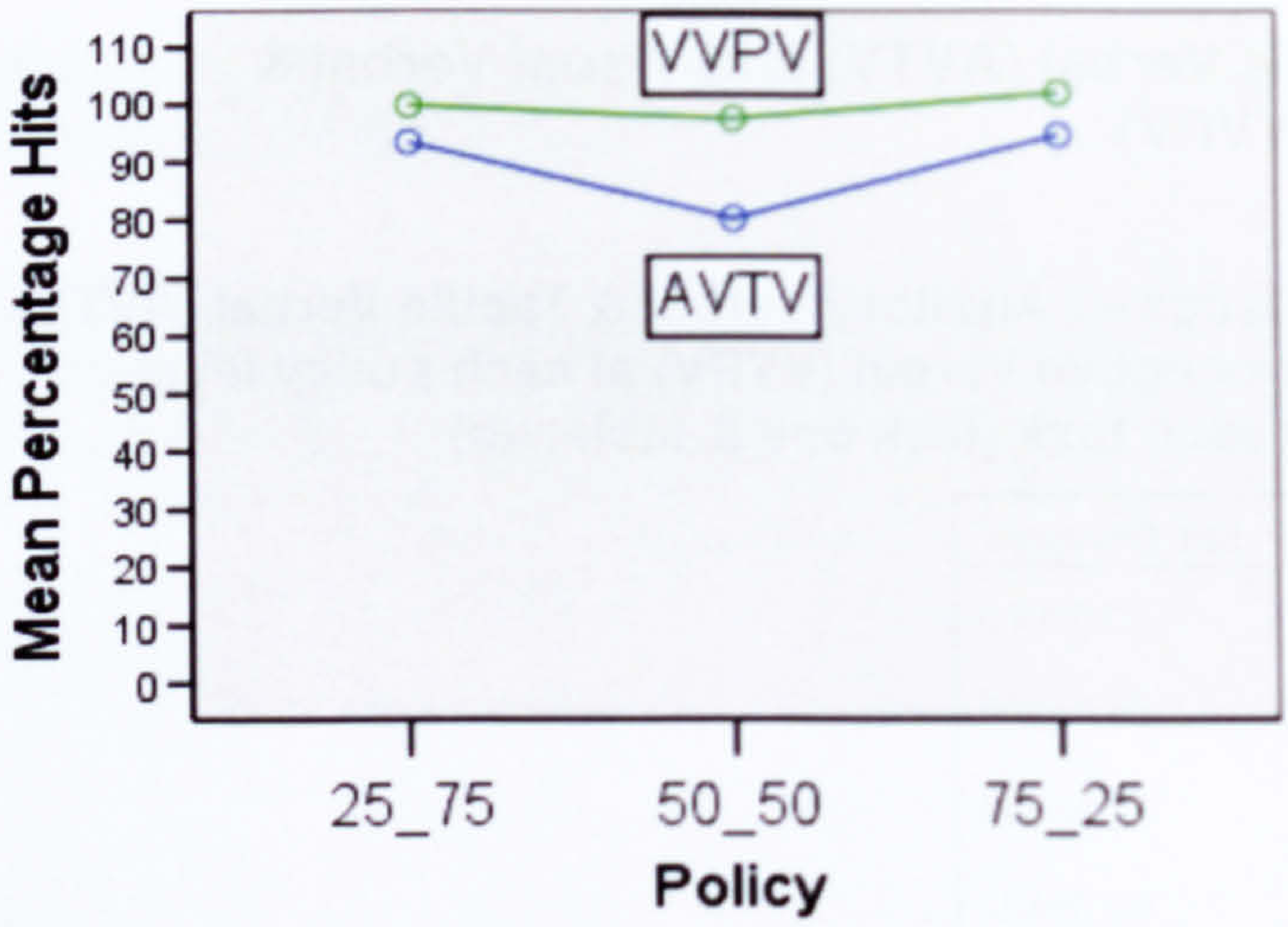


Figure 56: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTV & VVPV) by POLICY (25_75%, 50_50% & 75–25%)

Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Tactile Spatial (VVTS)

Table 89: Descriptive Statistics — Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTV 25_75 Task One (AV at 25%)	71.6919	17.79702
AVTV 25_75 Task Two (TV at 75%)	93.2563	30.14777
AVTV 50_50 Task One (AV at 50%)	64.4379	20.85860
AVTV 50_50 Task Two (TV at 50%)	81.0587	23.66000
AVTV 75_25 Task One (AV at 75%)	73.7955	16.47886
AVTV 75_25 Task Two (TV at 25%)	88.0291	32.01939
VVTS 25_75 Task One (VV at 25%)	76.0523	60.69395
VVTS 25_75 Task Two (TS at 75%)	57.5160	29.53852
VVTS 50_50 Task One (VV at 50%)	71.2944	52.40319
VVTS 50_50 Task Two (TS at 50%)	52.6725	29.30425
VVTS 75_25 Task One (VV at 75%)	75.1337	72.04952
VVTS 75_25 Task Two (TS at 25%)	63.5720	38.26615

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 16)} = 2.172$, $p = .160$). Therefore, participants' performance in the AVTV condition is not significantly different from their performance in the VVTS condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 32)} = .457$, $p = .637$) but there is of condition by task ($F_{(1, 16)} = 5.431$, $p = .033$). There is no significant three–way interaction effect of policy by task by condition ($F_{(2, 32)} = 1.239$, $p = .303$).

There is also a significant interaction between condition and task ($F_{(1, 16)} = 5.431$, $p = .033$). In AVTV, task two hits are greater than task one hits, whereas in VVTS, task one hits are greater than task two hits. This trend is illustrated in Figure 57.

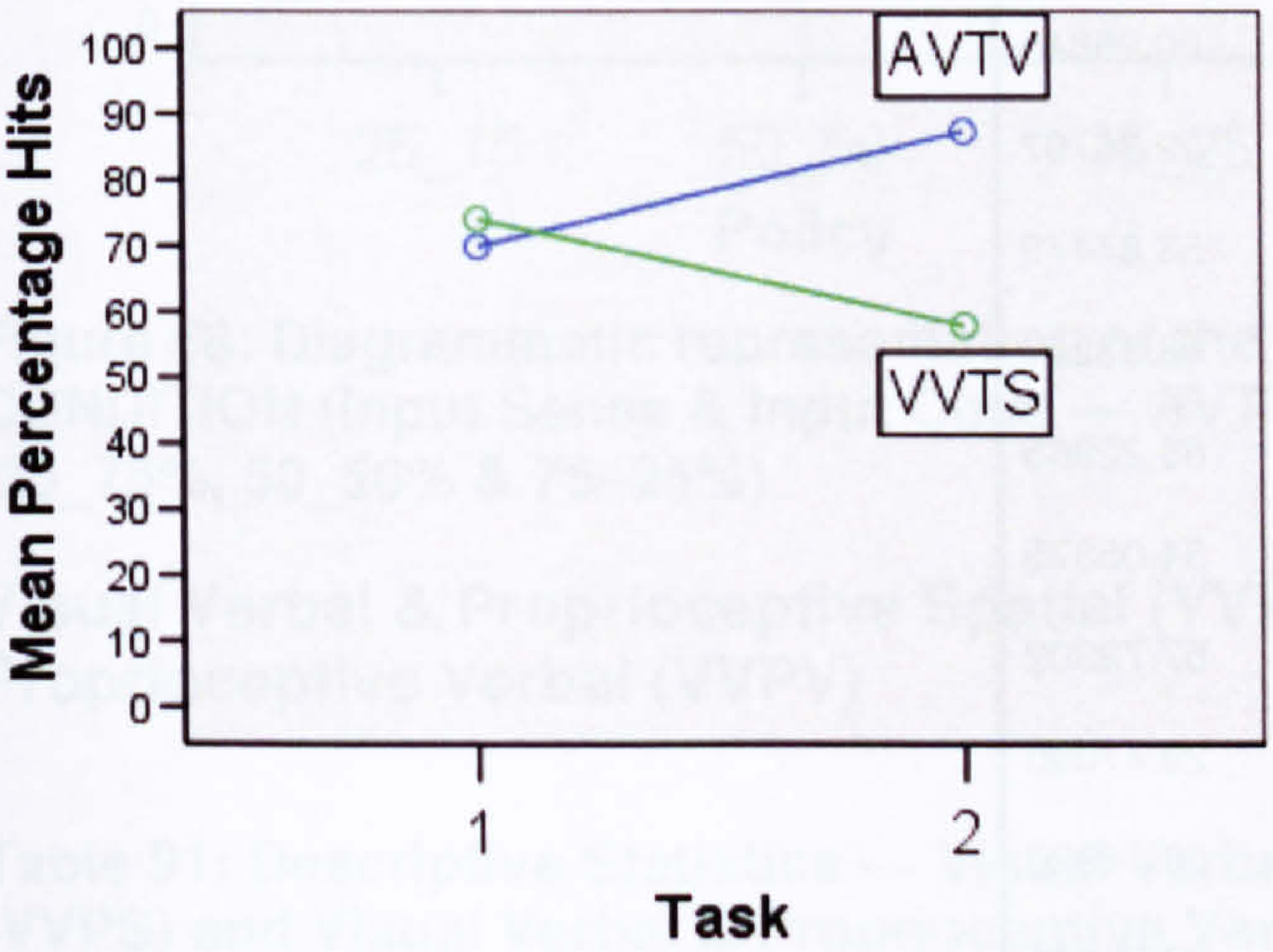


Figure 57 Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTV & VVTS) by TASK (task one & task two)

Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Tactile Verbal (VVTV)

Table 90: Descriptive Statistics — Auditory Verbal & Tactile Verbal (AVTV) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
AVTV 25_75 Task One (AV at 25%)	70.5046	18.19215
AVTV 25_75 Task Two (TV at 75%)	99.9806	60.25845
AVTV 50_50 Task One (AV at 50%)	63.7835	22.36797
AVTV 50_50 Task Two (TV at 50%)	88.7364	53.87479
AVTV 75_25 Task One (AV at 75%)	72.3770	16.83260
AVTV 75_25 Task Two (TV at 25%)	98.2782	65.22965
VVTV 25_75 Task One (VV at 25%)	77.8489	34.05375
VVTV 25_75 Task Two (TV at 75%)	95.2178	57.72302
VVTV 50_50 Task One (VV at 50%)	76.8047	29.47090
VVTV 50_50 Task Two (TV at 50%)	97.2887	58.14920
VVTV 75_25 Task One (VV at 75%)	88.7854	28.96846
VVTV 75_25 Task Two (TV at 25%)	99.5551	62.47173

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 21)} = 2.393$, $p = .137$). Therefore, participants' performance in the AVTV condition is not significantly different from their performance in the VVTV condition. There is a significant two–way interaction effect of condition by policy ($F_{(2, 42)} = 4.300$, $p = .020$). However, there is no significant two–way interaction effect of condition by task ($F_{(1, 21)} = 1.485$, $p = .236$) and no significant three–way interaction effect of policy by task by condition ($F_{(1.463, 30.730)} = 1.033$, $p = .347$). There is a significant interaction between condition and policy ($F_{(1, 21)} = 4.826$, $p = .039$). AVTV hits are roughly the same at 25_75 and 75_25 but dip at 50_50. VVTV hits increase from 25_75, through 50_50, to 75_25. This trend is illustrated in Figure 58.

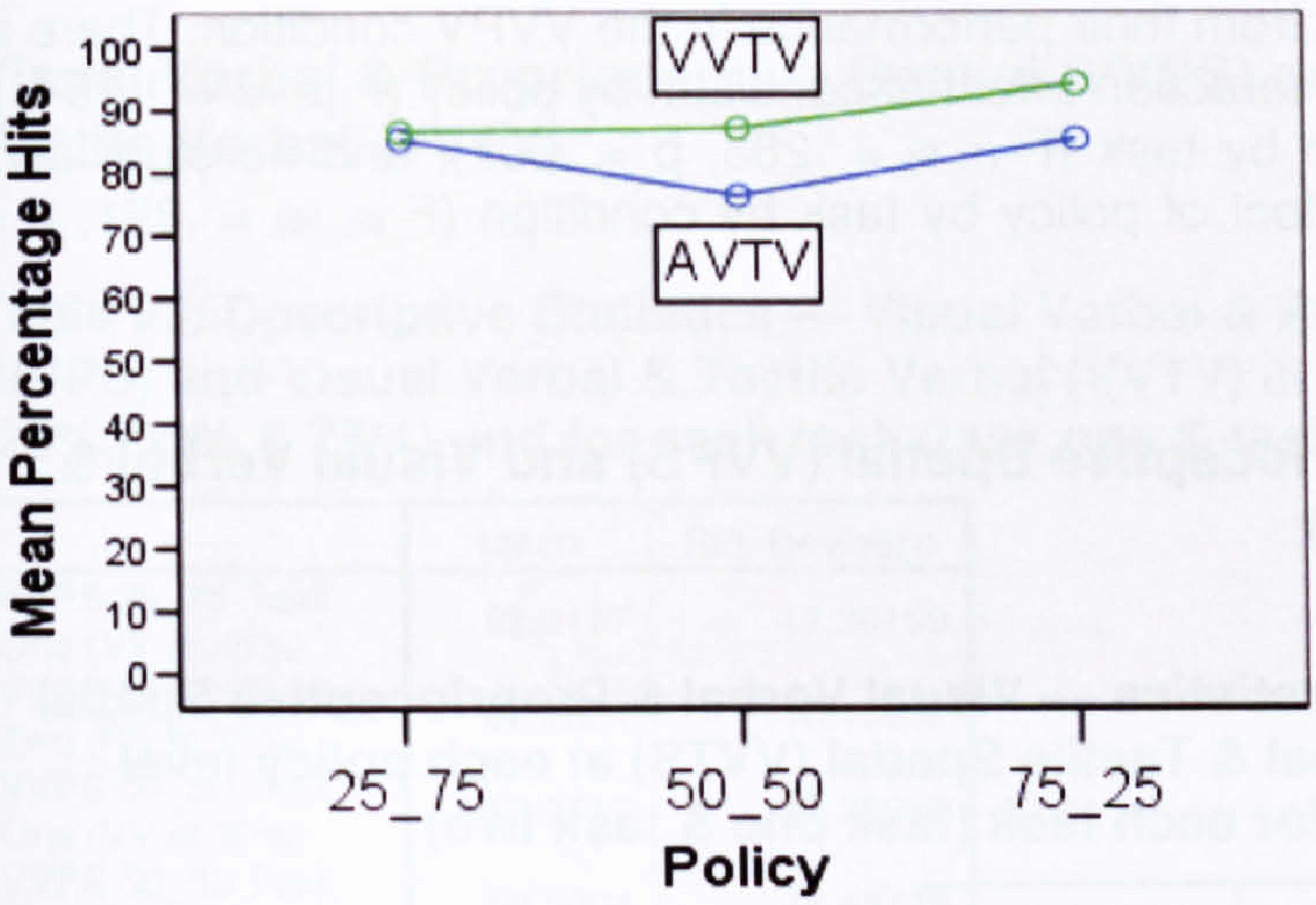


Figure 58: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — AVTV & VVTV) by POLICY (25_75%, 50_50% & 75–25%)

Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Proprioceptive Verbal (VVPV)

Table 91: Descriptive Statistics — Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Proprioceptive Verbal (VVPV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
VVPS 25_75 Task One (VV at 25%)	85.1212	17.67381
VVPS 25_75 Task Two (PS at 75%)	109.5397	112.27958
VVPS 50_50 Task One (VV at 50%)	80.2641	14.43864
VVPS 50_50 Task Two (PS at 50%)	64.7698	79.69556
VVPS 75_25 Task One (VV at 75%)	87.2814	17.59611
VVPS 75_25 Task Two (PS at 25%)	80.4841	99.83404
VVPV 25_75 Task One (VV at 25%)	89.6948	3.68989
VVPV 25_75 Task Two (PV at 75%)	106.5709	10.00224
VVPV 50_50 Task One (VV at 50%)	86.3095	7.92194
VVPV 50_50 Task Two (PV at 50%)	102.3810	19.07934
VVPV 75_25 Task One (VV at 75%)	91.1017	7.20175
VVPV 75_25 Task Two (PV at 25%)	101.9580	11.65347

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 9)} = .650$, $p = .441$). Therefore, participants' performance in the VVPS condition is not significantly different from their performance in the VVPV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 18)} = 1.154$, $p = .338$), nor of condition by task ($F_{(1, 9)} = .283$, $p = .607$), and no significant three–way interaction effect of policy by task by condition ($F_{(2, 18)} = .881$, $p = .431$).

Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Tactile Spatial (VVTS)

Table 92: Descriptive Statistics — Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std Deviation
VVPS 25_75 Task One (VV at 25%)	88.0177	17.39159
VVPS 25_75 Task Two (PS at 75%)	91.2831	110.14807
VVPS 50_50 Task One (VV at 50%)	82.3413	13.98060
VVPS 50_50 Task Two (PS at 50%)	59.5304	74.48719
VVPS 75_25 Task One (VV at 75%)	89.0224	16.45600
VVPS 75_25 Task Two (PS at 25%)	67.0701	95.58322
VVTS 25_75 Task One (VV at 25%)	58.0113	22.71002
VVTS 25_75 Task Two (TS at 75%)	50.7077	28.01816
VVTS 50_50 Task One (VV at 50%)	58.8665	20.29170
VVTS 50_50 Task Two (TS at 50%)	54.5503	32.41682
VVTS 75_25 Task One (VV at 75%)	60.1799	20.32996
VVTS 75_25 Task Two (TS at 25%)	62.5000	36.29520

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 11)} = 2.740$, $p = .126$). Therefore, participants' performance in the VVPS condition is not significantly different from their performance in the VVTS condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 22)} = 1.545$, $p = .236$), no significant two–way interaction effect of condition by task ($F_{(1, 11)} = .199$, $p = .665$), and no significant three–way interaction effect of policy by task by condition ($F_{(2, 22)} = .970$, $p = .395$).

Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Tactile Verbal (VVTV)

Table 93: Descriptive Statistics — Visual Verbal & Proprioceptive Spatial (VVPS) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
VVPS 25_75 Task One (VV at 25%)	88.0177	17.39159
VVPS 25_75 Task Two (PS at 75%)	91.2831	110.14807
VVPS 50_50 Task One (VV at 50%)	82.3413	13.98060
VVPS 50_50 Task Two (PS at 50%)	59.5304	74.48719
VVPS 75_25 Task One (VV at 75%)	89.0224	16.45600
VVPS 75_25 Task Two (PS at 25%)	67.0701	95.58322
VVTV 25_75 Task One (VV at 25%)	74.3594	16.94185
VVTV 25_75 Task Two (TV at 75%)	84.4239	29.52661
VVTV 50_50 Task One (VV at 50%)	73.3508	19.14830
VVTV 50_50 Task Two (TV at 50%)	80.0812	30.75918
VVTV 75_25 Task One (VV at 75%)	84.9947	11.57322
VVTV 75_25 Task Two (TV at 25%)	88.7472	21.28949

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 11)} = .012$, $p = .914$). Therefore, participants' performance in the VVPS condition is not significantly different from their performance in the VVTV condition. There is no significant two-way interaction effect of condition by policy ($F_{(2, 22)} = 1.085$, $p = .355$), no significant two-way interaction effect of condition by task ($F_{(1, 11)} = .693$, $p = .423$), and no significant three-way interaction effect of policy by task by condition ($F_{(2, 22)} = .402$, $p = .674$).

Visual Verbal & Proprioceptive Verbal (VVPV) and Visual Verbal & Tactile Spatial (VVTS)

Table 94: Descriptive Statistics — Visual Verbal & Proprioceptive Verbal (VVPV) and Visual Verbal & Tactile Spatial (VVTS) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
VVPV 25_75 Task One (VV at 25%)	70.0780	37.98057
VVPV 25_75 Task Two (PV at 75%)	80.1389	17.79676
VVPV 50_50 Task One (VV at 50%)	78.8499	18.85530
VVPV 50_50 Task Two (PV at 50%)	63.6111	29.95753
VVPV 75_25 Task One (VV at 75%)	73.6842	36.84211
VVPV 75_25 Task Two (PV at 25%)	88.8889	10.18350
VVTS 25_75 Task One (VV at 25%)	131.5789	147.36842
VVTS 25_75 Task Two (TS at 75%)	26.6865	28.23514
VVTS 50_50 Task One (VV at 50%)	127.0175	115.43646
VVTS 50_50 Task Two (TS at 50%)	33.5317	31.49891
VVTS 75_25 Task One (VV at 75%)	143.1579	170.49057
VVTS 75_25 Task Two (TS at 25%)	31.8452	43.37791

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1, 2)} = .024$, $p = .890$). Therefore, participants' performance in the VVPV condition is not significantly different from their performance in the VVTS condition. There is no significant two-way interaction effect of condition by policy ($F_{(2, 4)} = .050$, $p = .952$), no significant two-way interaction effect of condition by task ($F_{(1, 2)} = 2.883$, $p = .232$), and no significant three-way interaction effect of policy by task by condition ($F_{(2, 4)} = 4.965$, $p = .082$).

Visual Verbal & Proprioceptive Verbal (VVPV) and Visual Verbal & Tactile Verbal (VVTV)

Table 95: Descriptive Statistics — Visual Verbal & Proprioceptive Verbal (VVPV) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
VVPV 25_75 Task One (VV at 25%)	91.3701	46.30001
VVPV 25_75 Task Two (PV at 75%)	86.6548	15.63157
VVPV 50_50 Task One (VV at 50%)	113.7761	73.52395
VVPV 50_50 Task Two (PV at 50%)	82.1926	35.27277
VVPV 75_25 Task One (VV at 75%)	119.5489	89.85670
VVPV 75_25 Task Two (PV at 25%)	94.7619	11.08614
VVTV 25_75 Task One (VV at 25%)	102.1136	47.60708
VVTV 25_75 Task Two (TV at 75%)	143.0281	89.14621
VVTV 50_50 Task One (VV at 50%)	100.3676	39.99537
VVTV 50_50 Task Two (TV at 50%)	144.6337	101.15419
VVTV 75_25 Task One (VV at 75%)	108.3041	51.43440
VVTV 75_25 Task Two (TV at 25%)	146.4103	114.65646

The within-subjects ANOVA revealed that there is no effect of condition ($F_{(1,4)} = 2.640$, $p = .111$). Therefore, participants' performance in the VVPV condition is not significantly different from their performance in the VVTV condition. There is no two-way interaction effect of condition by policy ($F_{(1.023, 4.091)} = 1.490$, $p = .289$), nor of condition by task ($F_{(1, 4)} = 1.615$, $p = .273$), and no three-way interaction effect of policy by task by condition ($F_{(2, 8)} = .736$, $p = .509$). There is a significant interaction between condition and policy ($F_{(1, 4)} = 17.306$, $p = .014$). VVPV hits increase from 25_75 and 50_50, to 75_25. VVTV hits increase from 25_75, through 50_50, to 75_25. This trend is illustrated in Figure 59.

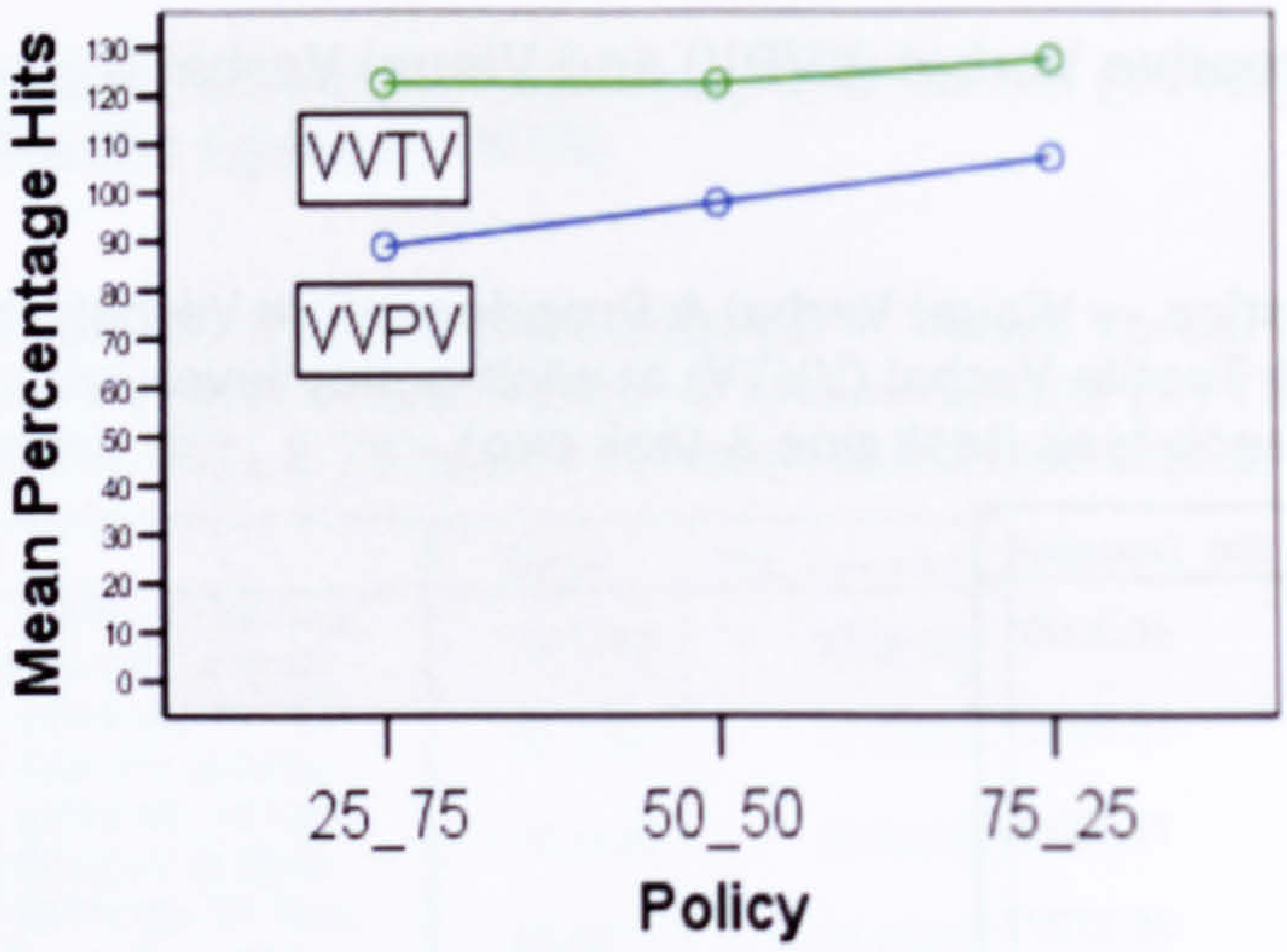


Figure 59: Diagrammatic representation of the interaction term CONDITION (Input Sense & Input Code — VVPV & VVTV) by POLICY (25_75%, 50_50% & 75–25%)

Visual Verbal & Tactile Spatial (VVTS) and Visual Verbal & Tactile Verbal (VVTV)

Table 96: Descriptive Statistics — Visual Verbal & Tactile Spatial (VVTS) and Visual Verbal & Tactile Verbal (VVTV) at each policy level (25%, 50% & 75%) and for each task (task one & task two)

	Mean	Std. Deviation
VVTS 25_75 Task One (VV at 25%)	73.5949	59.79772
VVTS 25_75 Task Two (TS at 75%)	55.9079	29.45747
VVTS 50_50 Task One (VV at 50%)	70.8690	50.87060
VVTS 50_50 Task Two (TS at 50%)	50.9368	29.36762
VVTS 75_25 Task One (VV at 75%)	73.2323	70.36225
VVTS 75_25 Task Two (TS at 25%)	62.8180	37.26119
VVTV 25_75 Task One (VV at 25%)	72.3598	23.42532
VVTV 25_75 Task Two (TV at 75%)	82.3353	36.46369
VVTV 50_50 Task One (VV at 50%)	73.1452	19.85578
VVTV 50_50 Task Two (TV at 50%)	83.8325	30.48743
VVTV 75_25 Task One (VV at 75%)	84.1597	11.20194
VVTV 75_25 Task Two (TV at 25%)	87.0893	29.59681

The within–subjects ANOVA revealed that there is no effect of condition ($F_{(1, 17)} = 3.641$, $p = .073$). Therefore, participants' performance in the VVTS condition is not significantly different from their performance in the VVTV condition. There is no significant two–way interaction effect of condition by policy ($F_{(2, 34)} = .479$, $p = .624$), no significant two–way interaction effect of condition by task ($F_{(1, 17)} = 2.584$, $p = .126$), and no significant three–way interaction effect of policy by task by condition ($F_{(2, 34)} = 1.393$, $p = .262$).

Summary of Results

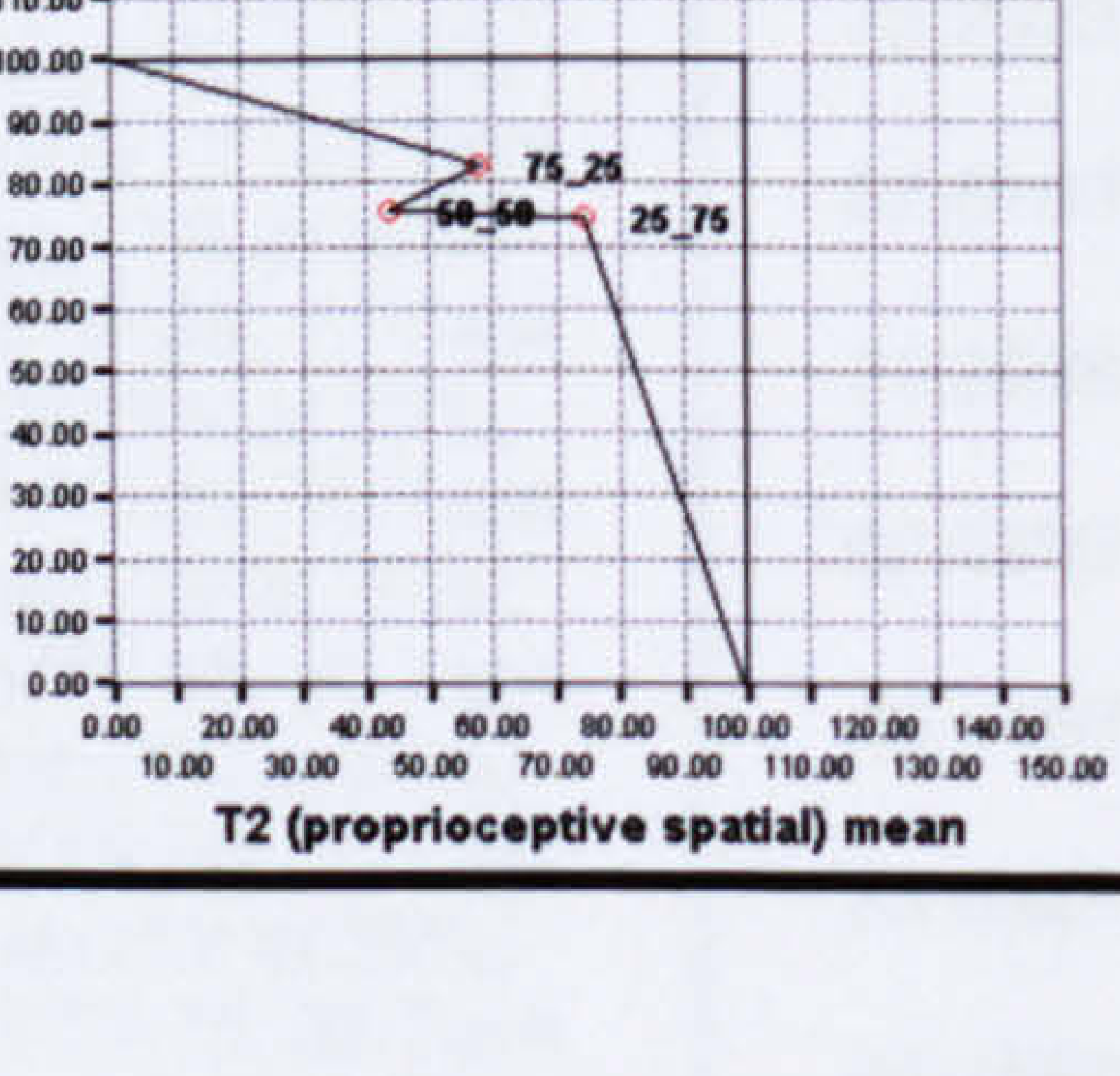
Table 97 summarises the results of the ANOVA tests with regards to the effect CONDITION (input sense and input code). As in Study One, it shows which conditions (which combinations of input sense and input code) were significantly different from one another and which were not. Each comparison is accompanied by snapshot reminders of the relevant POC curves.

Six comparisons yielded significant differences, including:

- Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Spatial (AVTS)
- Auditory Verbal & Proprioceptive Verbal (AVPV) and Auditory Verbal & Tactile Verbal (AVTV)
- Auditory Verbal & Proprioceptive Verbal (AVPV) and Visual Verbal & Tactile Spatial (VVTS)
- Auditory Verbal & Tactile Spatial (AVTS) and Auditory Verbal & Tactile Verbal (AVTV)
- Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Proprioceptive Verbal (VVPV)
- Auditory Verbal & Tactile Spatial (AVTS) and Visual Verbal & Tactile Verbal (VVTV)

The remaining twenty two comparisons yielded non–significant differences.

Table 97: Study Two Summary of Results — Effect of CONDITION

<table>
<tr><th colspan="3">EFFECT OF CONDITION</th></tr>
<tr><td colspan="2">COMPARISON</td><td>SIGNIFICANCE OF DIFFERENCE</td></tr>
<tr><td>AVPS

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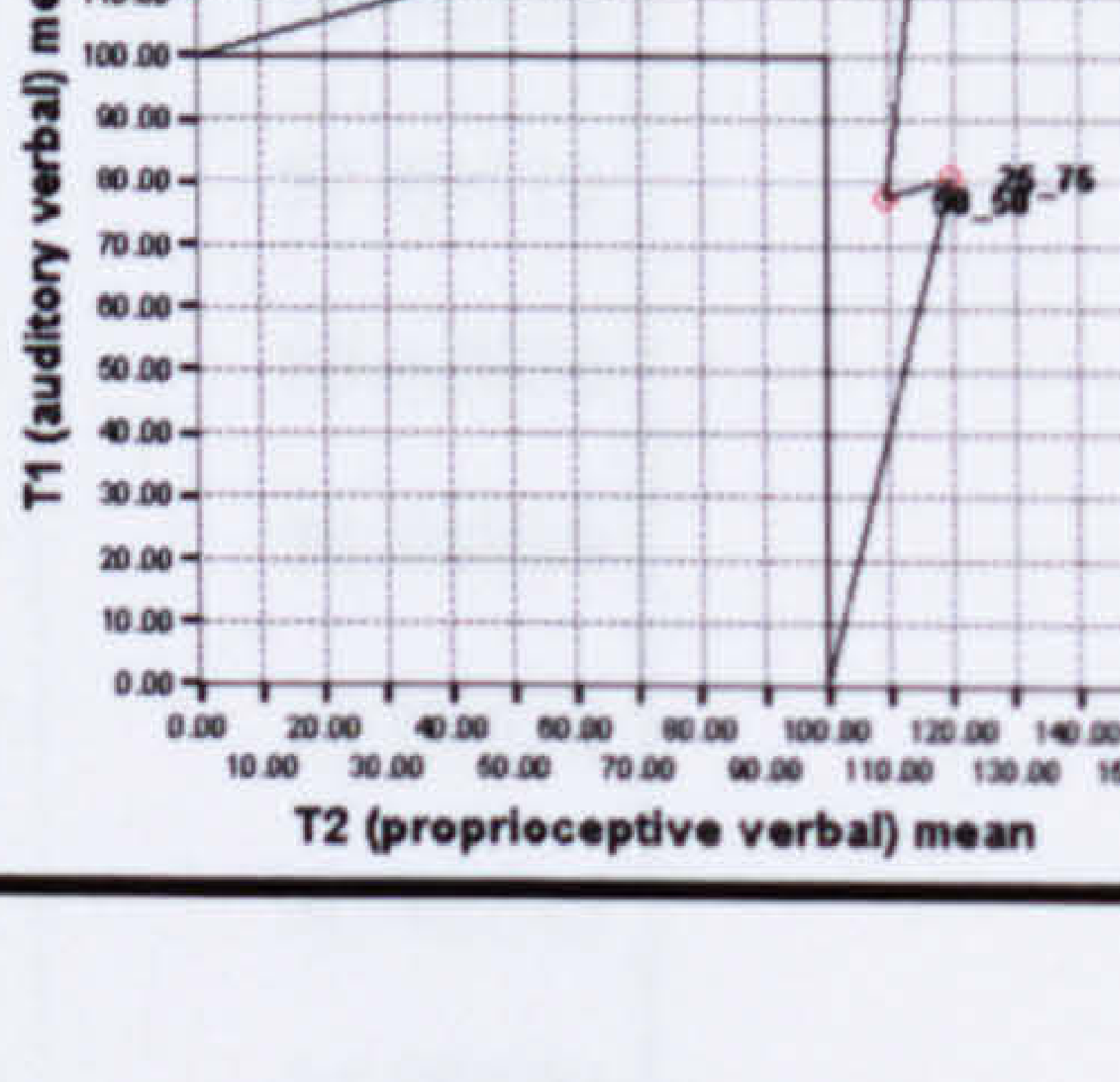
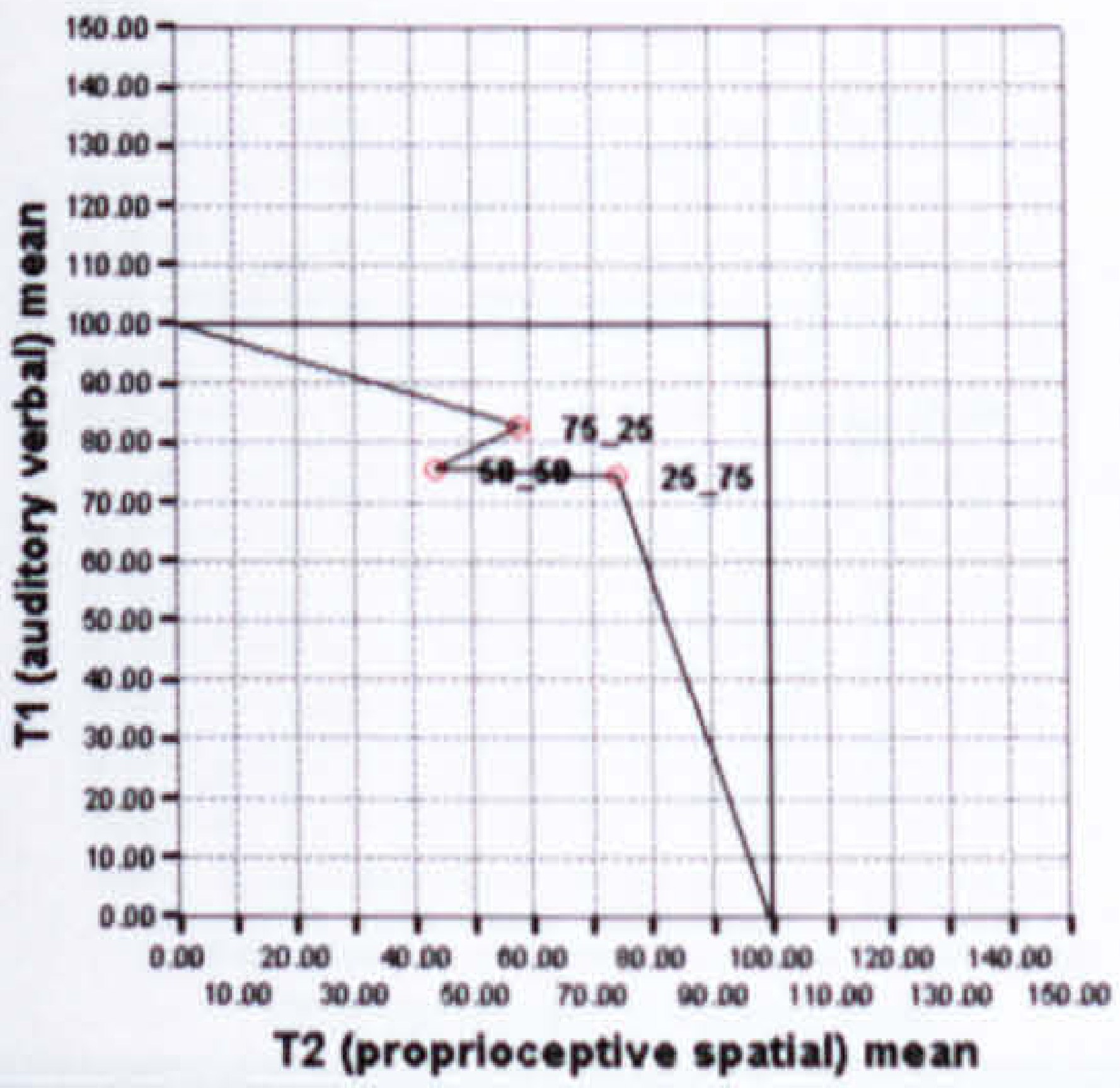
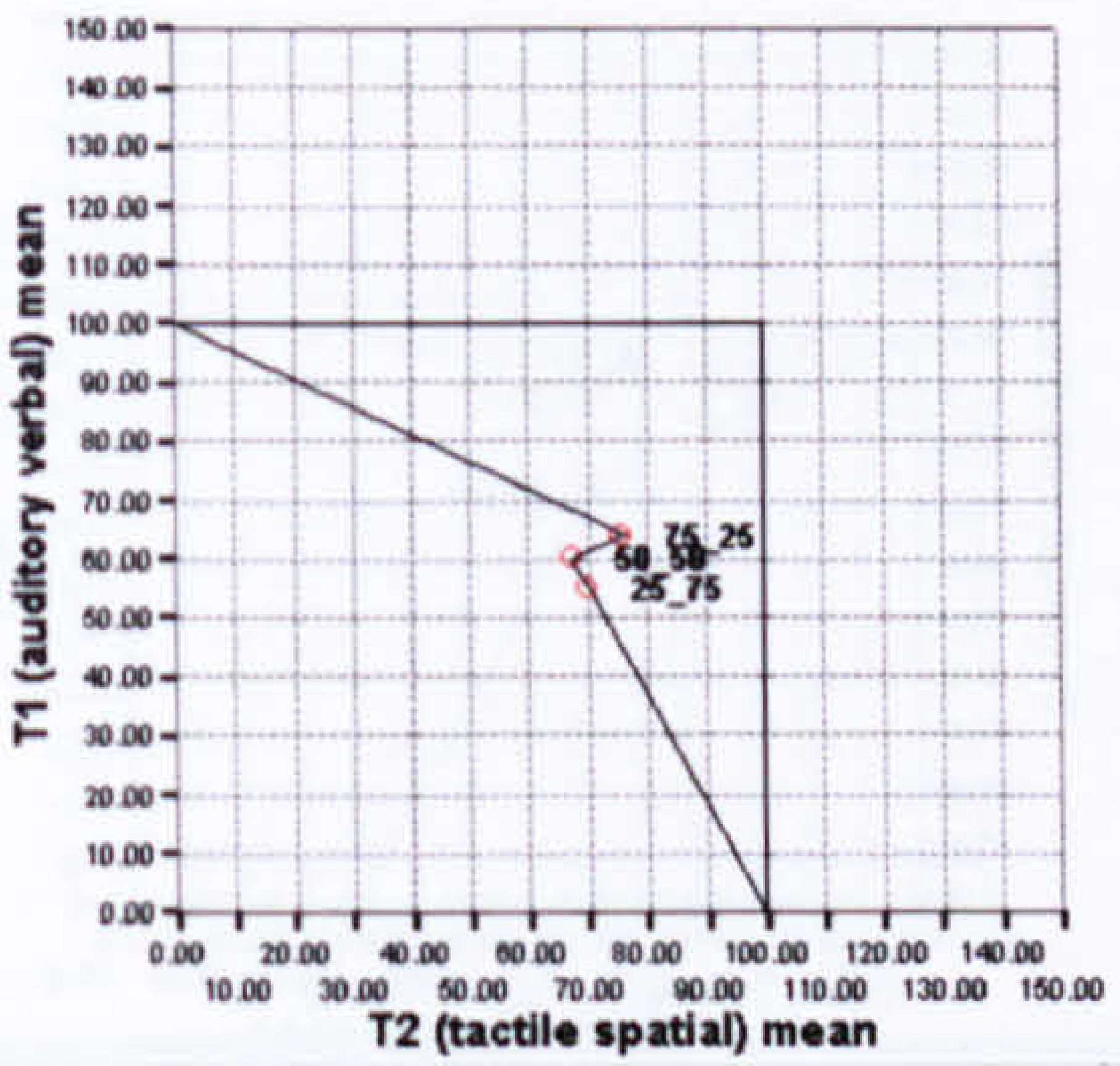
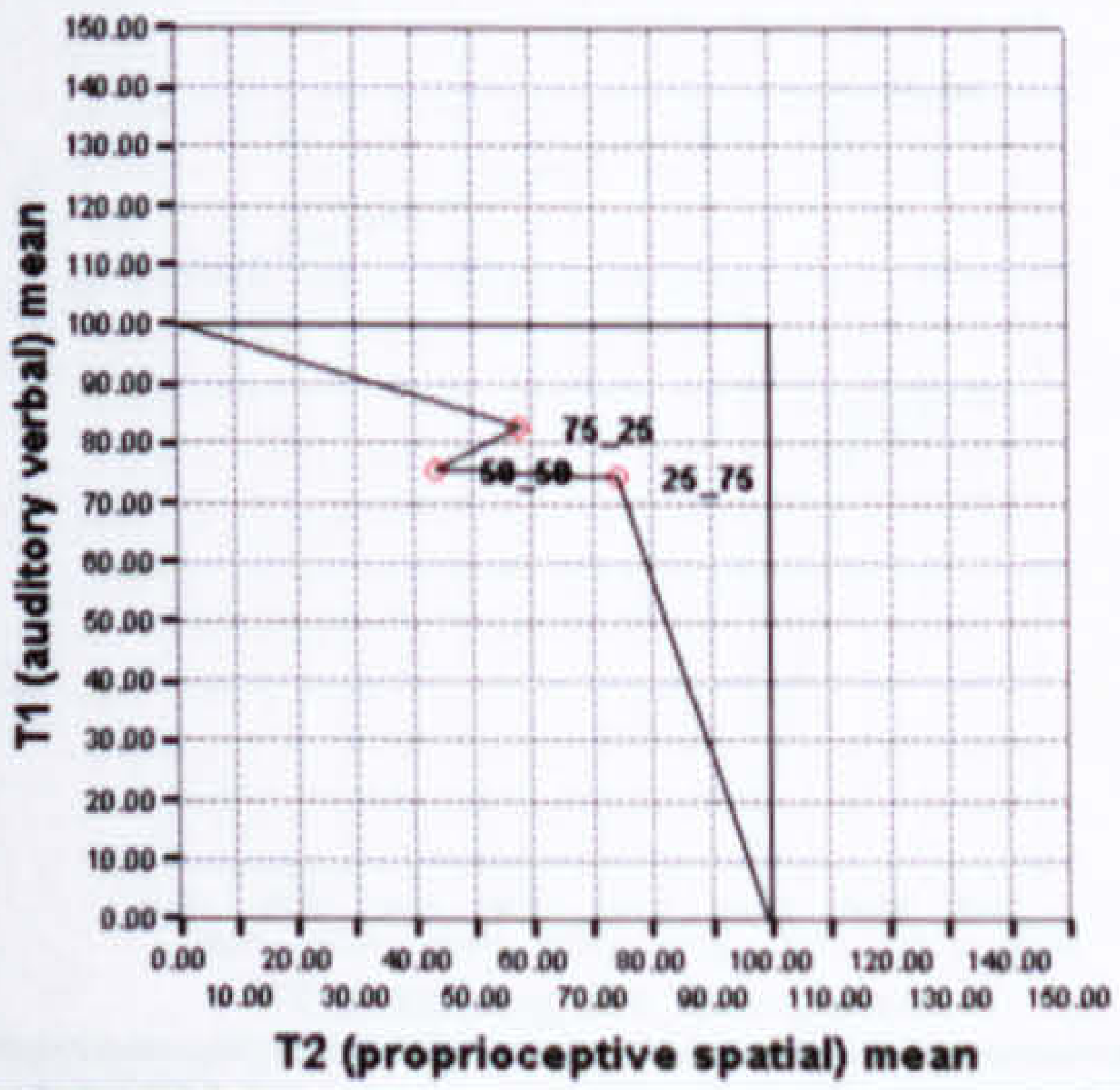
<td>AVPV

</td>
<td>Not Significant</td></tr>
</table>

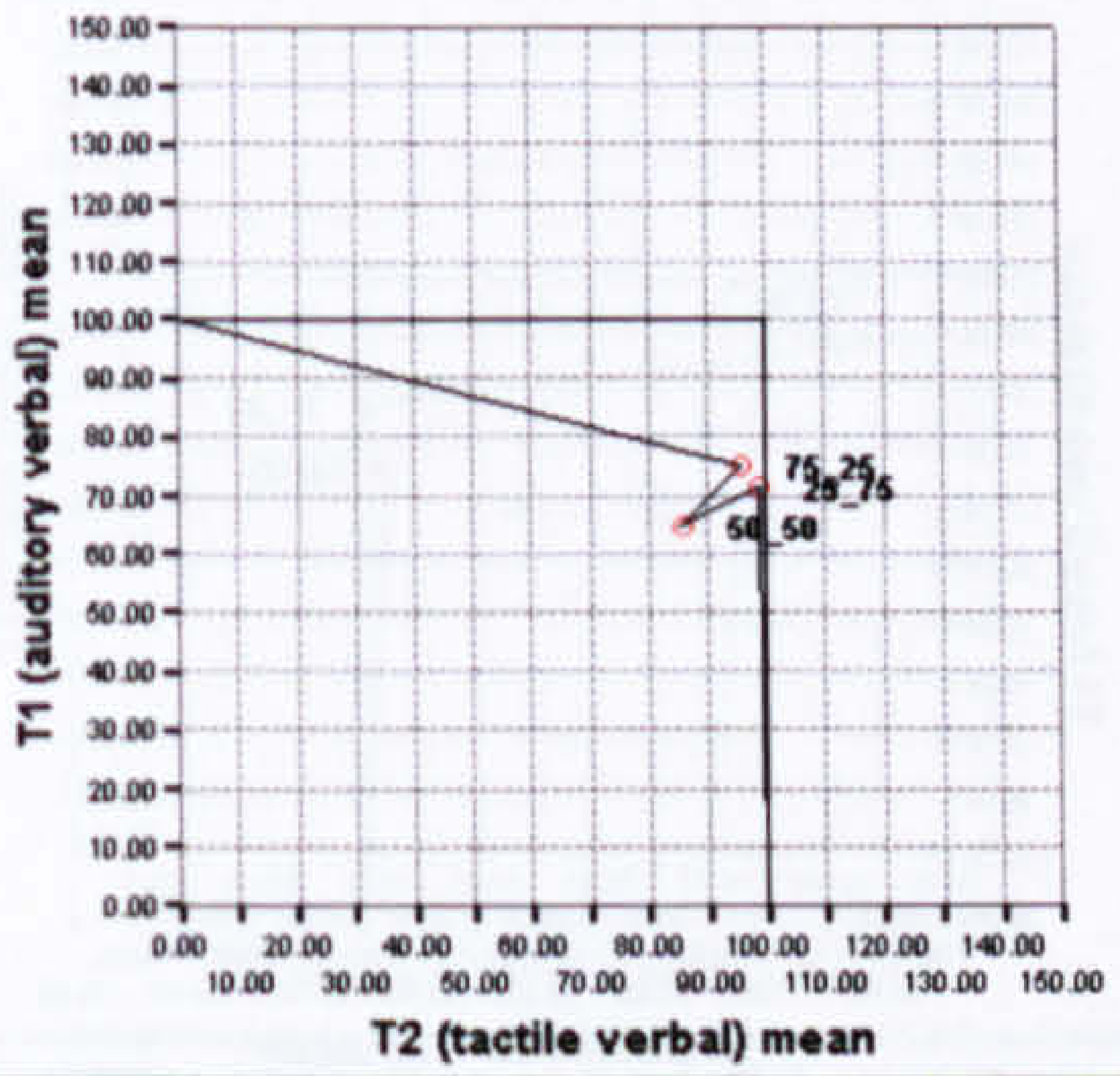
AVPS **AVTS** **Not Significant**



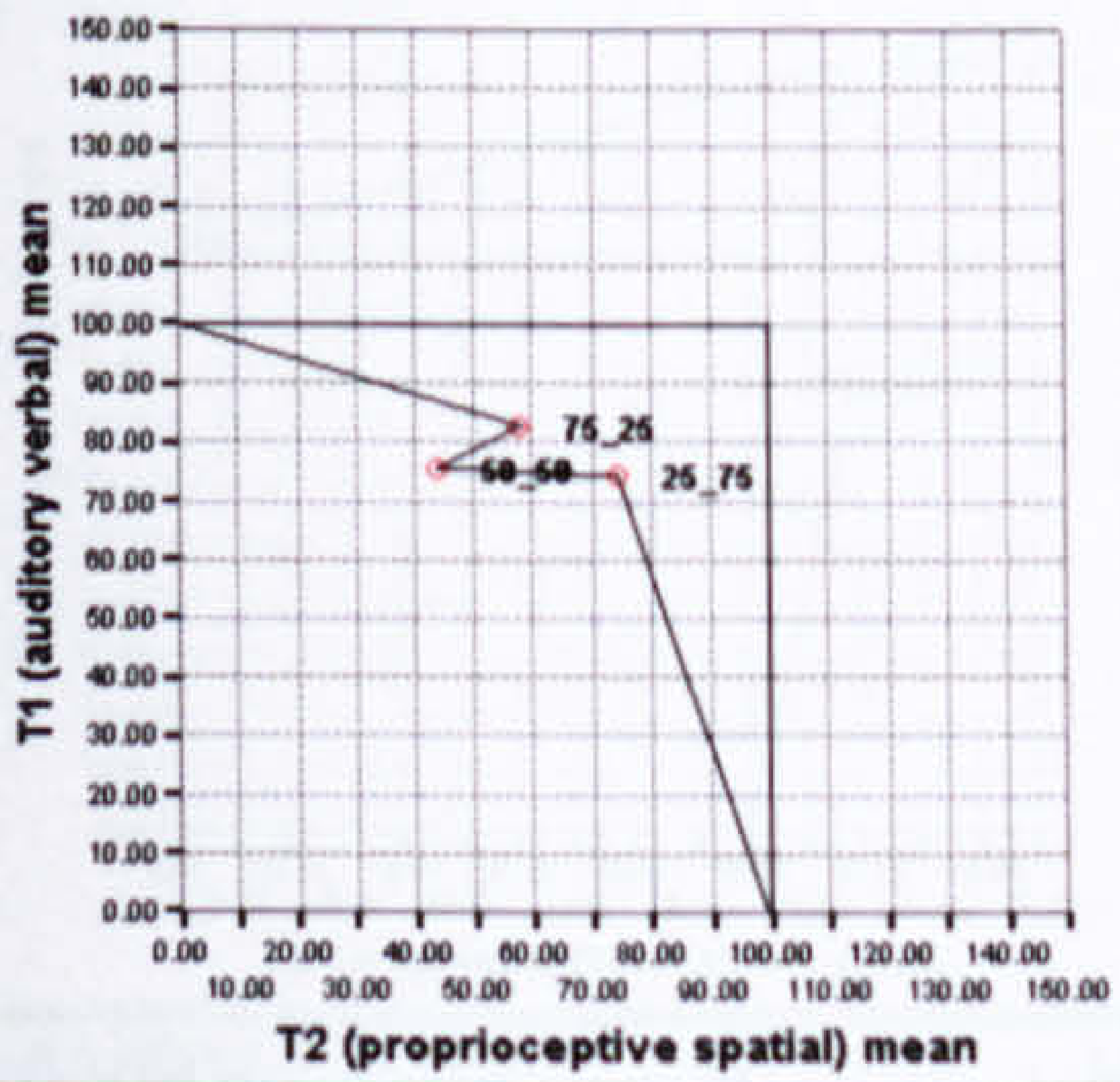


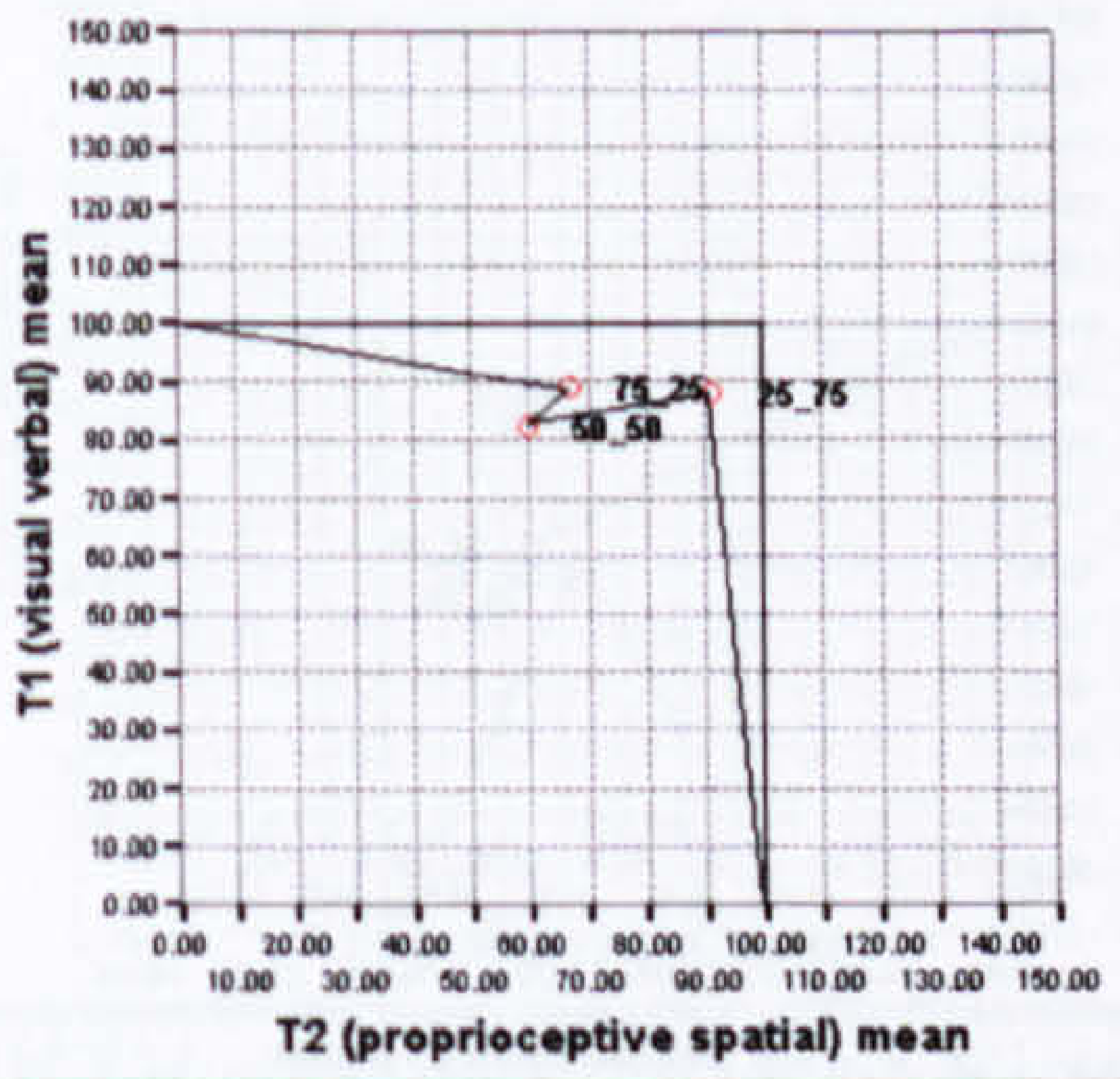
AVPS **AVTV** **Not Significant**



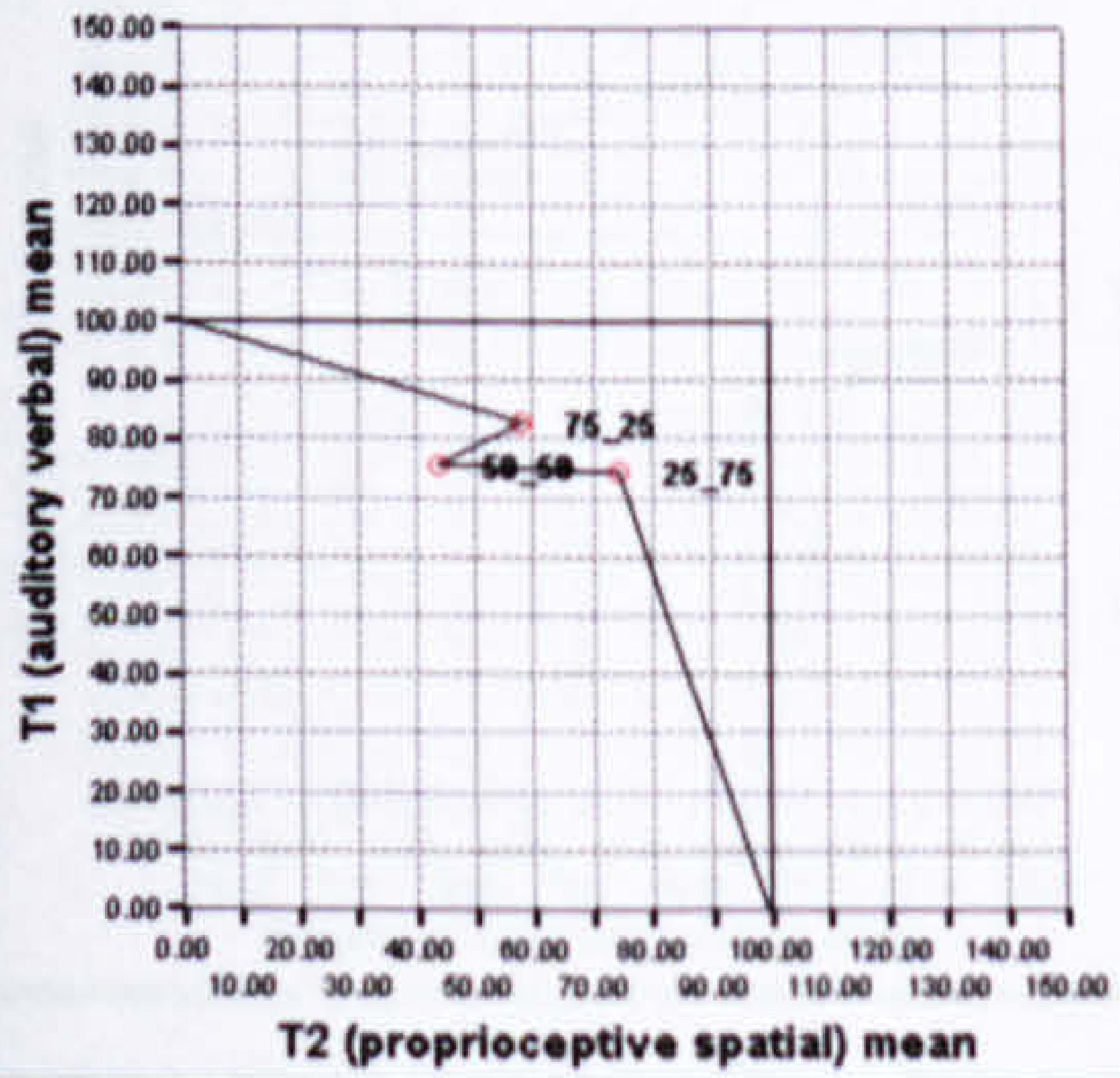


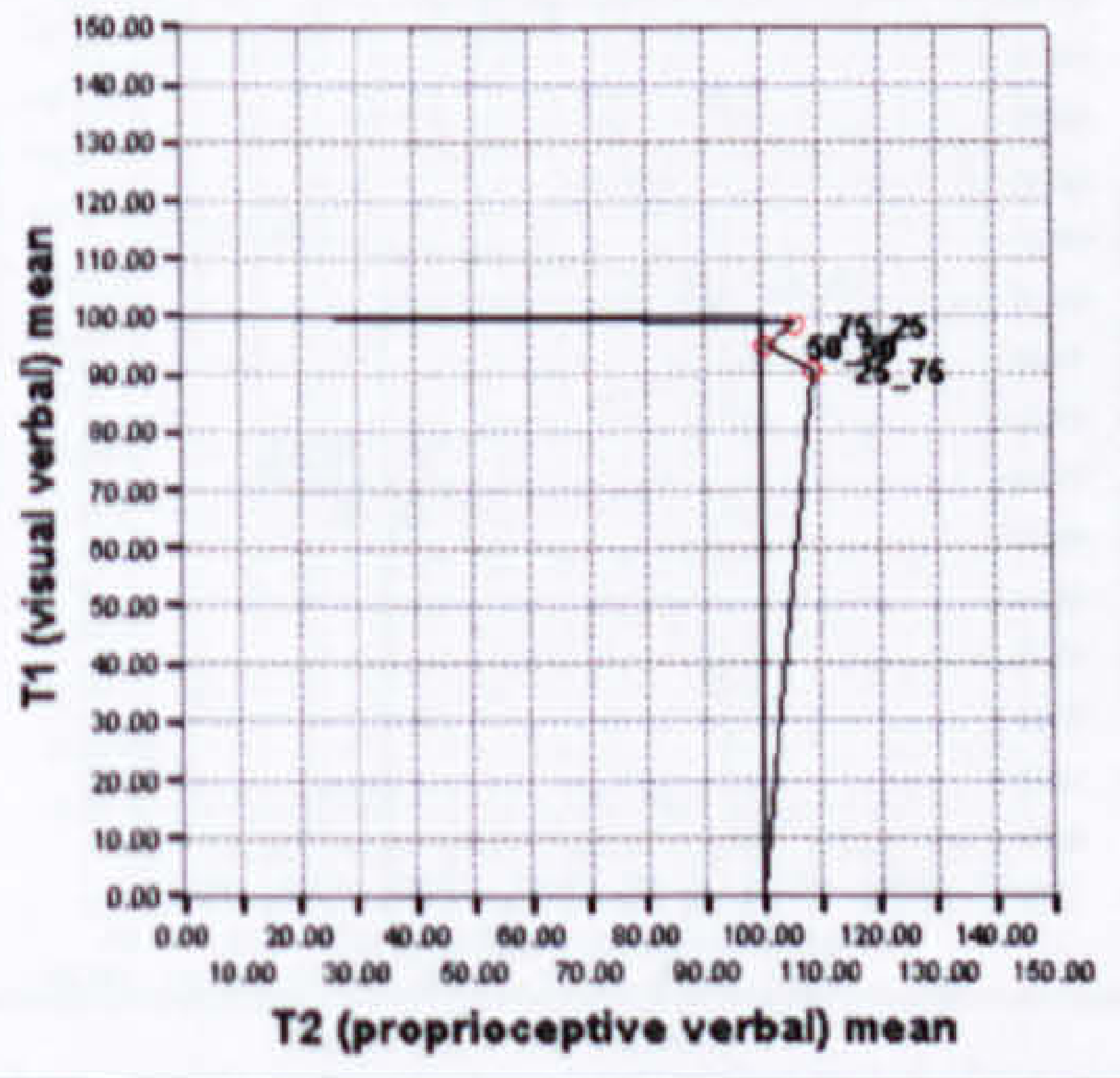
AVPS **VVPS** **Not Significant**



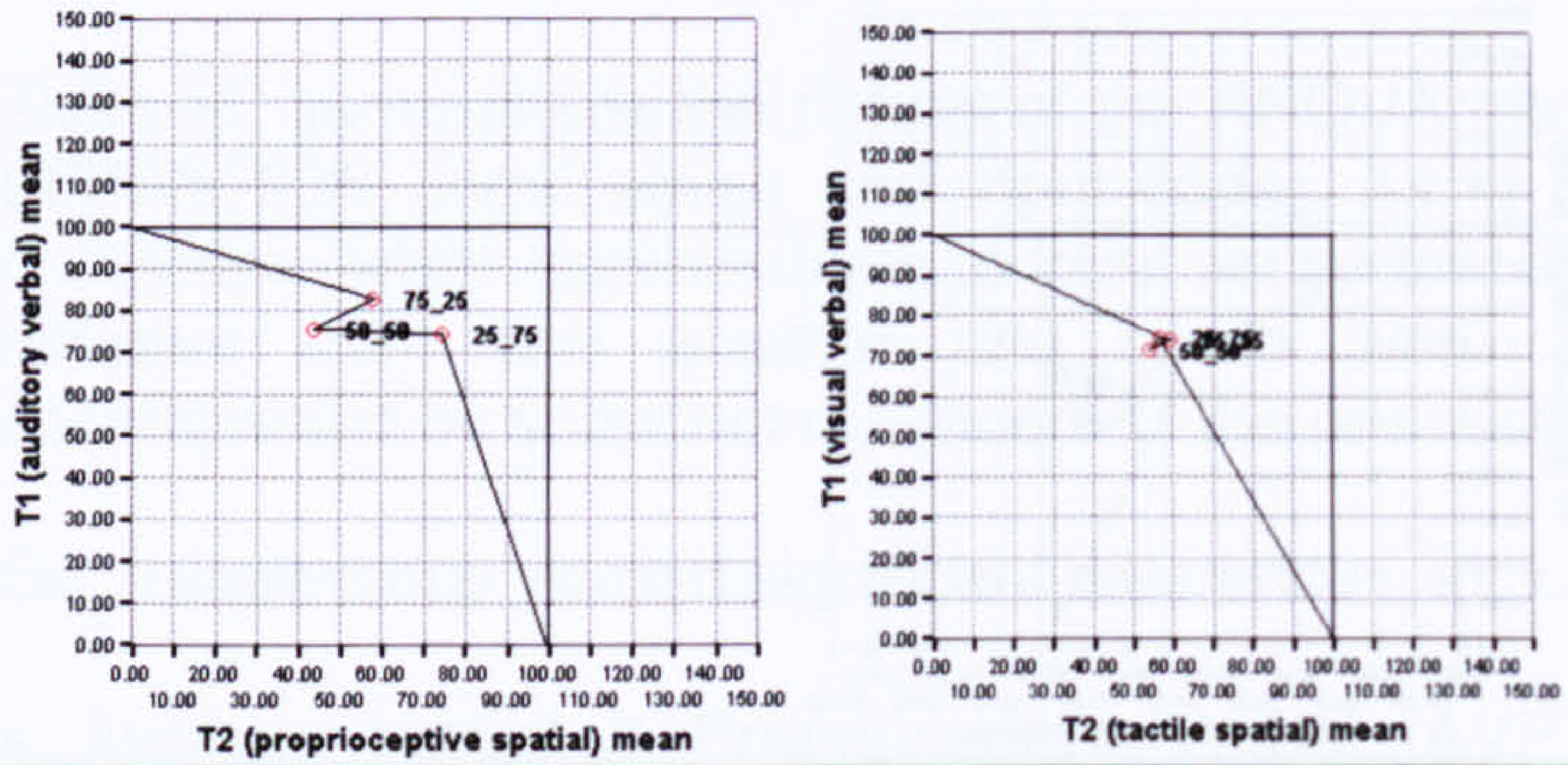


AVPS **VVPV** **Not Significant**

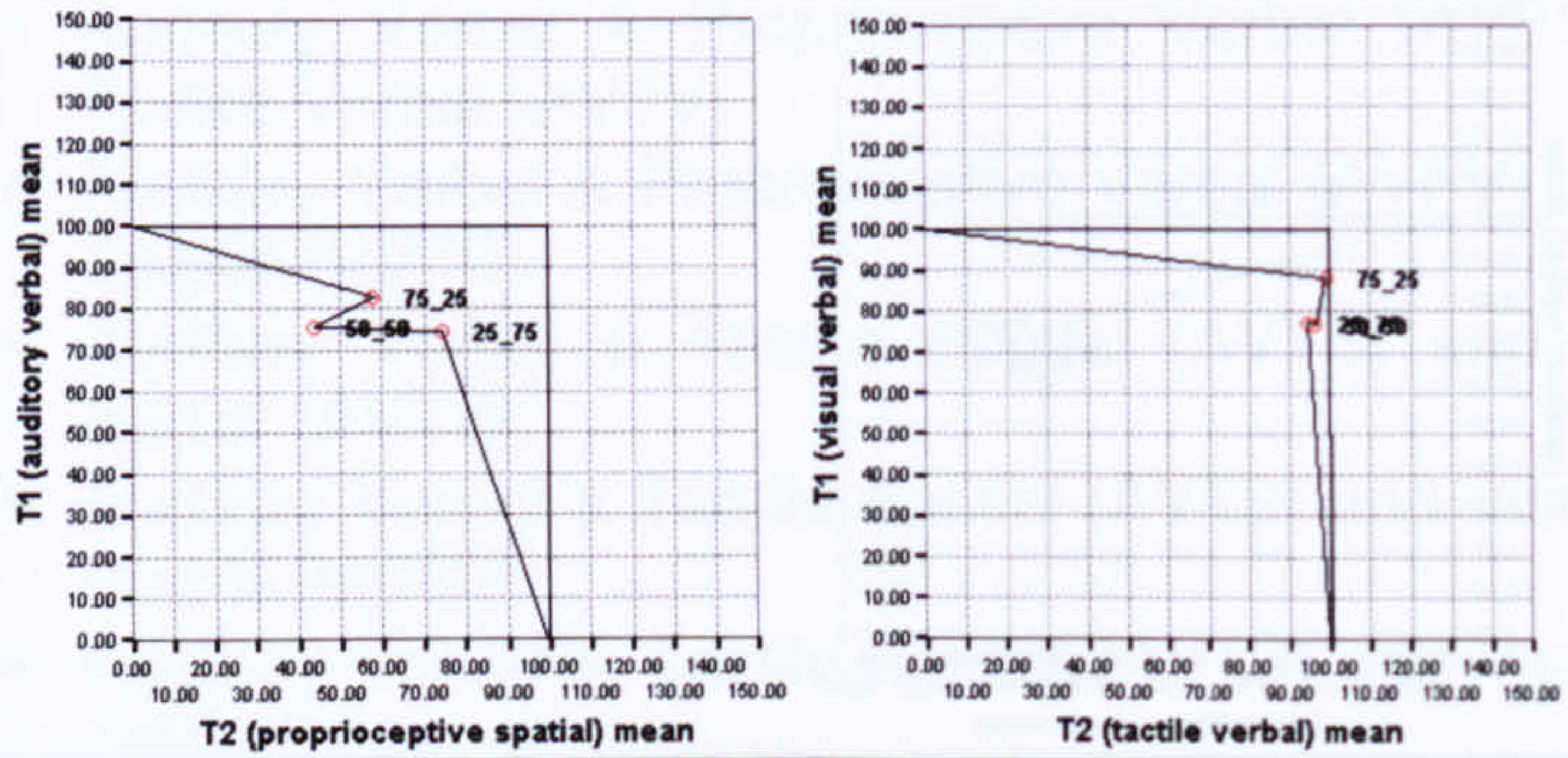




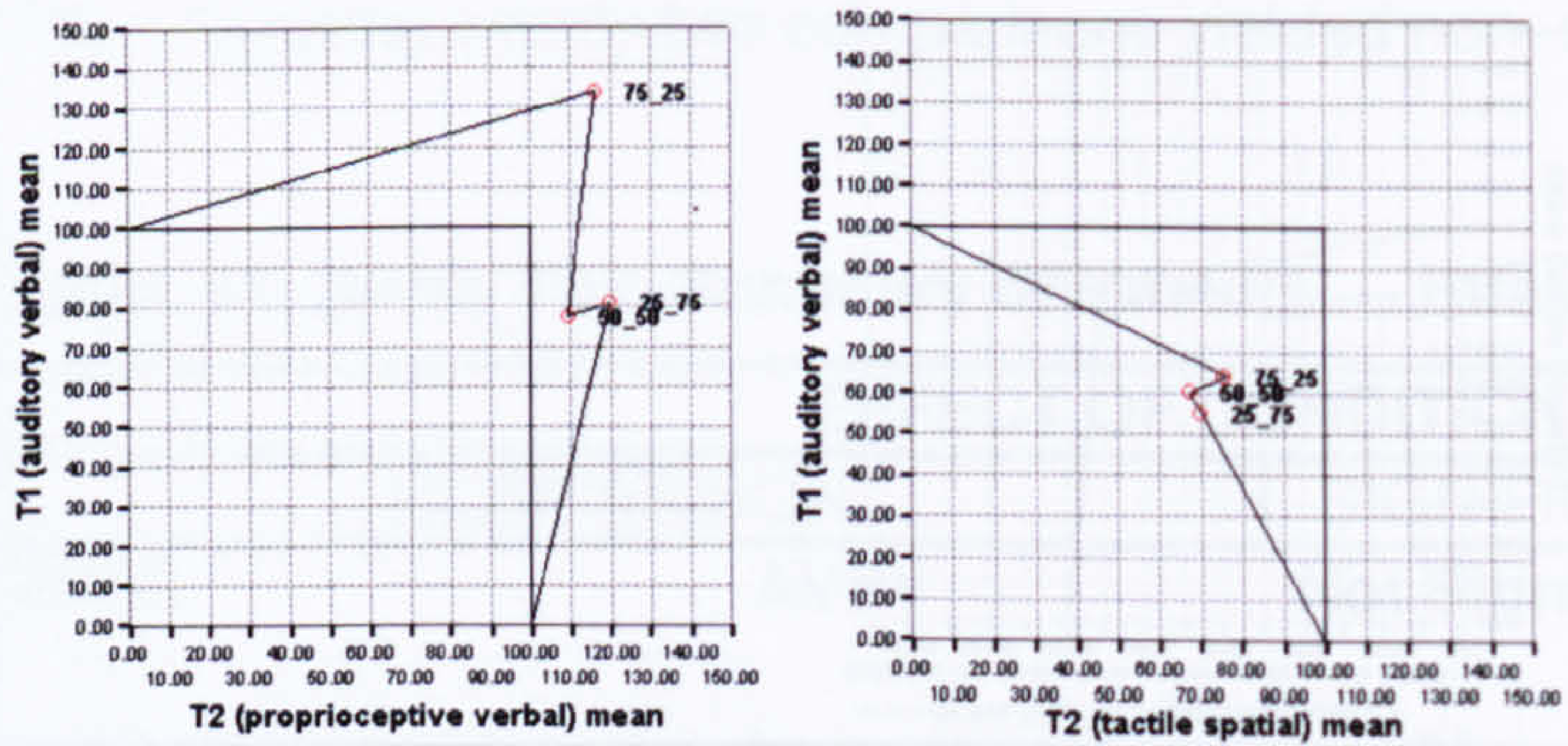
AVPS **VVTS** **Not Significant**



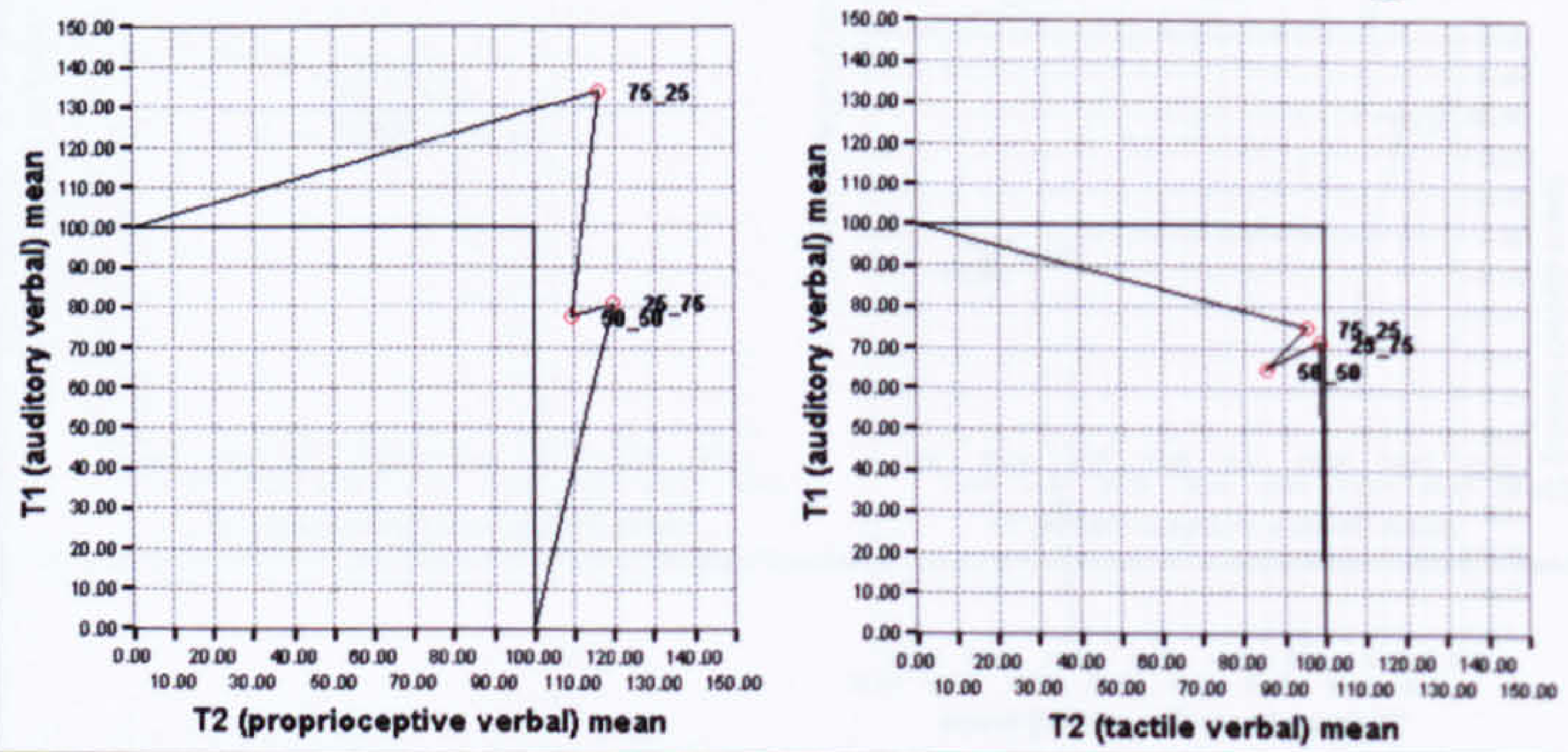
AVPS **VVTV** **Not Significant**



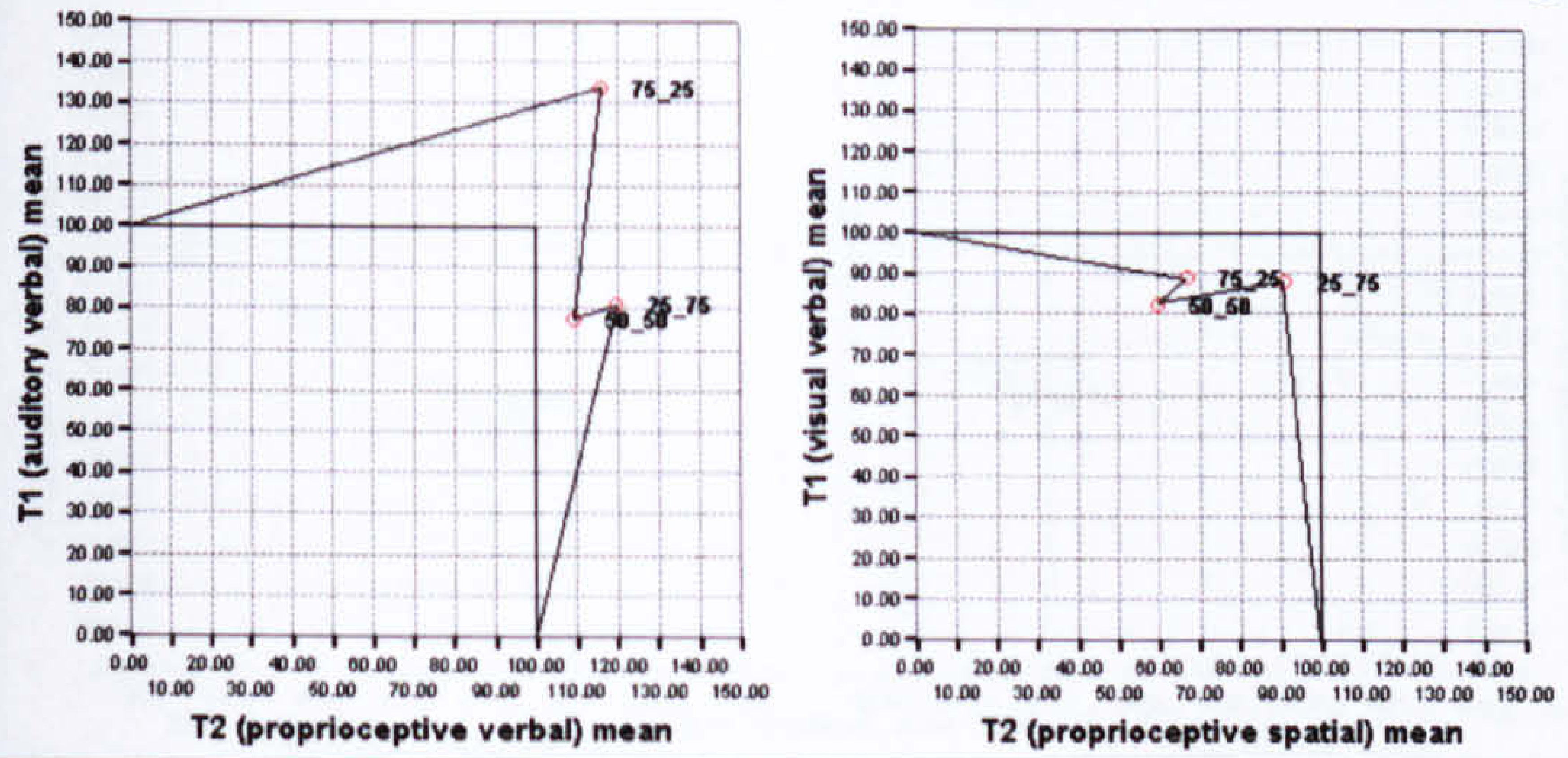
AVPV **AVTS** **Significant**



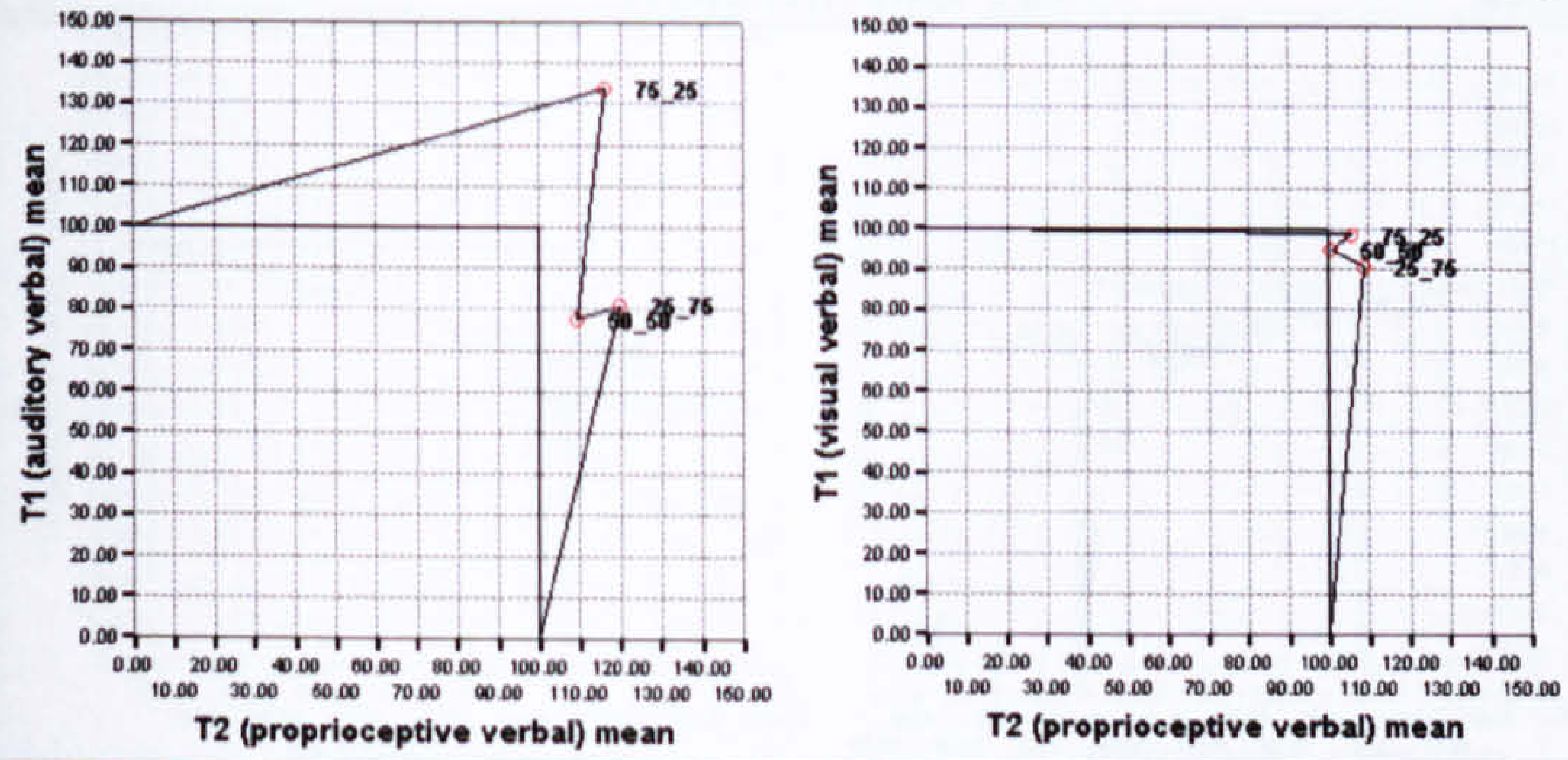
AVPV **AVTV** **Significant**



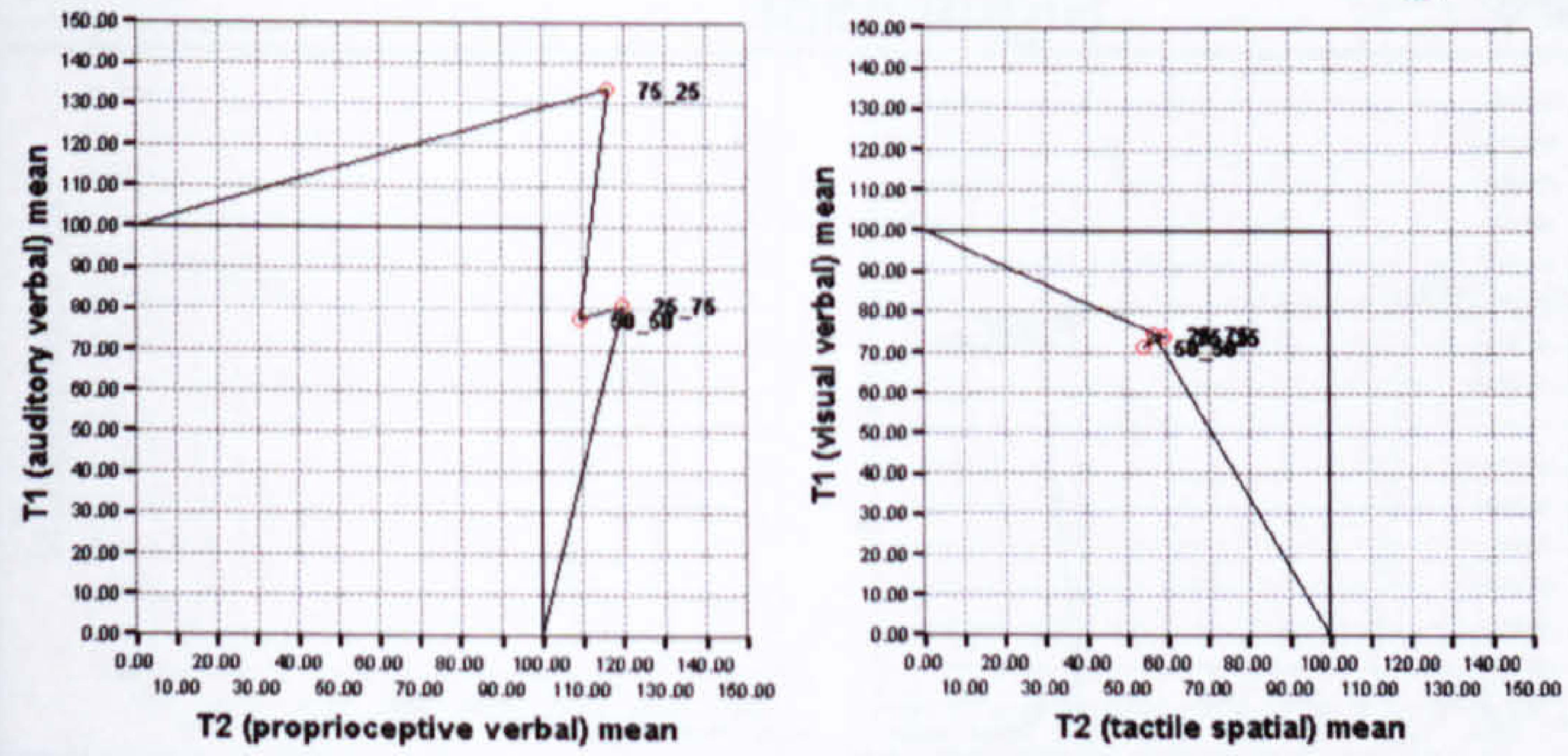
AVPV **VVPS** **Not Significant**



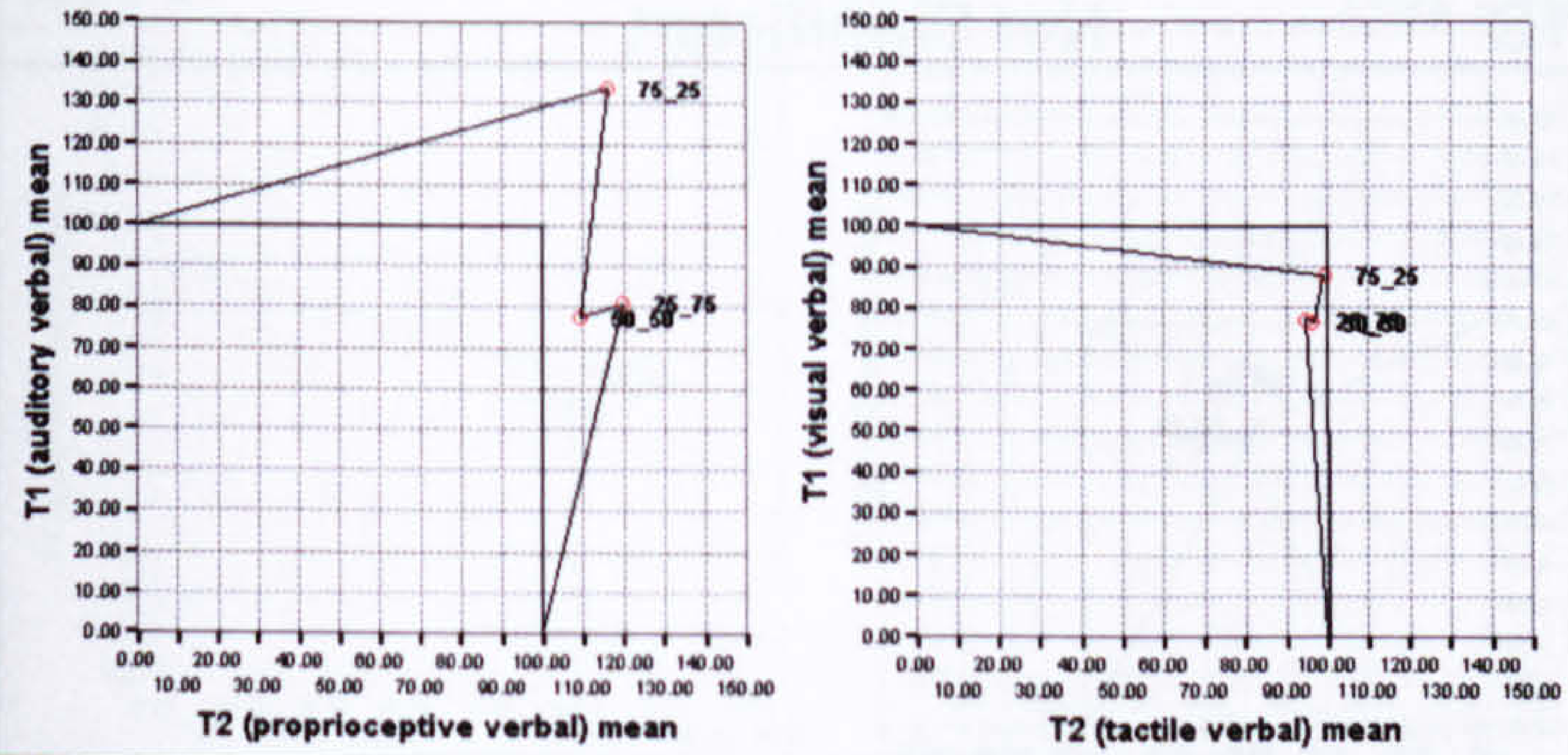
AVPV **VVPV** **Not Significant**



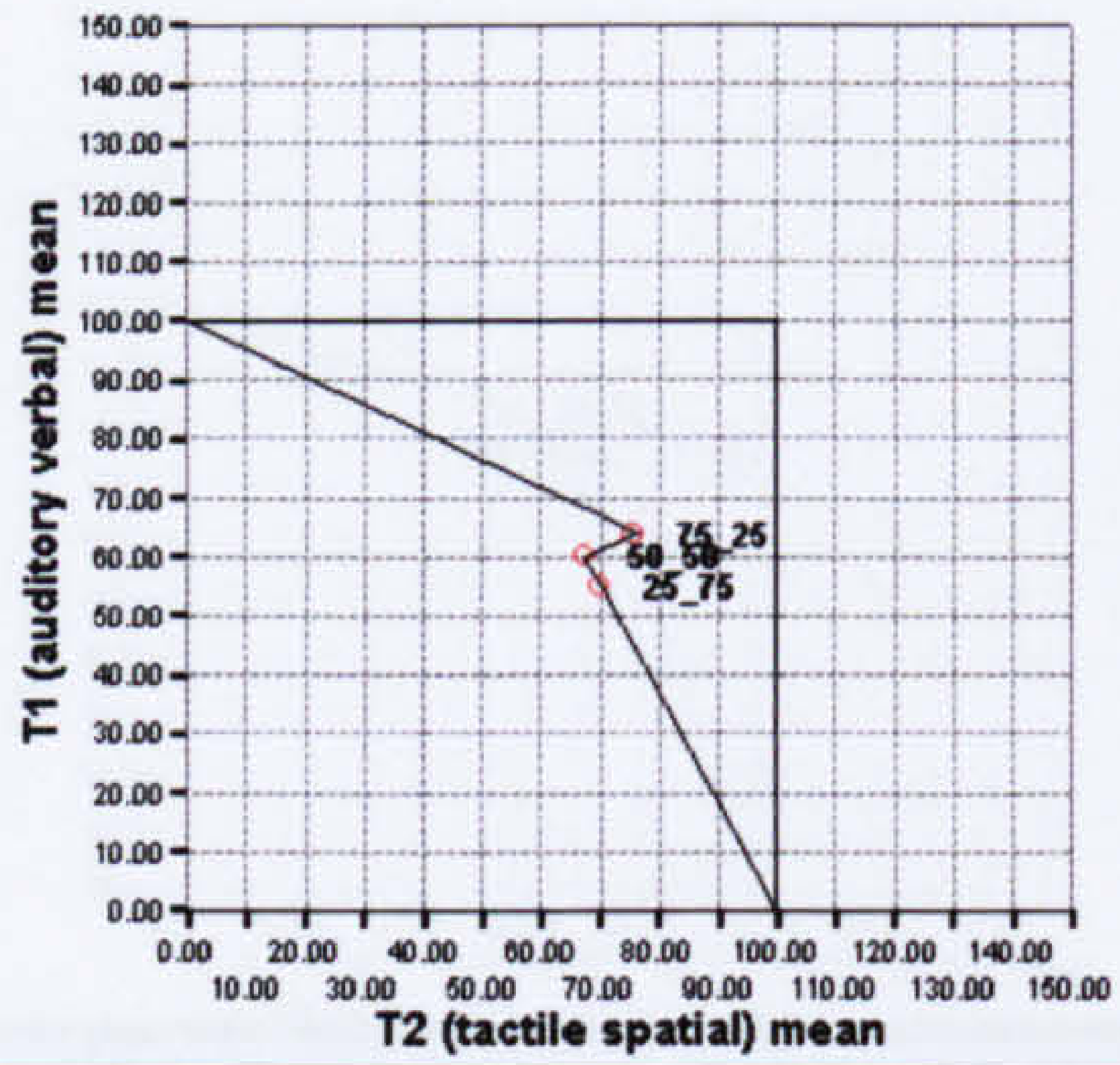
AVPV **VVTS** **Significant**

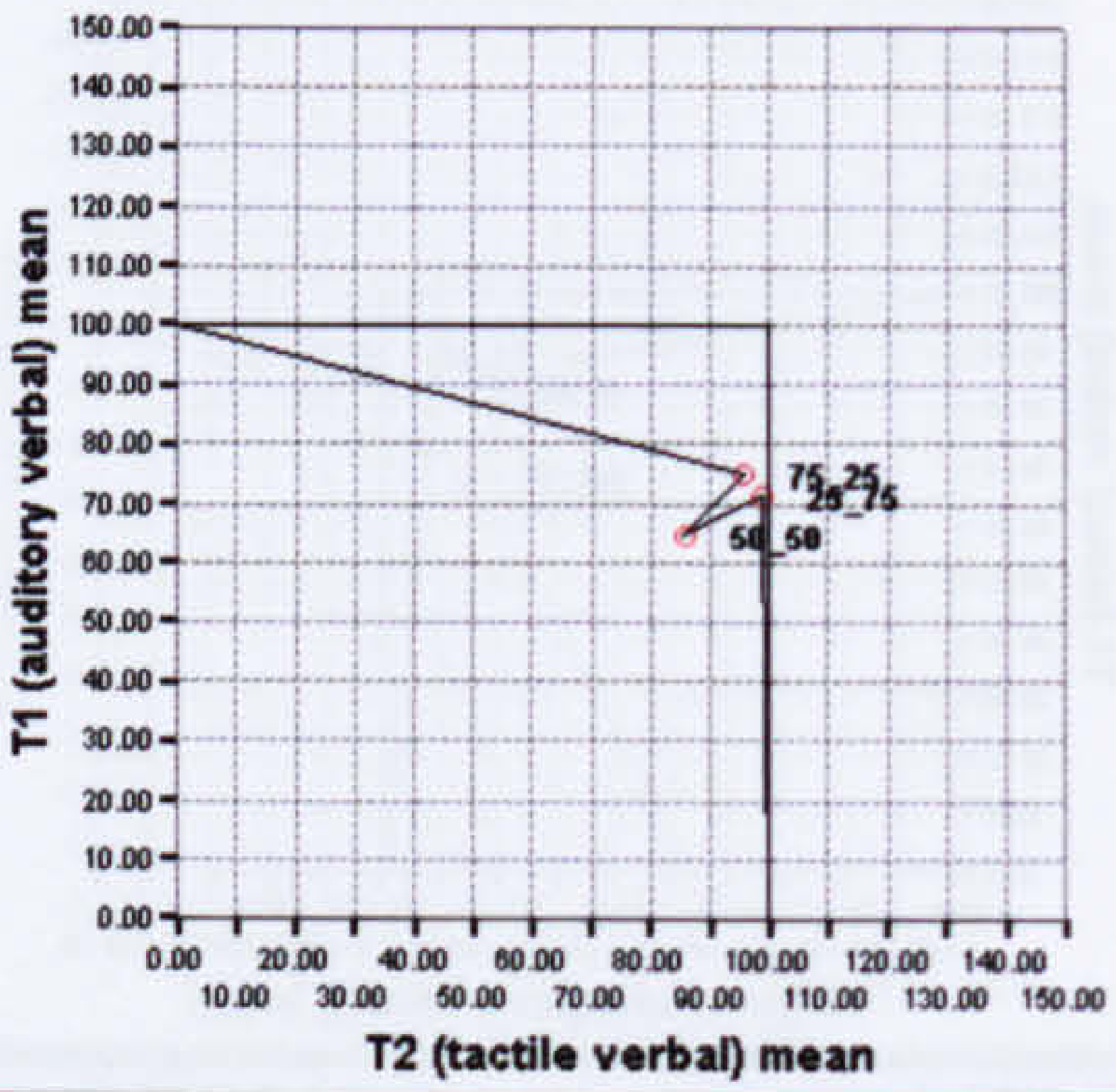


AVPV **VVTV** **Not Significant**

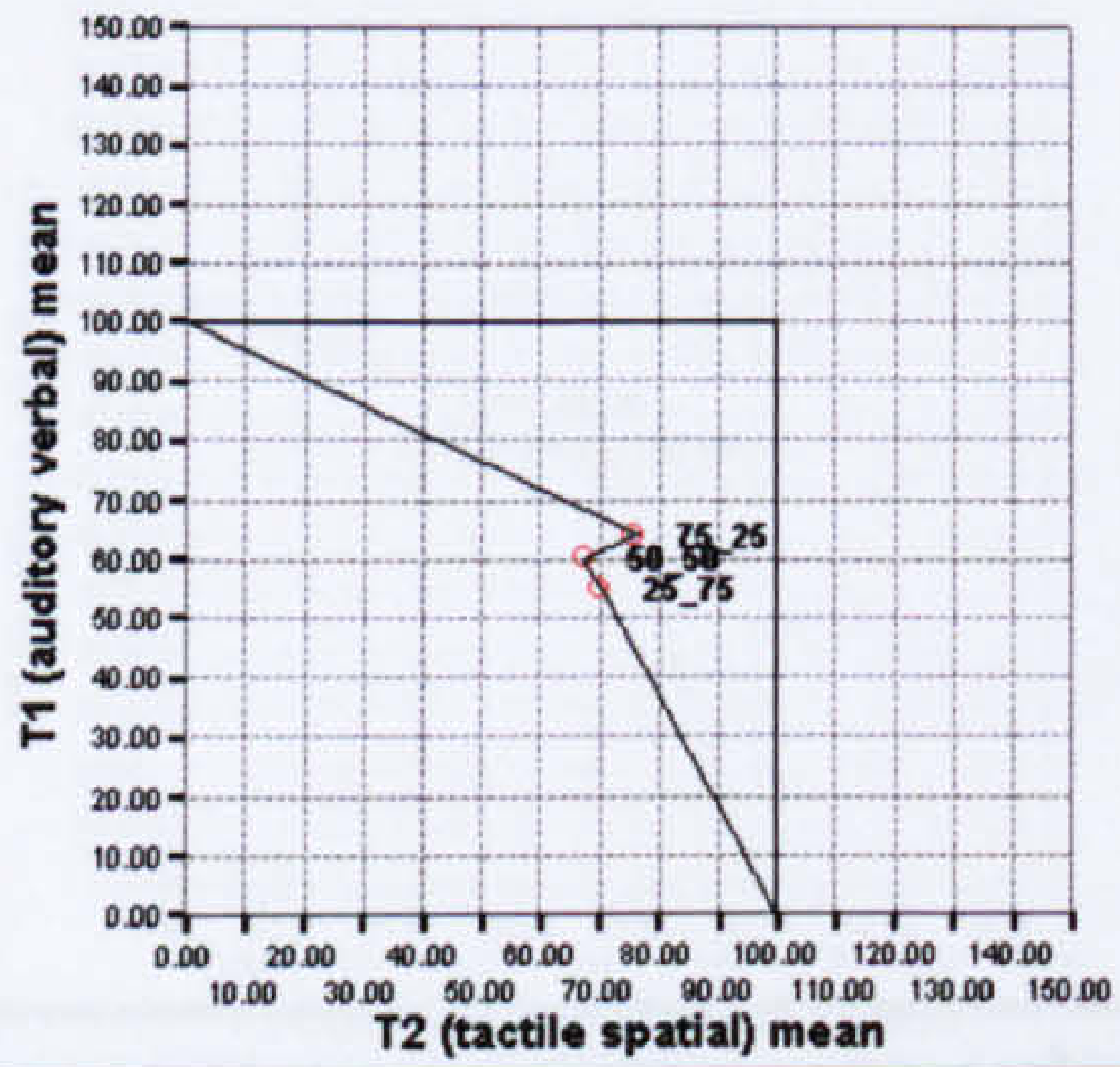


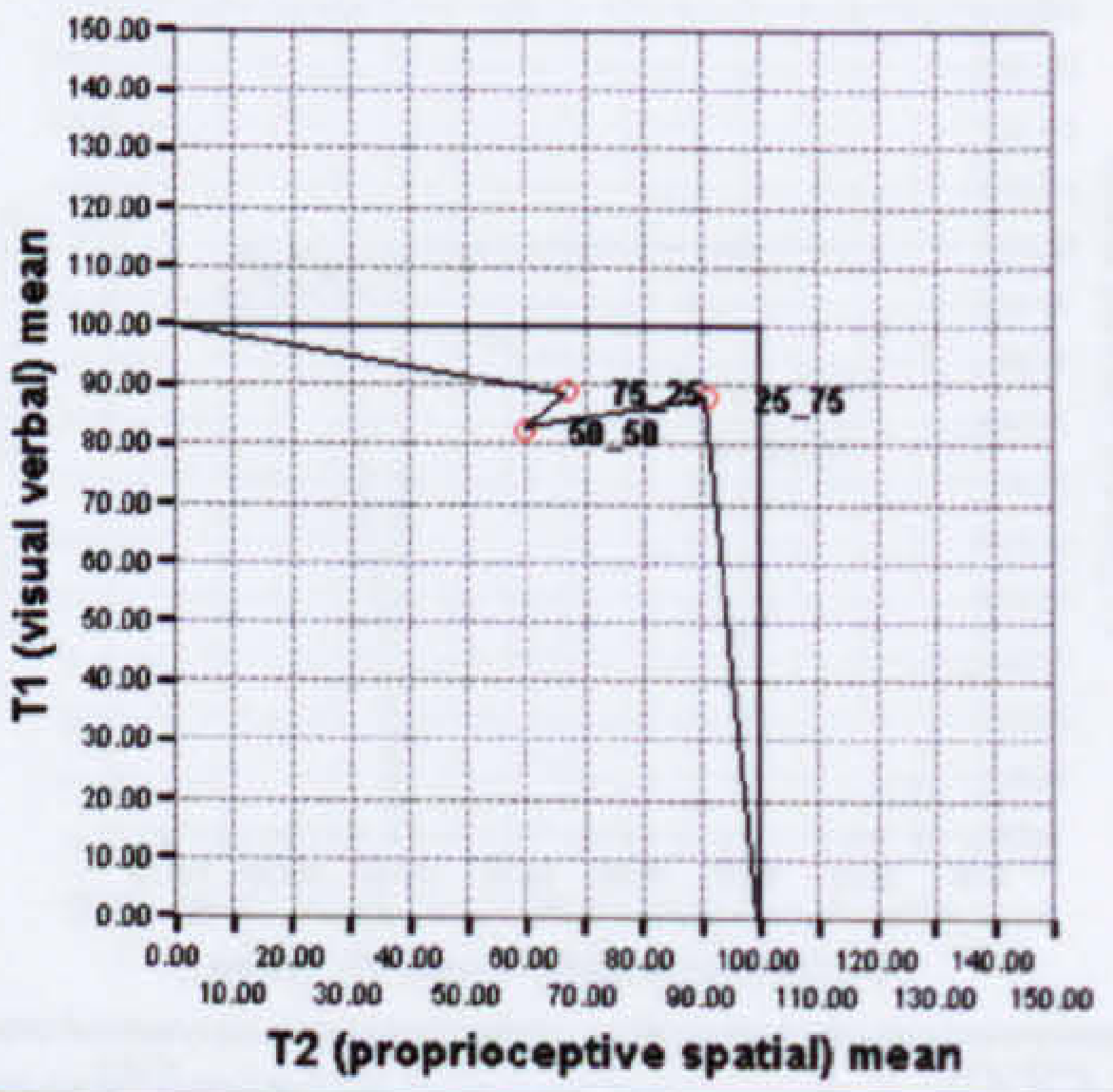
AVTS **AVTV** **Significant**



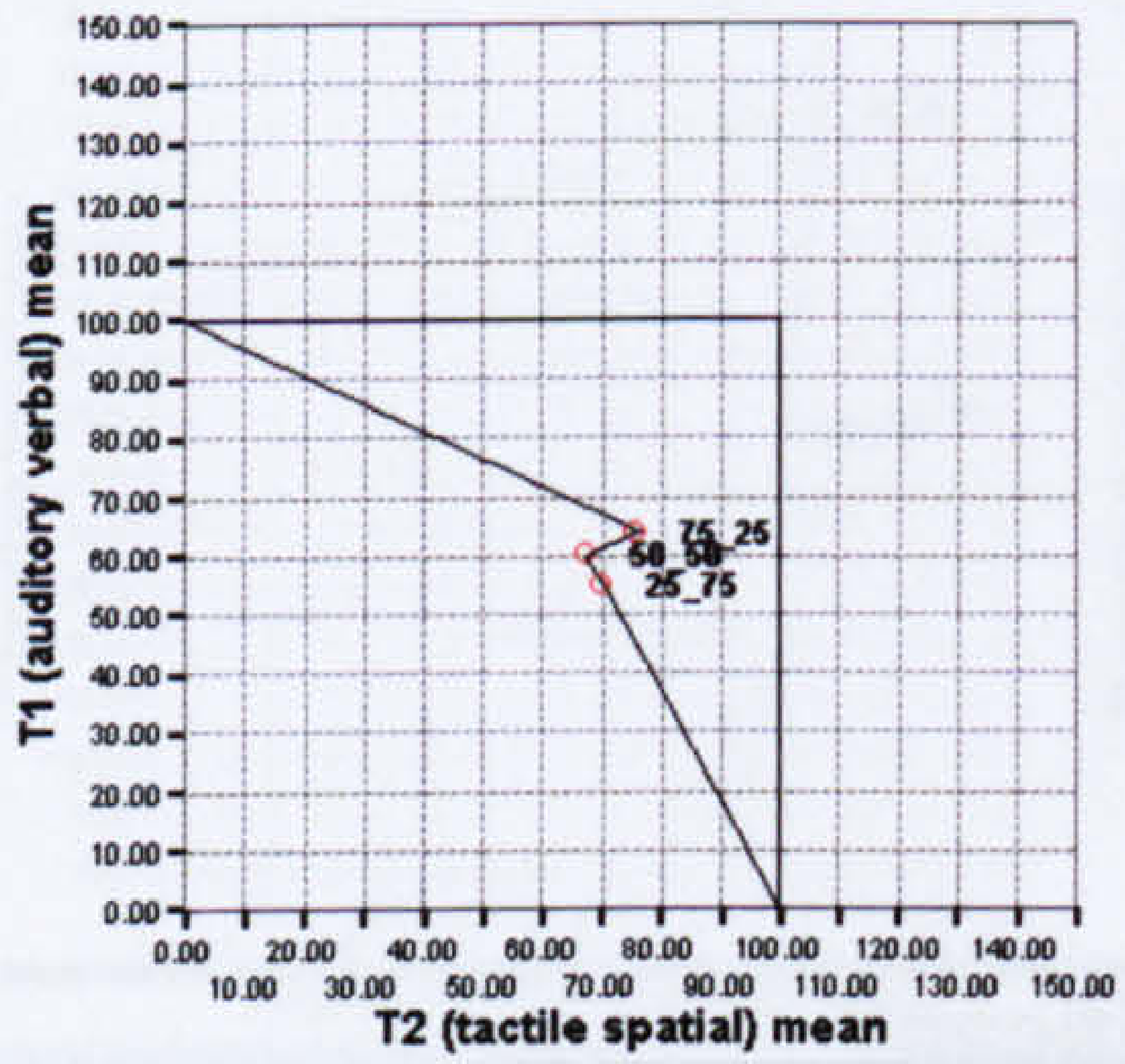


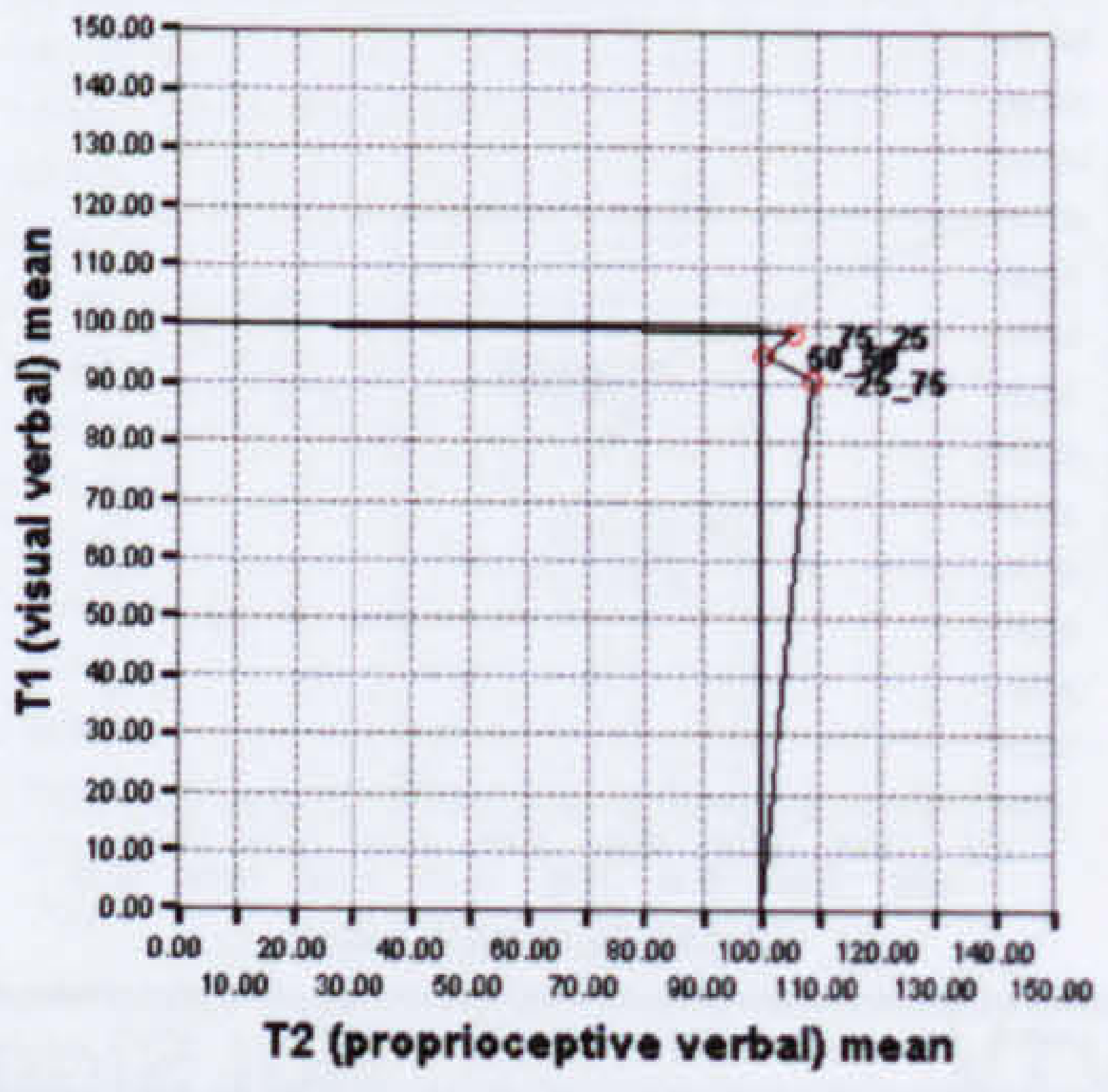
AVTS **VVPS** **Not Significant**



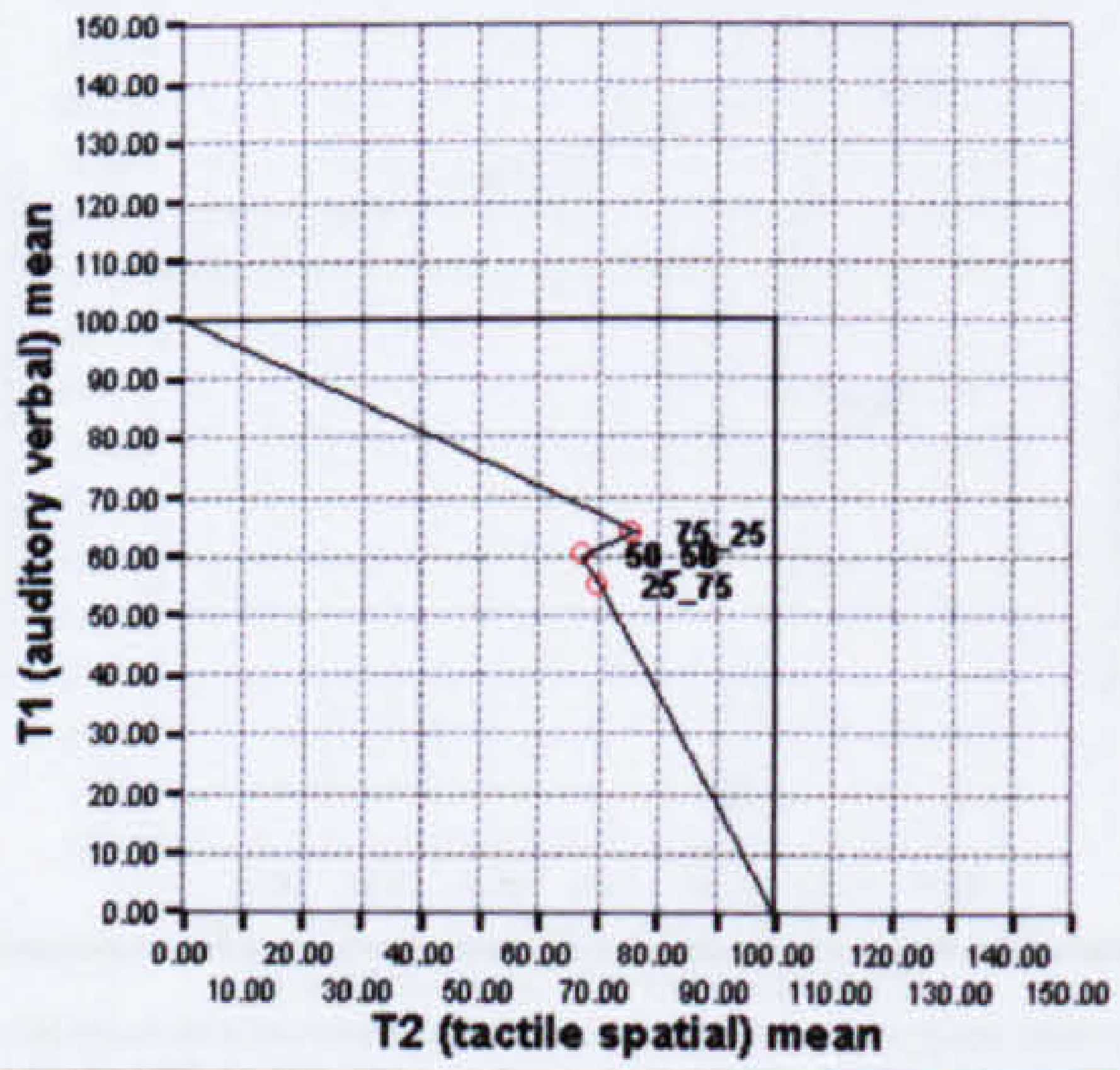


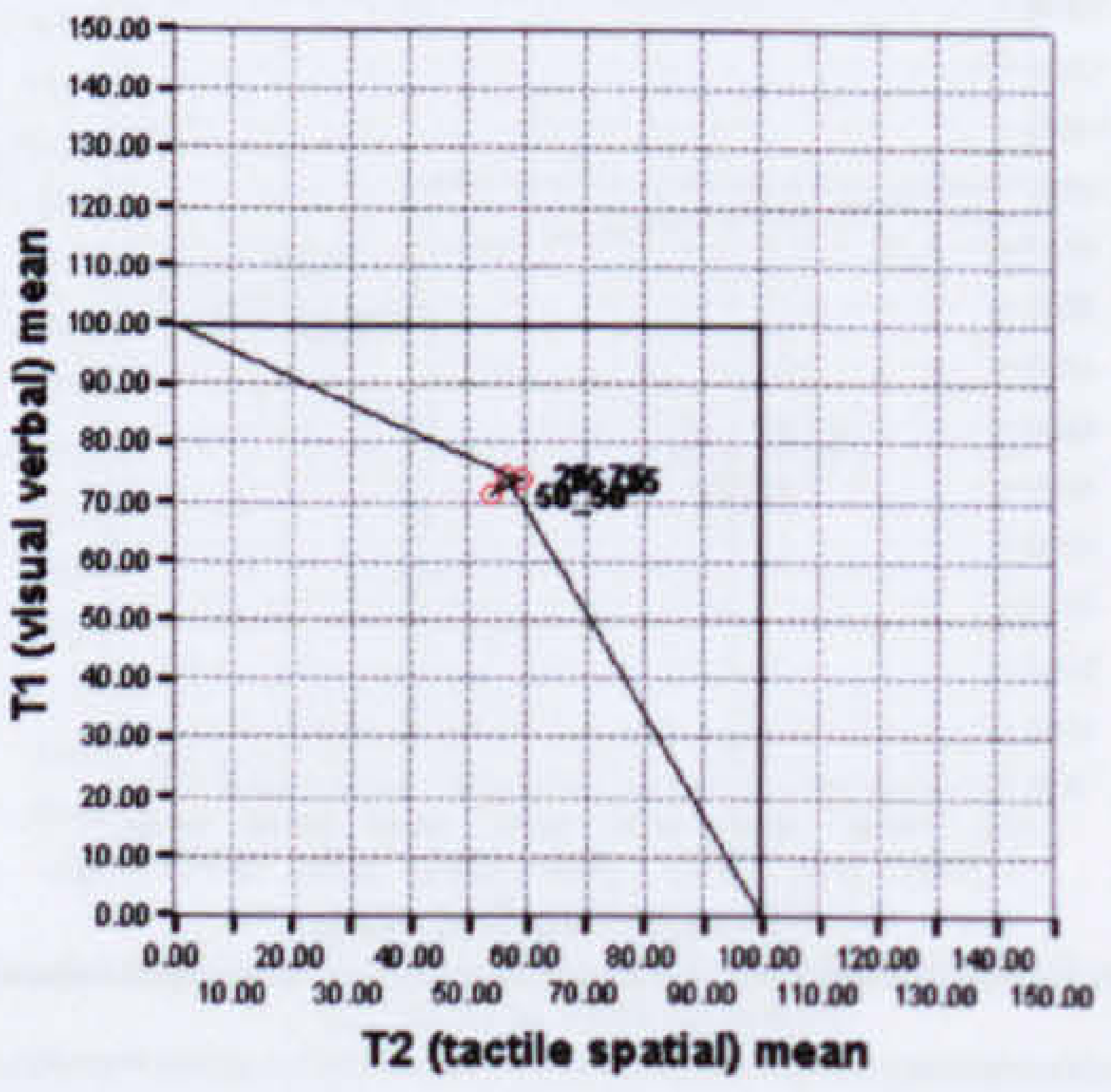
AVTS **VVPV** **Significant**



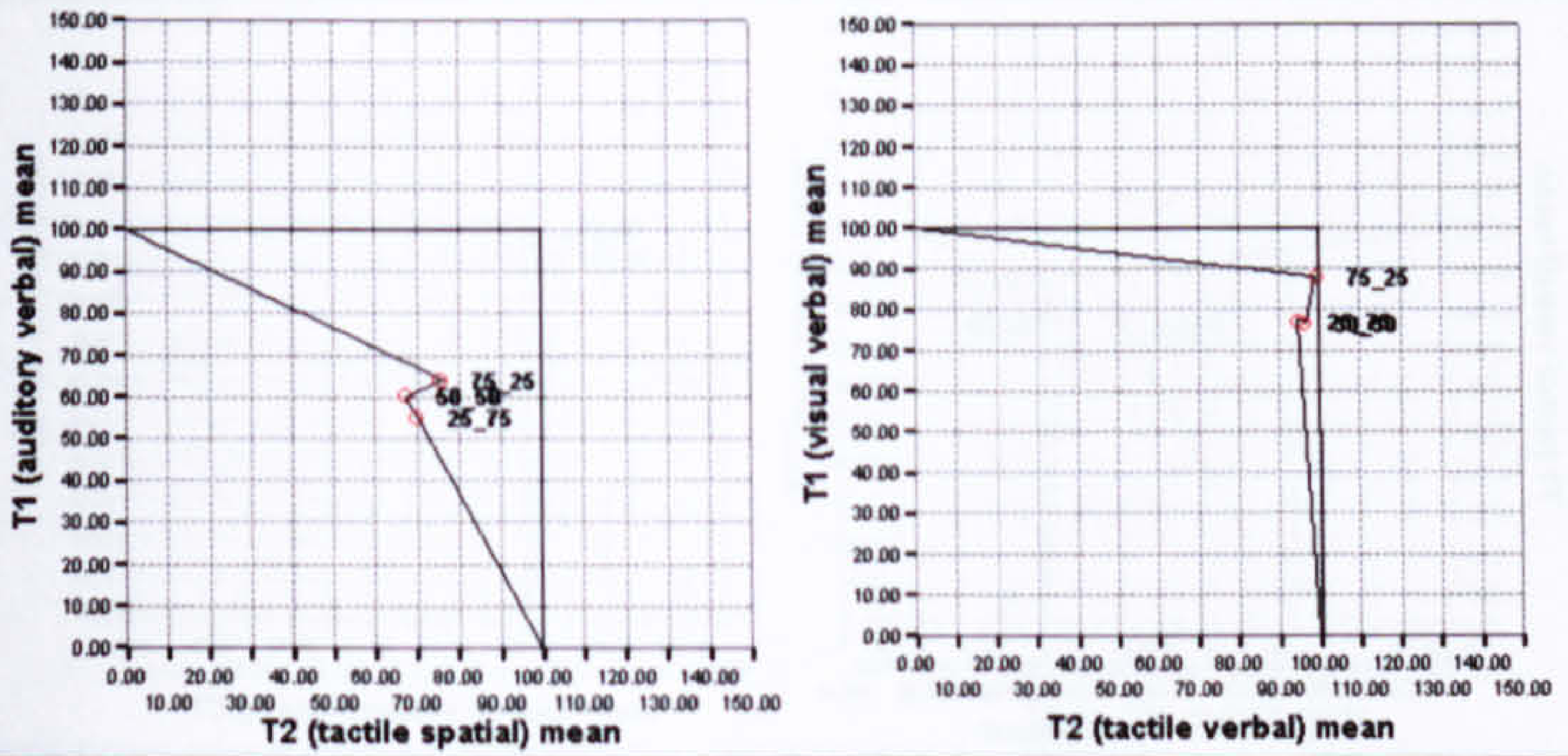


AVTS **VVTS** **Not Significant**

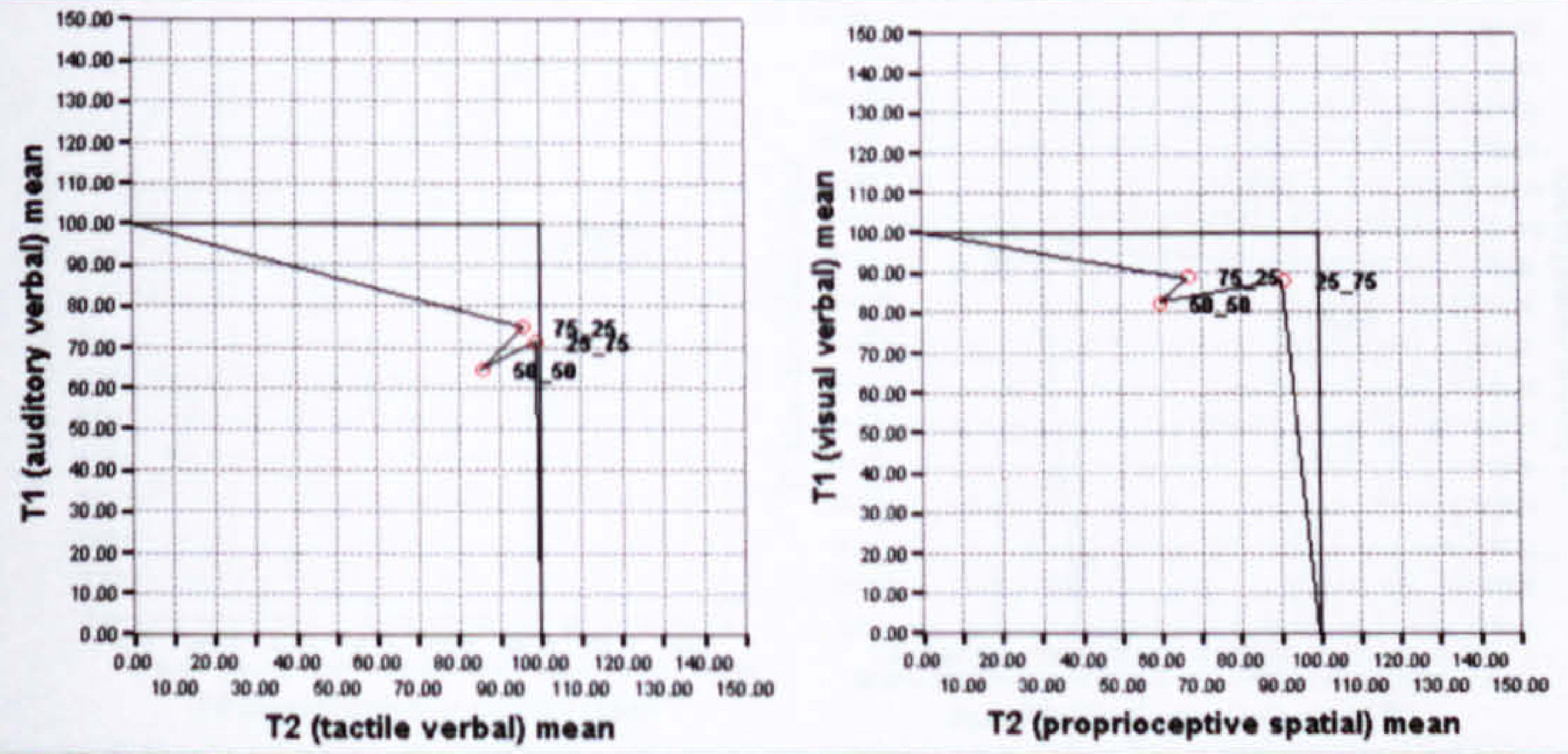




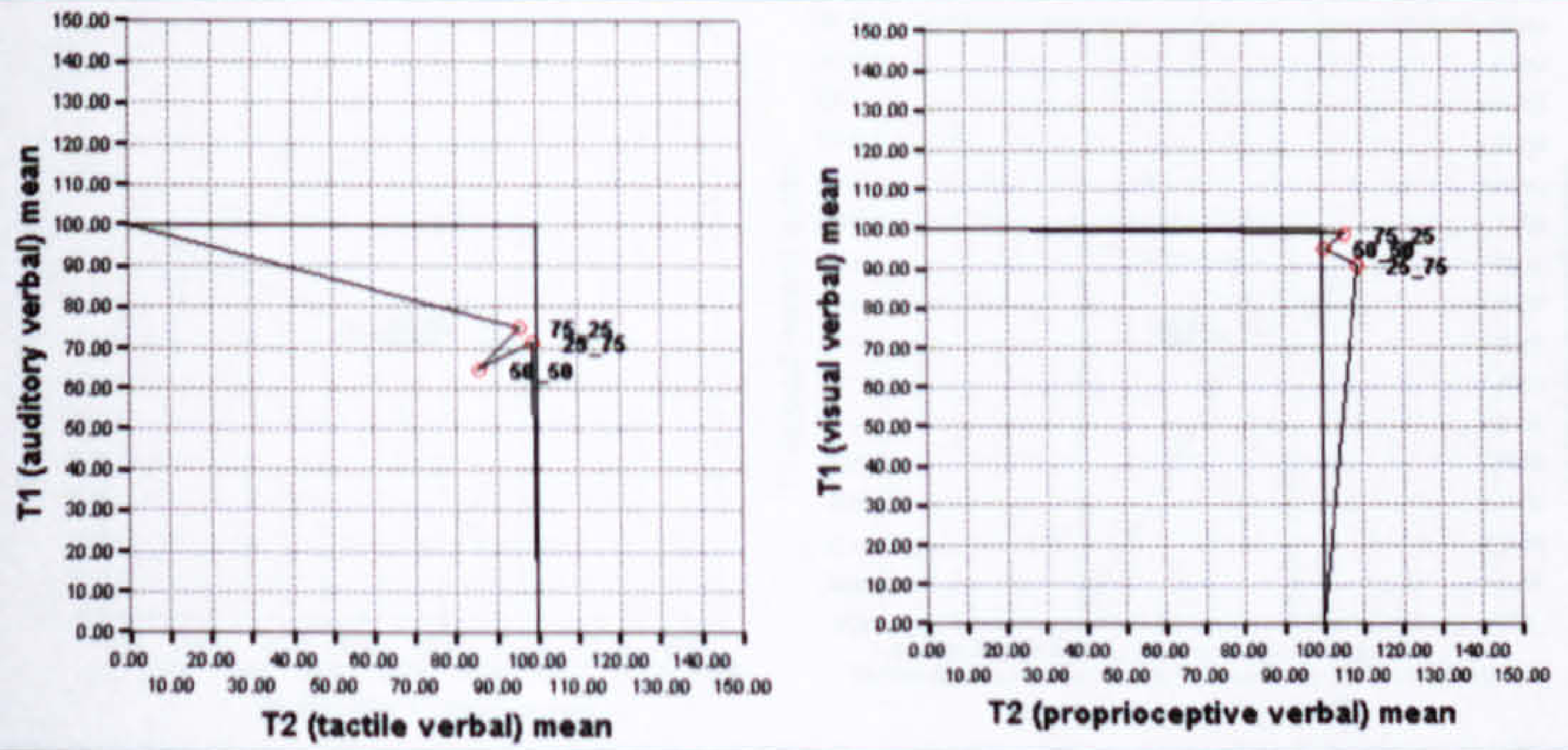
AVTS **VVTV** **Significant**



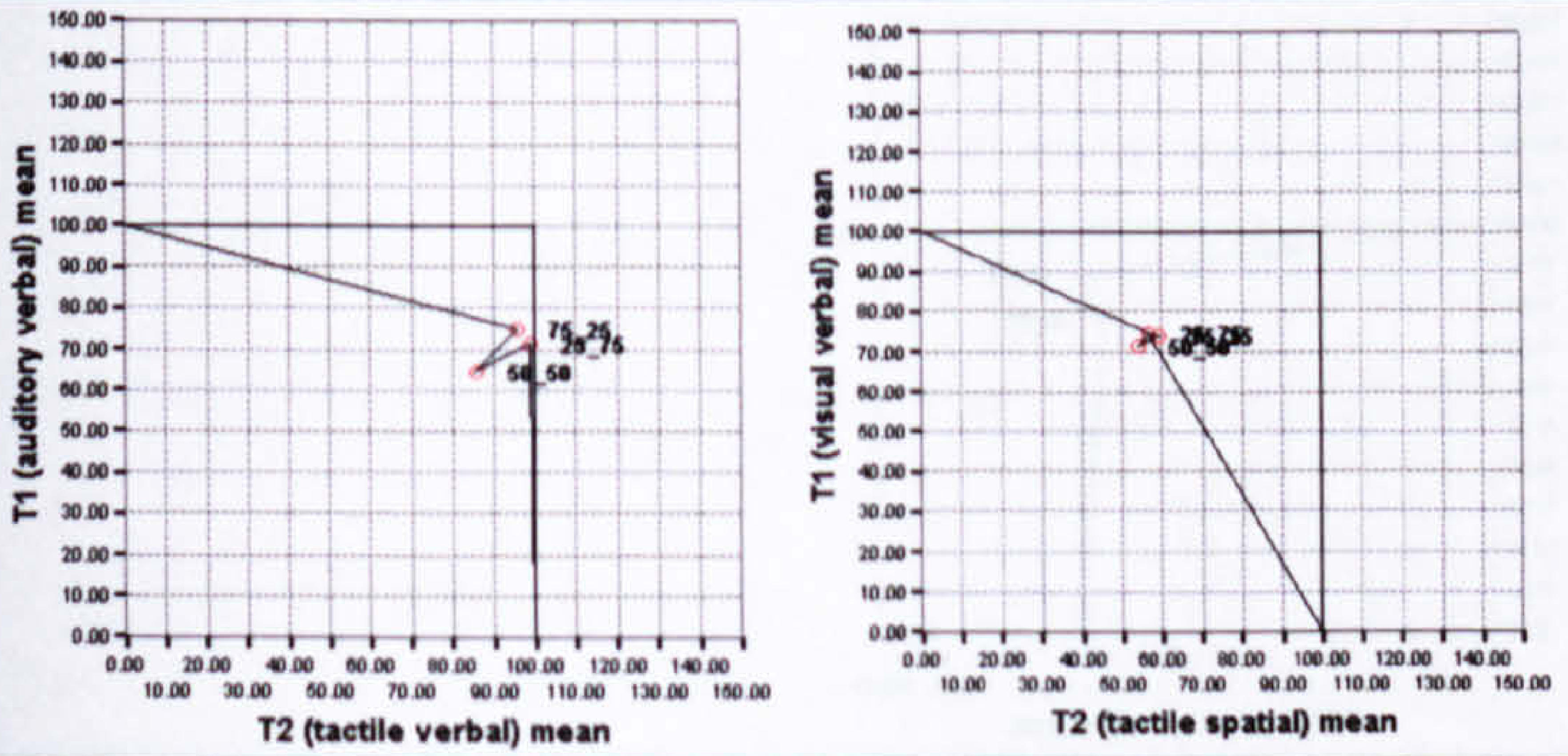
AVTV **VVPS** **Not Significant**



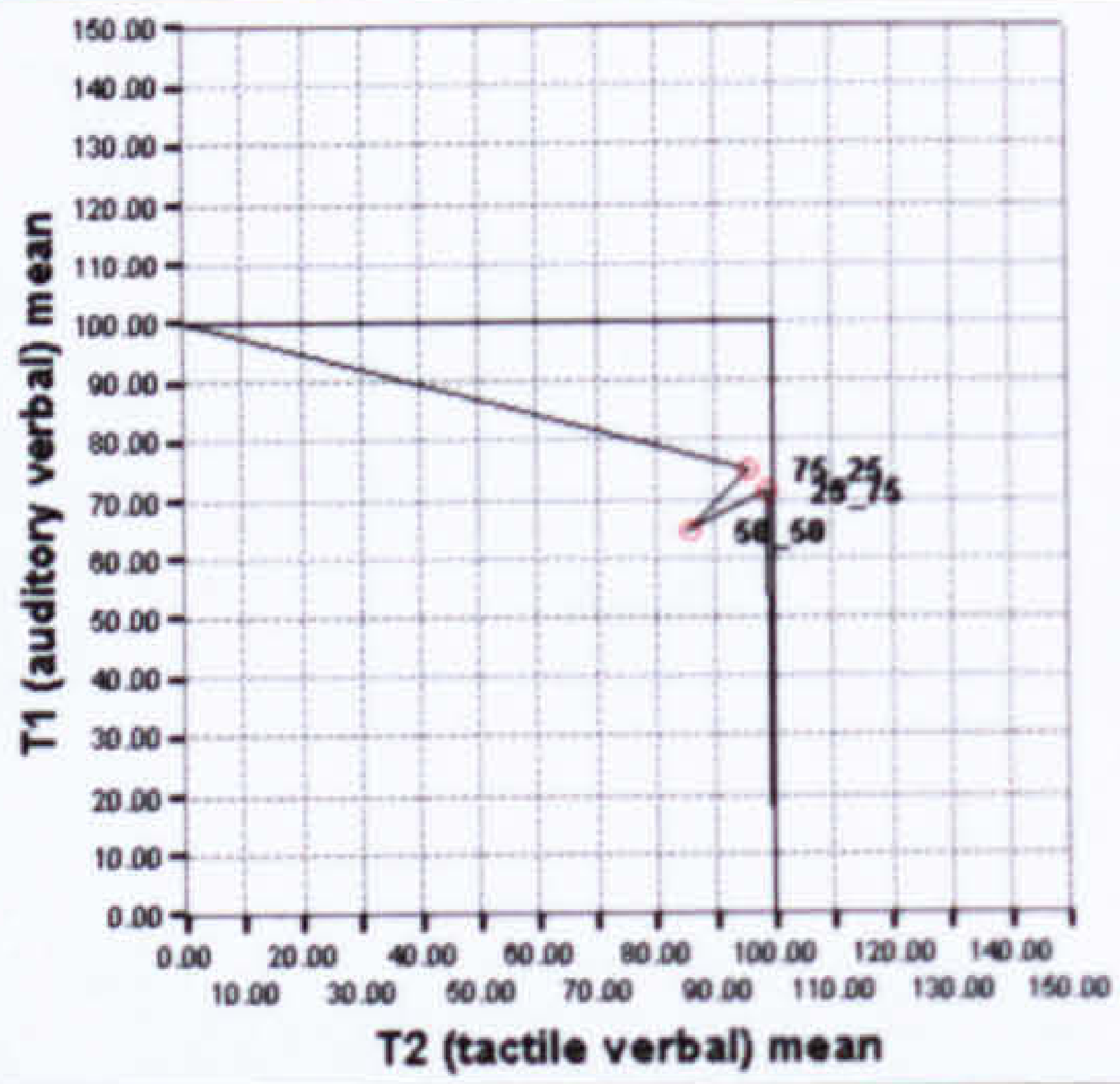
AVTV **VVPV** **Not Significant**

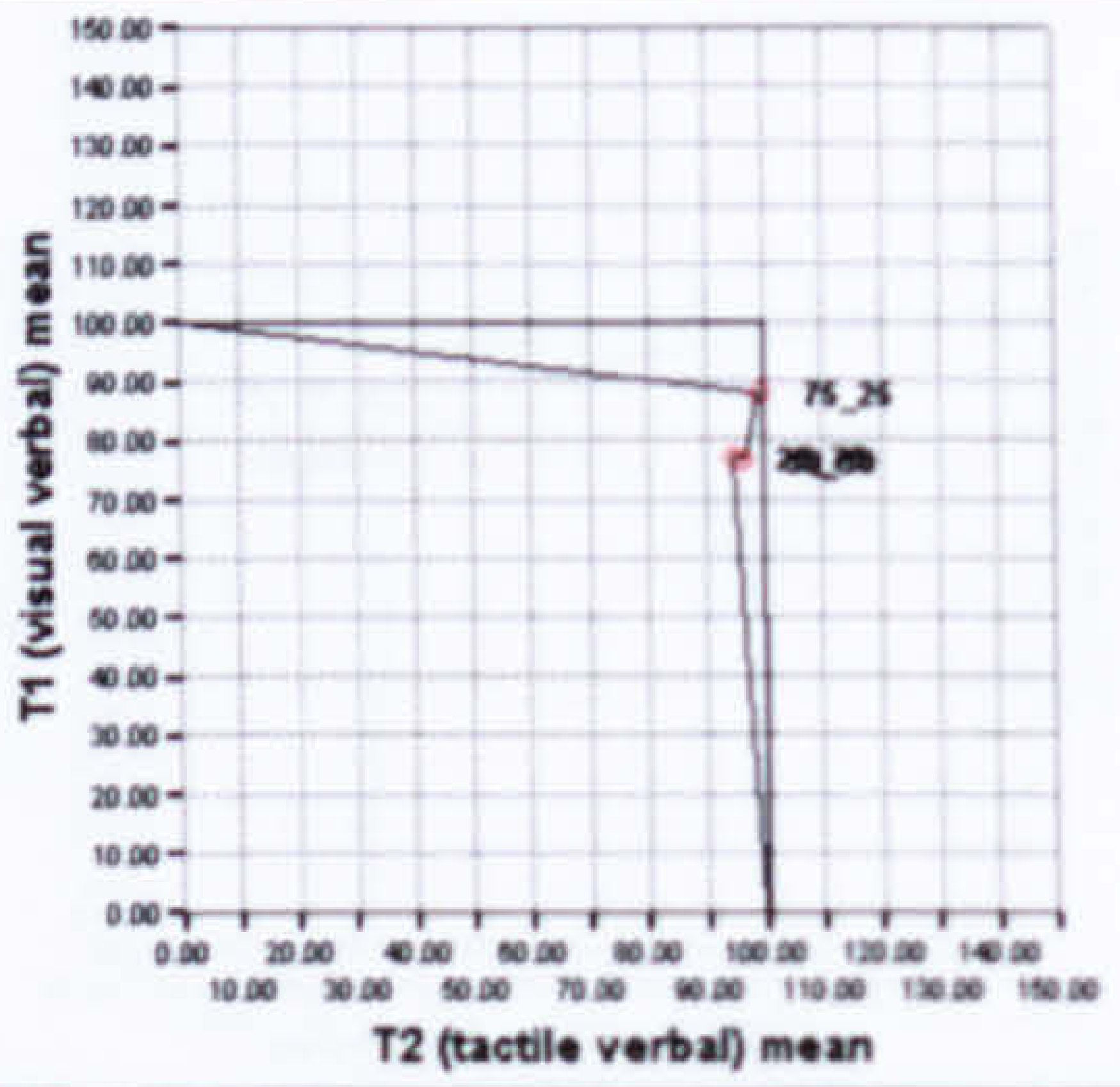


AVTV **VVTS** **Not Significant**

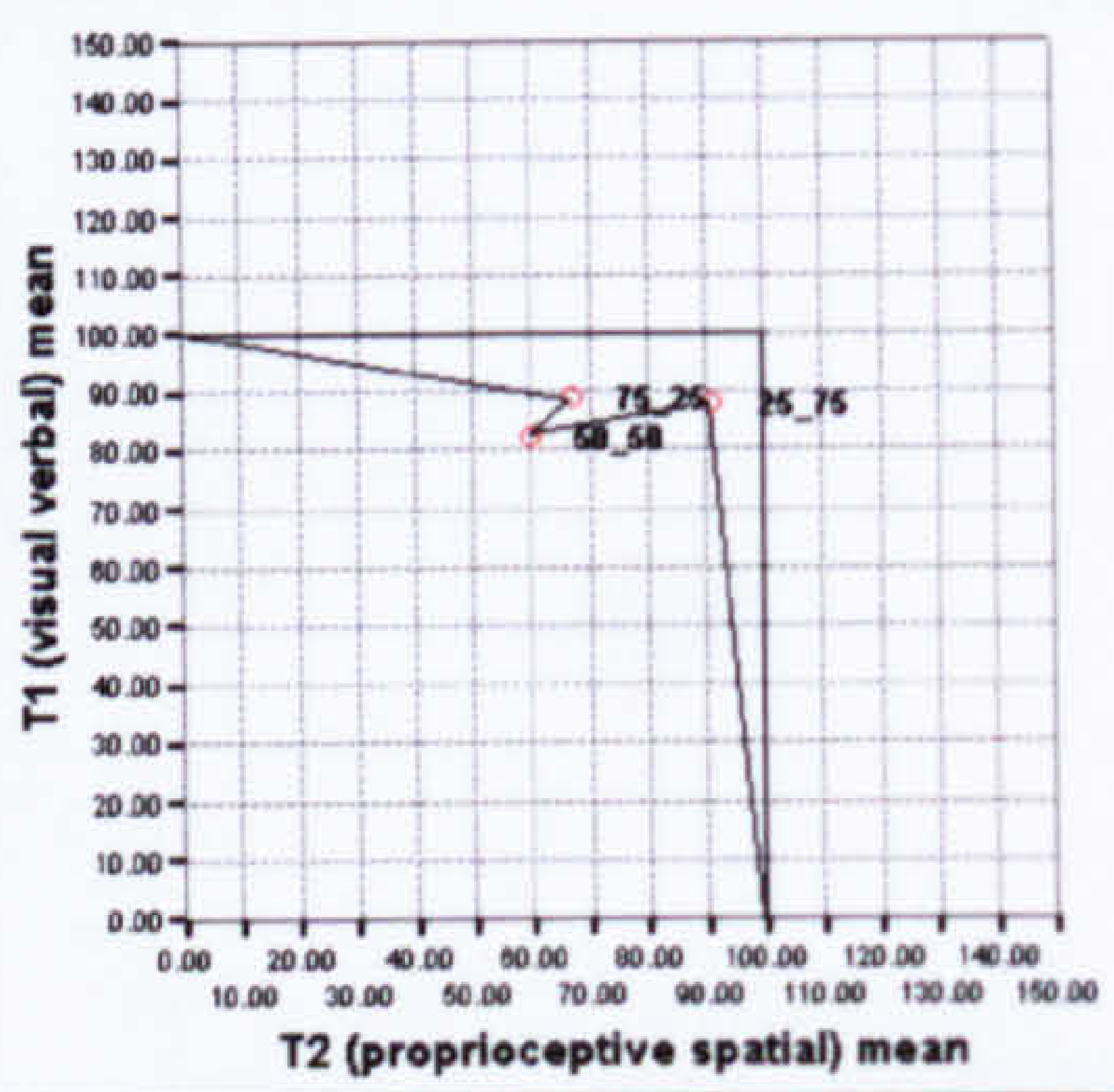


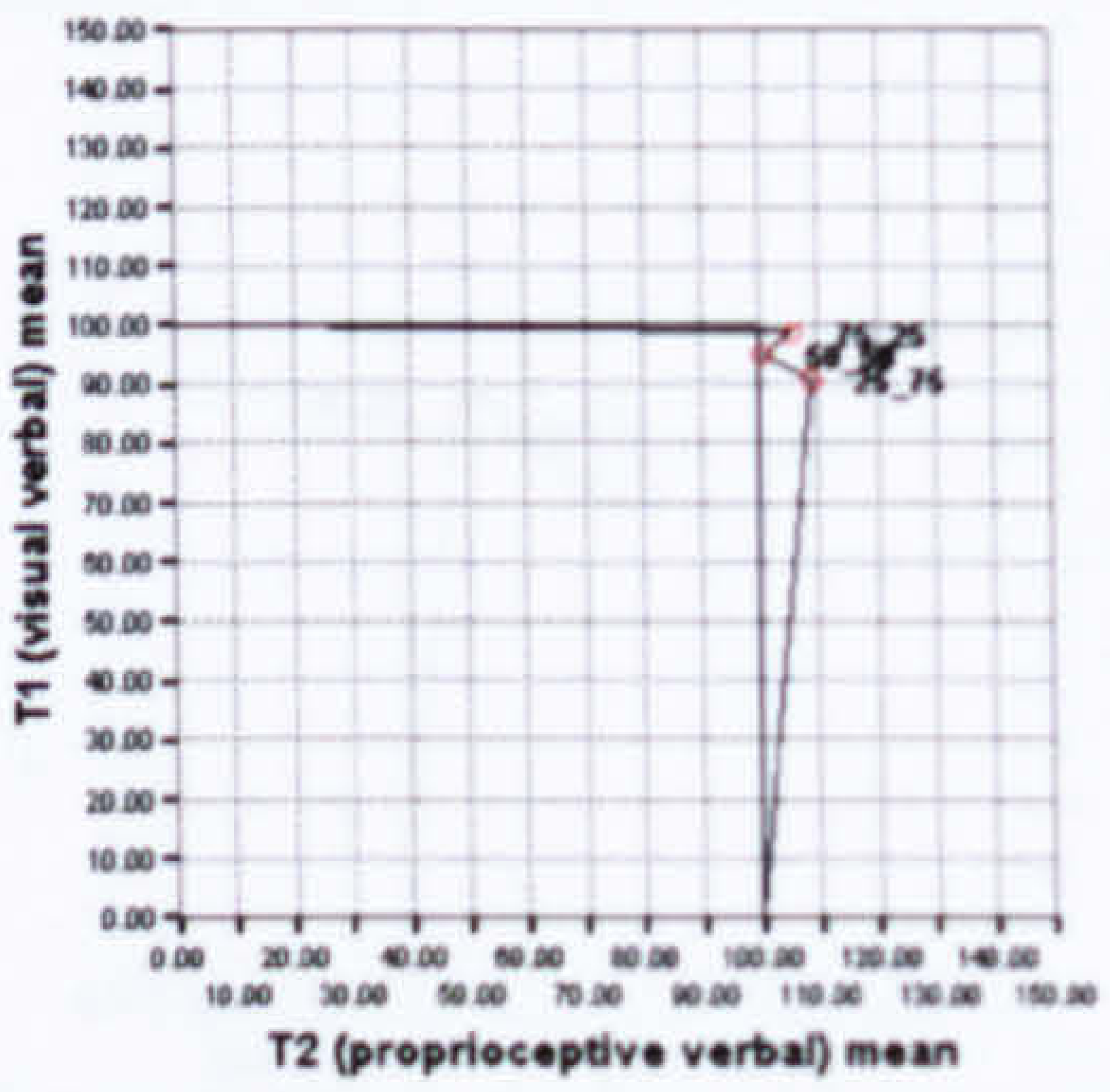
AVTV **VVTV** **Not Significant**



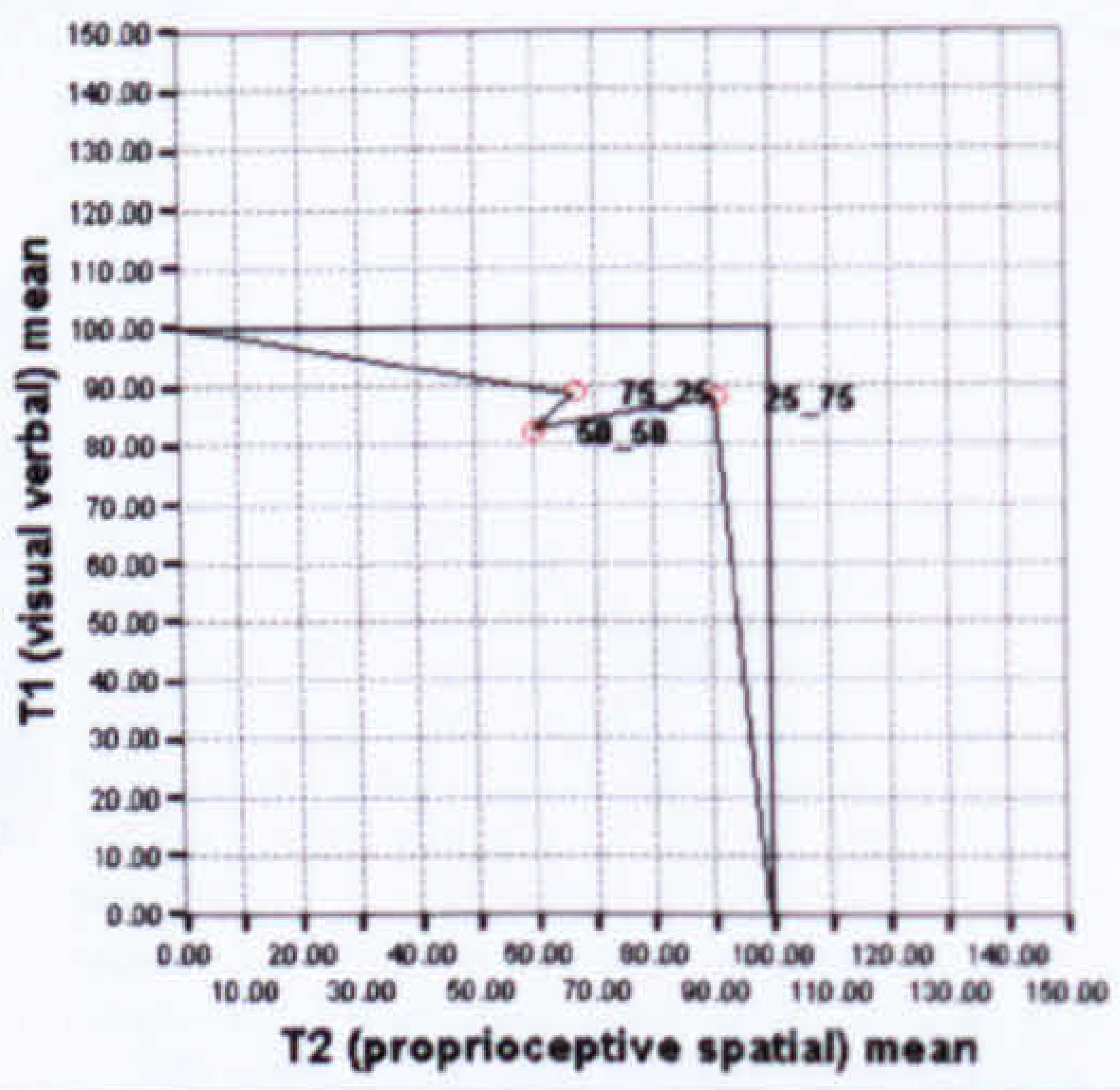


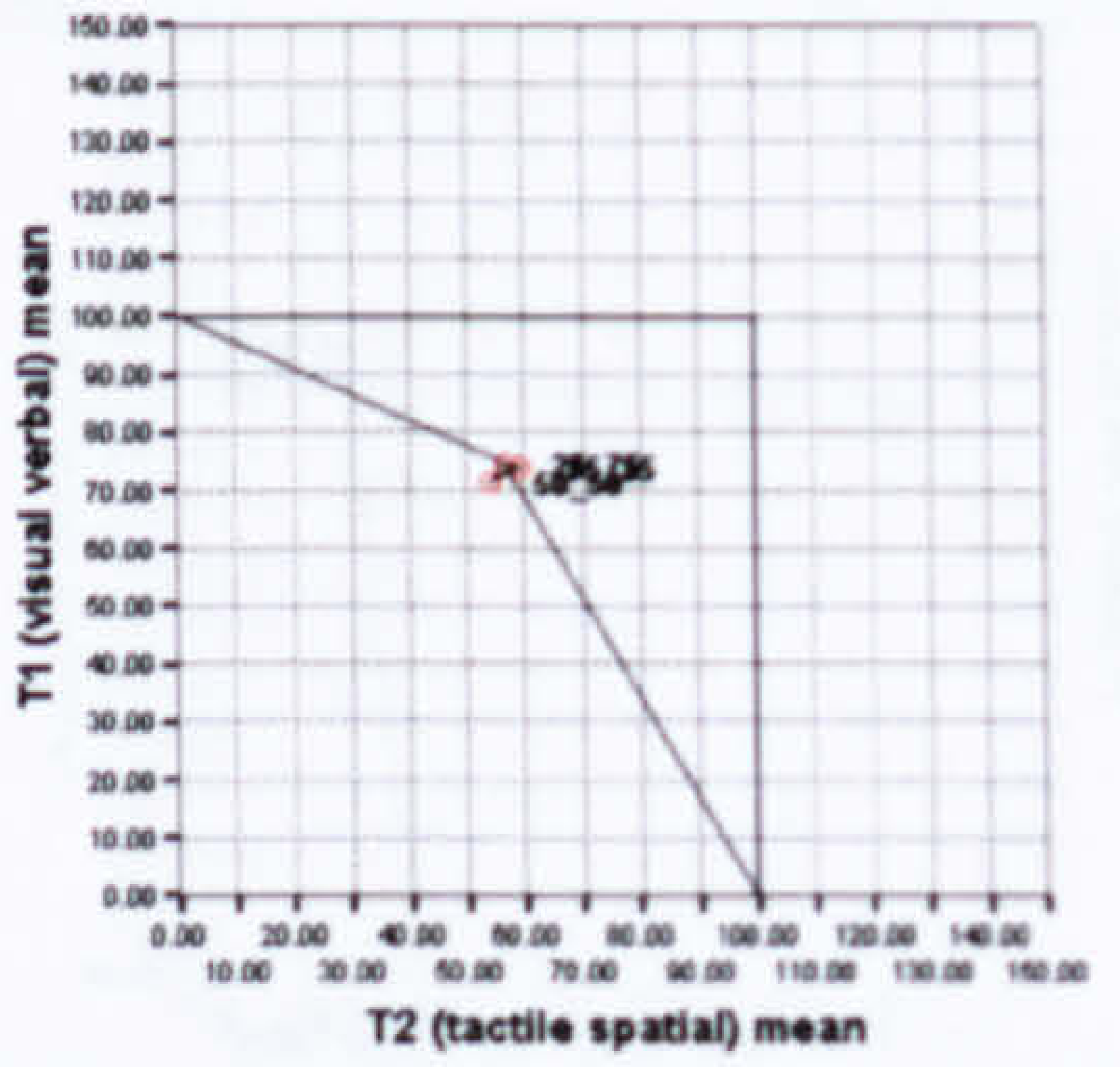
VVPS **VVPV** **Not Significant**



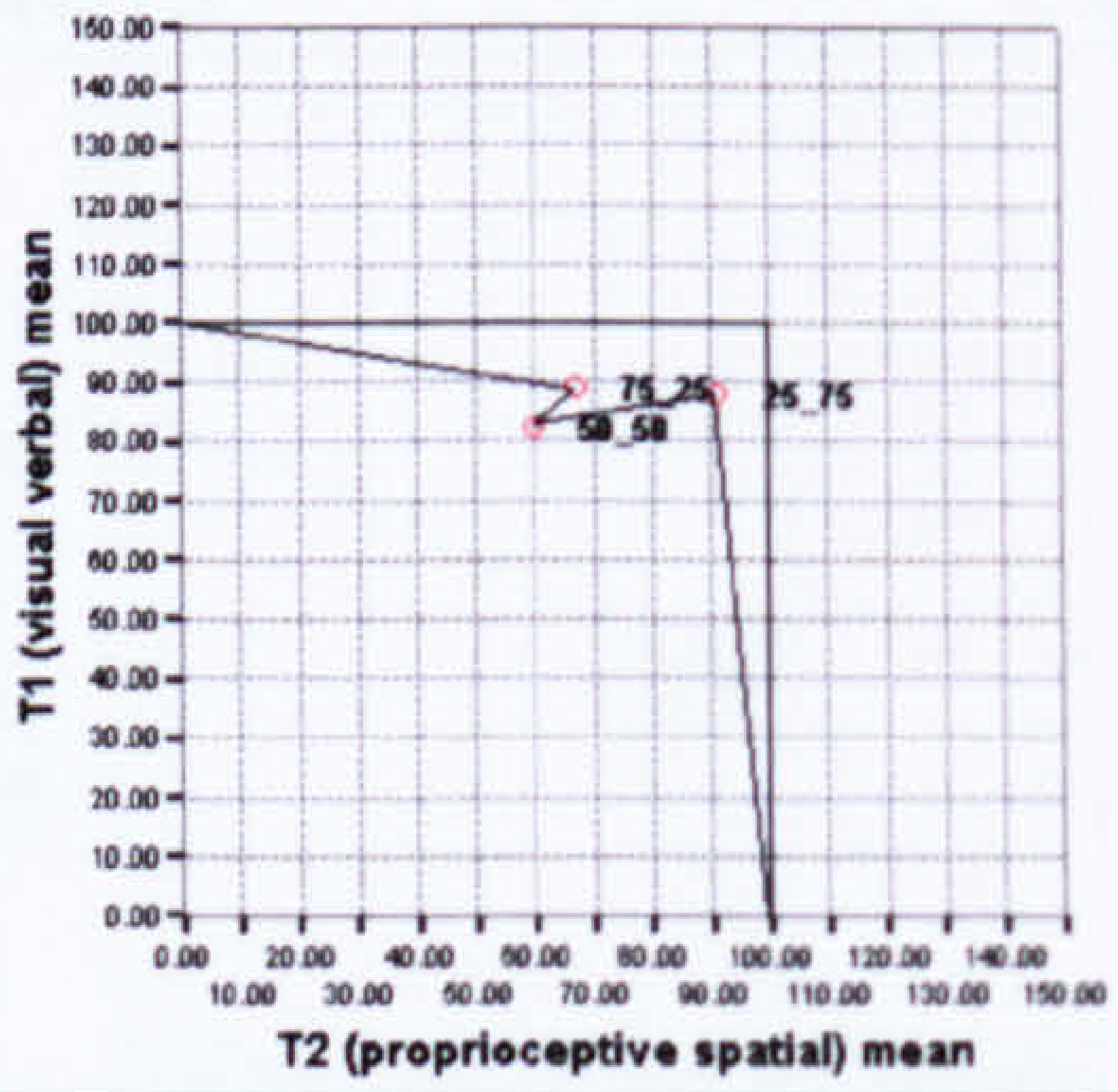


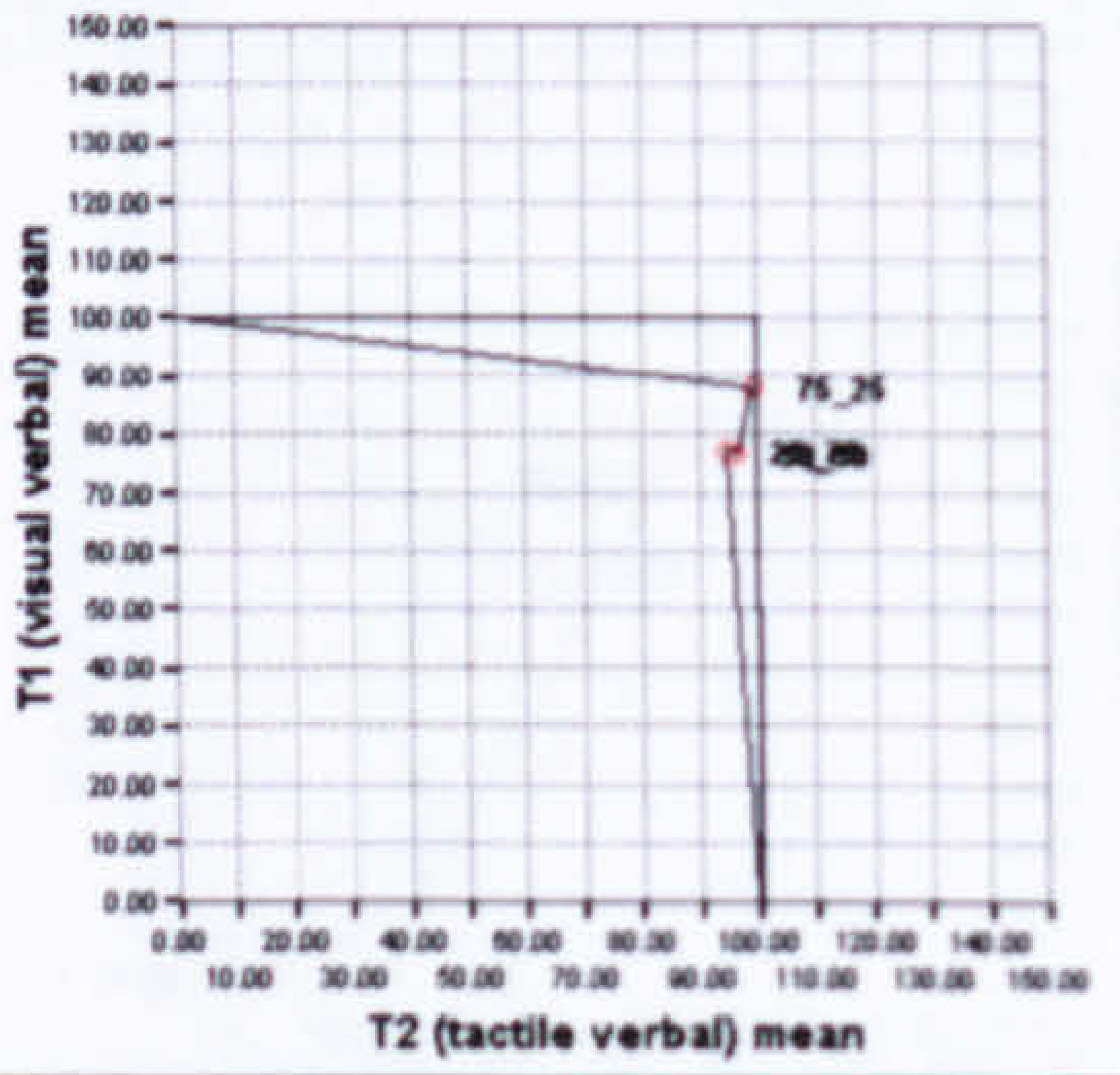
VVPS **VVTS** **Not Significant**



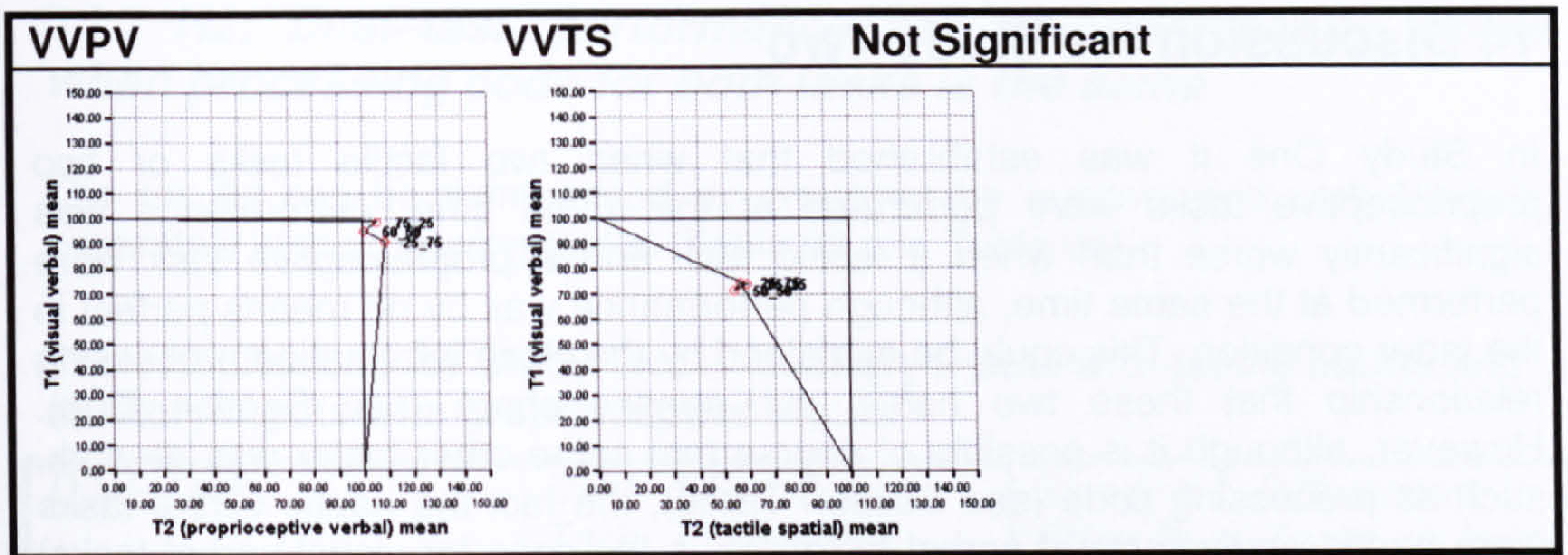


VVPS **VVTV** **Not Significant**

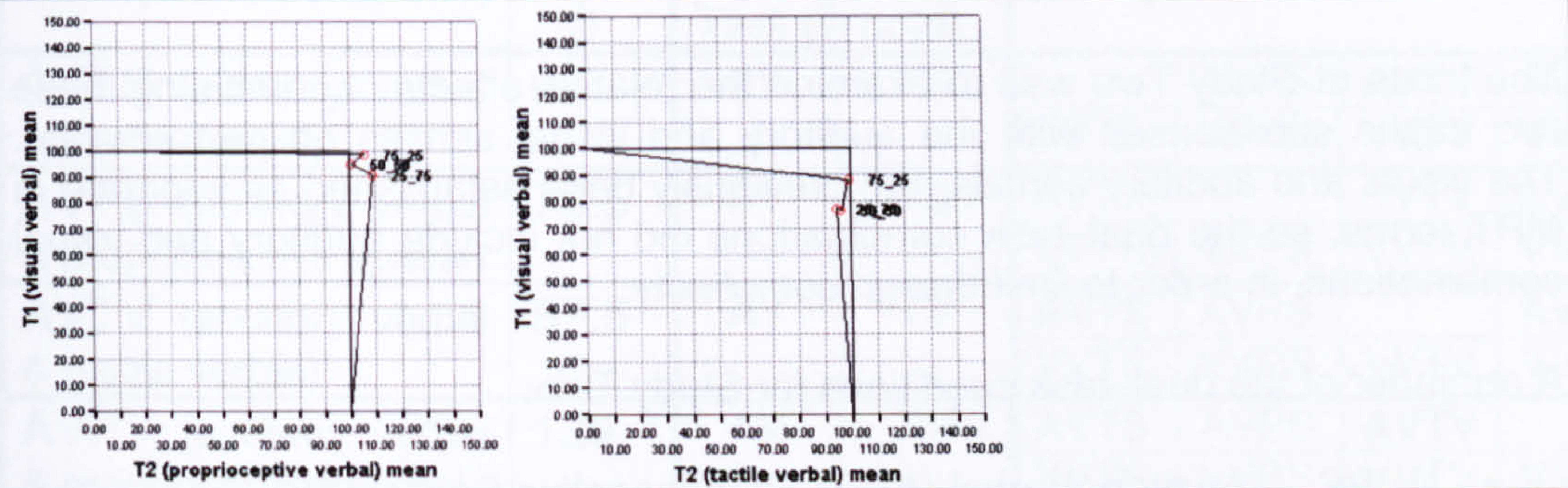




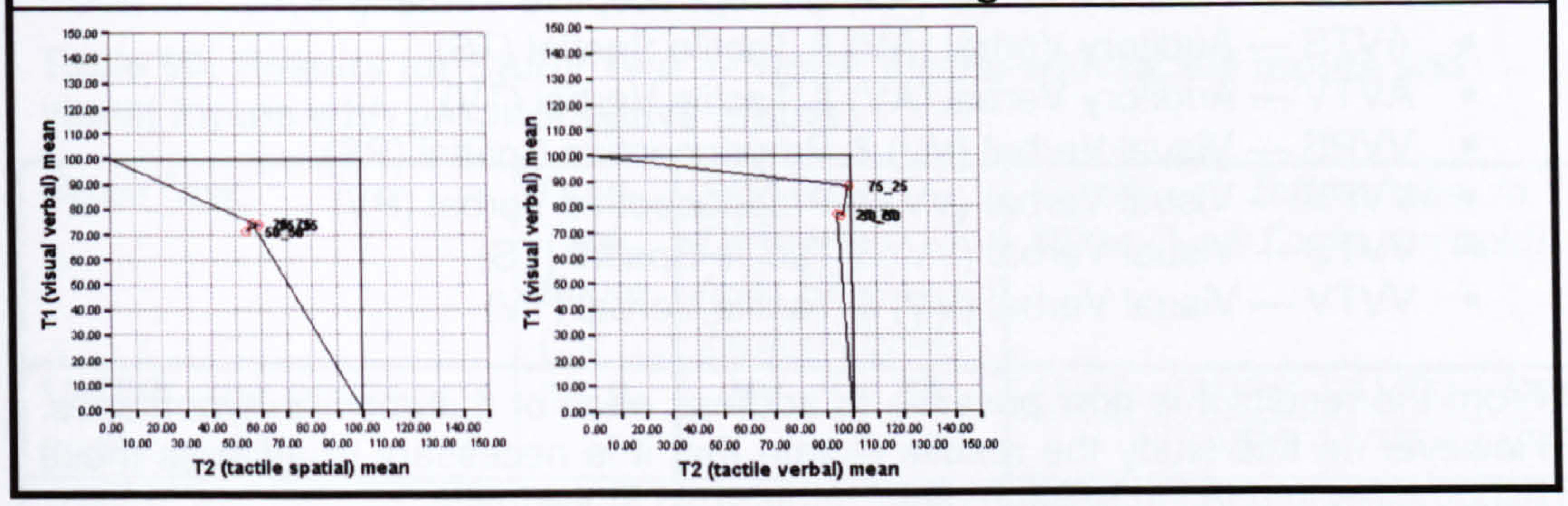
VVPV **VVTS** **Not Significant**



VVPV **VVTV** **Not Significant**



VVTS **VVTV** **Not Significant**



14 Discussion for Study Two

In Study One it was established that when two tactile tasks or two proprioceptive tasks were performed at the same time, performance was significantly worse than when a tactile task and a proprioceptive task were performed at the same time, although performance was by no means perfect in the latter condition. This could be explained by the close information processing relationship that these two haptic sub–senses share (see Section One). However, although it is possible of course that some other factor was at work, such as processing code (see Section Three), the fact the haptic verbal tasks were haptic *equivalents* of verbal tasks (as is the case for visual verbal tasks) (see Section 6.2), or perhaps the congruency of inputs (see Section Four).

The focus of Study Two was to examine the relative effects of combining these two haptic sub–senses with the auditory and visual senses on performance. The visual and auditory senses had previously been established as separate in MRT terms, so the dual–task combinations did not include auditory and visual combinations, in order to limit design complexity.

A reminder of the dual–task conditions for Study Two:

- AVPS — Auditory Verbal (AV) & Proprioceptive Spatial (PS)
- AVPS — Auditory Verbal (AV) & Proprioceptive Verbal (PV)
- AVTS — Auditory Verbal (AV) & Tactile Spatial (TS)
- AVTV — Auditory Verbal (AV) & Tactile Verbal (TV)
- VVPS — Visual Verbal (VV) & Proprioceptive Spatial (PS)
- VVPV — Visual Verbal (VV) & Proprioceptive Verbal (PV)
- VVTS — Visual Verbal (VV) & Tactile Spatial (TS)
- VVTV — Visual Verbal (VV) & Tactile Verbal (TV)

From the results it is now possible to address each of the specific hypotheses. However, in this study the results dictate that it is necessary to address these hypotheses in relation to each other rather than individually.

14.1 H1: No combinations of different senses will produce a performance decrement compared to single task conditions

This hypothesis is discussed with Hypothesis Two in the next section.

14.2 H2: Dual–task performance will be significantly worse when processing code for both tasks is the same

The results can be summarised by grouping the auditory and verbal results separately in the following tables (Table 98 and Table 99).

Table 98: Results for Study Two — auditory inputs with tactile inputs and auditory inputs with proprioceptive inputs

Dual–Task	*Dual–Task Score (%)*	*Significant Difference from Single–Task (in bold)*		*Significant Differences to the Other Dual–Tasks (in bold)*			
AVTS (auditory verbal & tactile spatial)	66	**AV**	**TS**		AVPS	**AVTV**	**AVPV**
				VVTS	VVPS	**VVTV**	**VVPV**
AVPS (auditory verbal & proprioceptive spatial)	75.5	**AV**	**PS**	AVTS		AVTV	AVPV
				VVTS	VVPS	VVTV	VVPV
AVTV (auditory verbal & tactile verbal)	87.5	**AV**	TV	**AVTS**	AVPS		**AVPV**
				VVTS	VVPS	VVTV	VVPV
AVPV (auditory verbal & proprioceptive verbal)	129	AV	PV	**AVTS**	AVPS	**AVTV**	
				VVTS	VVPS	VVTV	VVPV

Table 99: Results for Study Two — visual inputs with tactile inputs and visual inputs with proprioceptive inputs

Dual–Task	*Dual–Task Score (%)*	*Significant Difference from Single–Task (in bold)*		*Significant Differences to the Other Dual–Tasks (in bold)*			
VVTS (visual verbal & tactile spatial)	65.3	**VV**	**TS**	AVTS	AVPS	AVTV	**AVPV**
					VVPS	VVTV	VVPV
VVPS (visual verbal & proprioceptive spatial)	87.3	**VV**	PS	AVTS	AVPS	AVTV	AVPV
				VVTS		VVTV	VVPV
VVTV (visual verbal & tactile verbal)	91.5	**VV**	TV	**AVTS**	AVPS	AVTV	AVPV
				VVTS	VVPS		VVPV
VVPV (visual verbal & proprioceptive verbal)	105	VV	PV	**AVTS**	AVPS	AVTV	AVPV
				VVTS	VVPS	VVTV	

The first hypothesis (refer to Section 13.1 for this hypothesis) again addresses the effect of input sense on dual– task performance. More specifically: it was expected that there would be minimal or no decrement in performance from the single task to the dual–task condition as a result of input sense. This prediction was made on the basis that there were no same–sense dual–tasks in Study

Two; each combination included either a visual and proprioceptive, visual and tactile, auditory and proprioceptive, or auditory and tactile duo of tasks.

The second hypothesis once more examines the effect of information processing code (referred to as code) on dual-task performance. As in Study One and in line with previous dual-task findings, it was hypothesised that there would be decrement in performance as a result of processing code, As mentioned, in both studies, same-code conditions include two spatial tasks or two verbal tasks, whereas, different-code conditions include those with one spatial task and one verbal task.

In contrast to many of the results from Study One, the results of Study Two do not support MRT or Wickens's MRT model in terms of ether separate sensory resources or separate processing codes. However, there is a powerful and consistent pattern of results when one splits the results into two groups (auditory versus visual). From the columns entitled 'Dual-Task Score' and 'Significant Difference from Single-Task', within Table 98 and Table 99, it can be seen that there is very little difference between the auditory set of results and the visual set of results.

It is necessary to quickly mention though that, for the dual-task VVTS, significant single to dual-task differences, for the VV element, are only found at the 50% allocation policy and not at 25% or 75%. This is an odd result with no obvious explanation, especially when all three allocation policies have almost identical results (see Figure 43); it is likely that the non significant results at two of the policies are due to large variances. However, this makes very little difference to the overall pattern of results obtained.

As mentioned, there is a strikingly similar pattern of results in both the auditory and visual groups. Within each group the lowest score occurs when auditory or visual scores are combined with the tactile spatial task, then proprioceptive spatial, then tactile verbal and finally at the other extreme proprioceptive verbal. In both groups the two with the lowest scores are the combinations with the spatial processing codes (i.e. different processing codes) and the two with the highest scores are those with the verbal processing codes (i.e. same processing codes).

Perhaps most interesting is the fact that the highest scoring auditory dual-task and highest scoring visual dual-task (both of which are paired with proprioceptive verbal tasks) have scores that are higher than their single task scores (129% and 105% respectively). This is unexpected because these two dual-tasks have the same processing code, which Wickens's model suggests would cause a certain amount of performance decrement.

This suggests that auditory and visual tasks (that are 'symbolic' verbal in nature) not only score better when combined with haptic tasks that have the same 'processing code', but that it is desirable to have this combination (particularly it seems when the haptic task is a proprioceptive task). Note that this effect could have been a product of the tasks' processing codes, i.e. they were designed to be symbolic as explained before and are therefore neither spatial nor verbal strictly speaking. However, because all of the 'verbal' tasks were designed to be symbolic of some item of information, the aim was that these tasks were all of the same type (i.e. non–spatial symbolic inputs) and therefore any effects can be considered valid in principle. Therefore, in Study Two, processing codes of the same type appear to be associated with enhanced performance compared with processing codes of different types, especially when the dual–task input senses are auditory & proprioceptive or visual & proprioceptive.

This makes sense in relation to recent neuroscientific findings, described in Section Four, showing that multisensory summation within single cells can be superadditive (Stein et al., 2004). However, for this to occur, the findings suggest that this occurs not as a result of specific sensory combination or processing code but as a result of input 'congruency' (Stein et al., 2004). More specifically, when two inputs are congruent (in spatial and temporal terms), the cells receiving these multi–sense inputs often produce outputs that are greater than the sum of the inputs (i.e. output is enhanced) (Stein et al., 2004). This effect is associated with improved performance (Stein et al., 2004). Similarly, the determining factor as to whether multi–sensory cells dampen outputs seems to be input spatial and temporal incongruency (Stein et al., 2004; King, 2004).

These effects were observed within an area of the brain (the superior colliculus), which is involved in the spatial directing of the organs and limbs involved in control of attention and responses (Stein et al., 2004). It makes sense that spatio–temporal factors are important in multi–sense spatial tasks because the nature of the tasks would demand coherent spatial cues. Shared spatio–temporal factors are probably important in linking separate inputs to the same event in other types of tasks, such as verbal tasks. The ventriloquism effect is an example of discrepant auditory and visual inputs; the inputs originate from different locations and the brain makes the error of deciding that the source of the sound originates from the visual input location (probably because this is the dominant sense). In effect, 'performance' suffers as a result of discrepant spatio–temporal factors.

However, there may be other factors, important to other types of tasks that are affected by congruency. For example, variations in visual brightness in relation to variations in auditory pitch and loudness also produce perceptions of congruent versus incongruent inputs (Marks, et al., 1987; Marks, 1974; 1989). There is also a linguistic relationship these between visual and auditory congruency perceptions i.e. sounds are referred to as high–pitched or low–pitched and the higher–pitched the sound the higher it is positioned spatially on the musical stave and vice versa. Many of the visual–auditory factors that determine discrepancy or non–discrepancy are quite abstract and do not have a 'common acoustic or optical referent' (Marks, 2004). In these cases it appears to be the linguistic label that is the linking 'referent' (Marks, 2004), suggesting that associations with linguistic labels may be automatically made in the early–

stages of information processing when the congruency of basic multi–sensory features is determined.

The point here is that there may be many different factors that determine whether multi–sensory inputs will be perceived as congruent or incongruent; some are spatio–temporal factors, and some seem to be linked to linguistic labels, which may be relevant in verbal and symbolic tasks. Certainly, the congruency of multi–sensory inputs is a factor that seems to be growing in importance within neuroscience.

Returning to the results, Wickens's model would also suggest that combinations such as AVTS and VVTS would be ideal as they in theory require no resource sharing in terms of sensory input or processing code. However, performance in both these combinations was poor and on a par with PSPV in Study One. In fact these two combinations score less well than all of the T_P_ combinations, which should be alarming to interface designers. This again, may be related to congruency of inputs.

However, the pattern of significances is inconsistent. There is a significant difference between the highest scoring combination (AVPV) and the two lowest scoring combinations (AVTS and VVTS). There is also a significant difference between the second highest scoring combination (VVPV) and one of the lowest scoring combinations (AVTS) but not the other lowest scoring combination (VVTS). This is odd because the AVTS score virtually identical to the VVTS score, so one would expect the difference between VVTS and VVPV to also be significant. A practical reason for the lack of significance would be the difference in degrees of freedom; this is substantially smaller in the non–significant comparison, which would have made achieving a significant result more difficult. If this is the reason for the non–significance, then repeating this comparison with a larger sample would confirm this.

Finally, because monitoring the on–screen effort allocation indicators was essentially a visual spatial task then according to Wickens's model, the presence of that visual feedback and task of monitoring that visual feedback may cause interference with other visual or spatial tasks. However, this was controlled as much as possible by also presenting the effort allocation feedback during the single task conditions.

14.3 Summary

The results from Study Two revealed a pattern of results that was not apparent in Study One. The first hypothesis in Study Two predicted that there would be no performance decrement as a result of input sense (tactile, proprioceptive, auditory and visual) However, there were significant decrements in performance across all but two dual–task combinations suggesting that a substantial amount of 'resource' sharing had occurred, particularly in the cases of AVTS and VVTS, which were on a par with that suffered in Study One during the PSPV dual–task.

The two dual–tasks that did not suffer any decrement in Study Two were AVPV and VVPV and in fact the performance on these two dual–tasks was better than single task performance. The pattern of these results suggested that performance decrements were not related to input sense but to processing code. However, in contrast with Wickens's model, those dual–tasks with same processing code had better performance than those with different processing code and it was argued that input congruency versus incongruency was a possible causal factor in this.

V: FINAL DISCUSSION

15.1 Overview & Discussion

This research has been prompted by the recent surge of interest in the benefits of haptic displays and their potential to off-load the visual and auditory senses within multi-display environments such as the cockpit. Aircrew are susceptible to visual overload in particular, as modern aircraft place great emphasis on their ability to extract and interpret information from multiple visual displays and visual display modes. Overload is a causal factor in loss of situation awareness, which can have very serious consequences.

The premise that haptic displays could reduce workload is very much based on the MRT of dual-task performance, which was encapsulated in Wickens's MRT Model (1980). MRT argues that within- but not between-sense dual-task interference will occur when tasks compete for the same sensory resource (visual or auditory). Similarly, the theory also argues that within- but not between-processing-code dual-task interference will occur when tasks compete for the same processing code resource (spatial or verbal). Therefore, in theory, because haptic tasks will not be competing for the same sense resource as visual or auditory tasks, then the haptic sense could represent an untapped resource that can be used to off-load these other senses.

However, virtually no studies have addressed concurrent performance of two haptic (tactile or proprioceptive) tasks, which has left the issue of haptic workload capacity and the impact of haptic displays on visual and auditory workload open to speculation. In addition, because haptic tasks have been almost completely left out of research into dual-task performance, theories (including MRT) have been based solely on visual and auditory dual-task findings. However, the haptic sense is a major contributor to information processing and therefore must be considered in the development of any theory of dual-task performance. This research aims to address this gap in knowledge.

In addition, it is possible that current theories of dual-task performance are oversimplistic. The principles behind MRT (i.e. separate resources), can be traced to the traditional hierarchical and modular view of information processing. This is the view that information is processed in increasingly more complex centres, and that sensory inputs are processed in unisensory brain areas before converging at multisensory brain areas towards the end of the process. However, recent neuroscientific findings suggest that multisensory processing can influence processing in 'unisensory' areas of the brain (e.g. Schroeder & Foxe, 2004) and that, whereas multisensory processing often leads to better performance, sometimes it leads to poorer performance (for example, when the inputs are spatially or temporally incongruous) (e.g. Stein et al., 2004). Therefore, one cannot assume that by spreading tasks across different senses to reduce workload, this will in itself always lead to better performance.

Study One examined haptic workload capacity and looked specifically at the tactile and proprioceptive sub–senses as most haptic displays utilise these types of haptic inputs and, because it is possible to lose only one of these sub–senses (e.g. Sacks, 1970), it is possible that these two types of input are treated as separate senses by the brain. The results of Study One suggested that when two concurrent tasks comprised different haptic sub–senses, namely one tactile task and one proprioceptive task, then performance was significantly better than when the two concurrent tasks were both tactile or both proprioceptive in nature (see Figure 60).

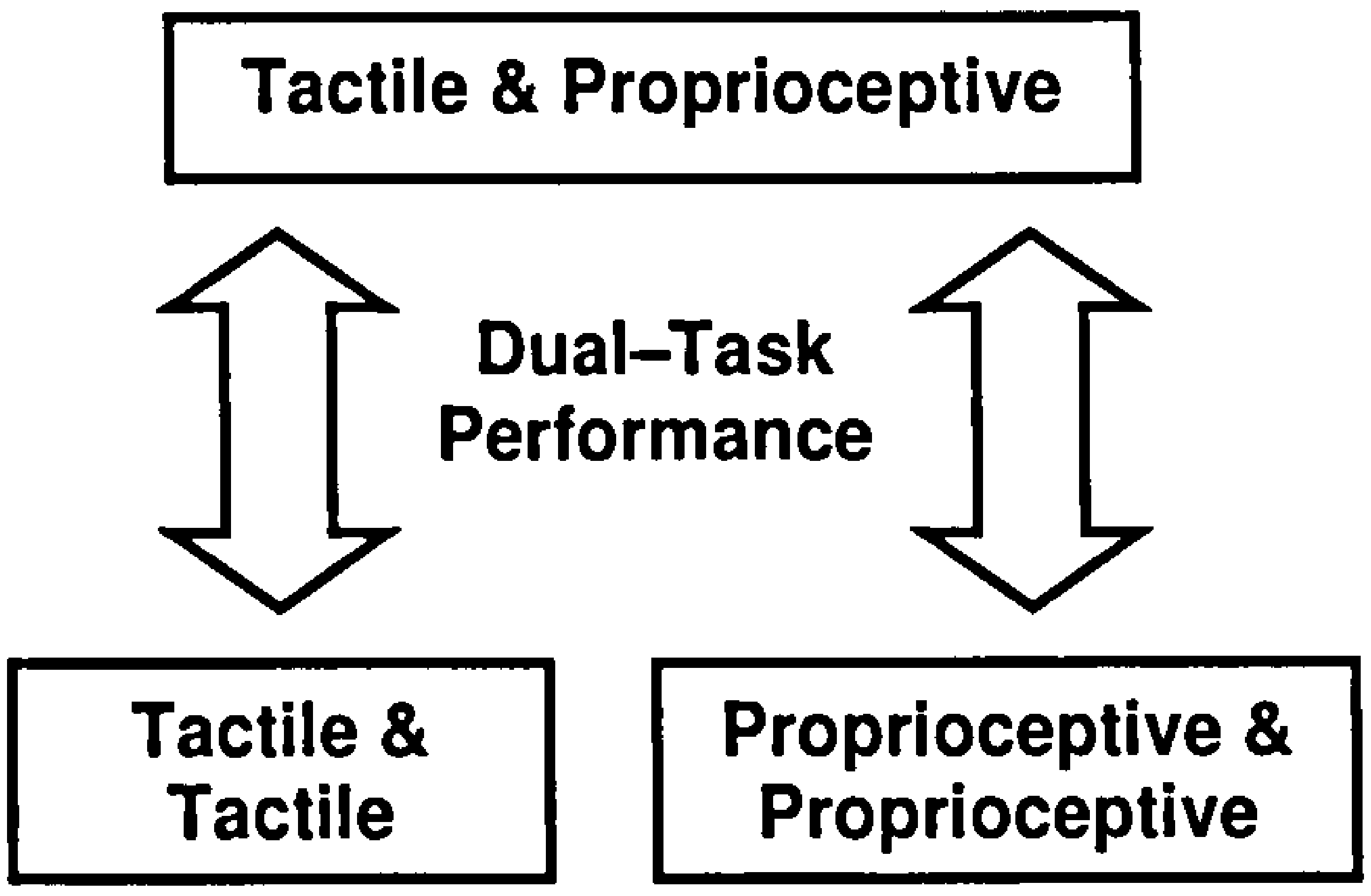


Figure 60: The Results of Study One Summarised

Crucially, there was significant decrement in performance for two concurrent tactile tasks and two concurrent proprioceptive tasks. In fact, the degree of performance decrement represented below 50% of single task performance in the tactile & tactile condition and 60% of single task performance in the proprioceptive & proprioceptive condition, which, in MRT terms indicates complete and approaching complete (respectively) sharing of resources.

Assuming one takes these results to indicate that the tactile and proprioceptive sub–senses are treated as separate senses by the brain (in the same way that the auditory and visual senses are), these findings are in line with MRT and Wickens's MRT Model, whereby two same–sense tasks are associated with significant dual–task decrement. However, this argument is circular because the assumption of sensory separation used here to support MRT, is based on the MRT assumption that sensory separation/ non–separation is a factor in dual–task performance.

Therefore, other explanations need to be explored, especially in light of the recent neuroscientific findings, suggesting that the line between uni–sensory and multisensory processing is more blurred than previously thought. The circularity problem mentioned in the previous paragraph would be less of a problem if in the future supporting evidence for the importance of sensory separation in dual-task performance could be obtained from other disciplines (such as psychophysics or neuroscience). Psychophysical research offers such potential support where the attentional blink phenomenon was found to occur within but not between senses (e.g. Duncan et al., 1997). However, other psychophysical research suggests that it is not sensory separation that is the defining factor in whether interference occurs or not, but input discrimination (e.g. Shapiro et al., 1995). Similarly, neuroscientific research supports the notion that multisensory feedback (and therefore sensory separation) is associated with better performance than unisensory feedback (e.g. Stein et al., 2004). However, more recent neuroscientific research suggests that it is not sensory separation as such that is the important factor but whether the inputs conflict or contradict one another (i.e. whether they are congruent or incongruent) (e.g. Stein et al., 2004). Therefore, there may be other explanations for dual-task results, apart from whether inputs are separable in terms of senses.

Nevertheless, it stands to reason that there will be physiological limitations to processing two inputs at the same time using the same sense, for example, it is not possible to use foveal vision to focus on two things at the same time, as reflected in Wickens's updated MRT Model (2002). Within–sense physiological limitations are indicated by the within–sense attentional blink phenomenon (Duncan et al., 1997), which suggests that an input requires a certain processing time period before a second input of the same sense can be processed. Neuroscientific research also indicates that multisensory inputs are often summated at the single cell level in certain parts of the brain (Stein et al., 2004) and this serves to enhance output from that cell and seems to be reflected by improved performance (Stein et al., 2004). Therefore, as mentioned, there may be other possible explanations for these findings, although, because the notion of resources is an abstract one, one could argue that it simply serves to represent dual–task performance findings, rather than the mechanisms behind these findings. However, this does not solve the issue that the theory behind MRT is rather circular and that therefore it may not be wise to make generalisations from it without demonstrating actual effects and understanding the combined neuroscientific and psychological explanations for the mechanisms behind the effect.

Aside from the theoretical issues mentioned above, the practical implication of these results is that haptic workload is likely to be exceeded if two tactile displays or two proprioceptive displays are presented to the pilot (or other user) at the same time. One can infer therefore that presentation of multiple tactile tasks (such as a navigational task and a targeting task, as proposed by NAMRL for their tactile display called TSAS), would lead to increased haptic workload. On the other hand, these results suggest that haptic workload is less likely to be exceeded if the concurrent haptic displays comprise one tactile display and one proprioceptive display (such as targeting via TSAS and the use of a force–feedback stick).

Wickens's MRT Model (1980) has been modified to incorporate the findings of Study One, see Figure 61. In this figure, the line between the added tactile and proprioceptive resources is dashed to represent the fact that the division between these two sub–senses may not be clear–cut.

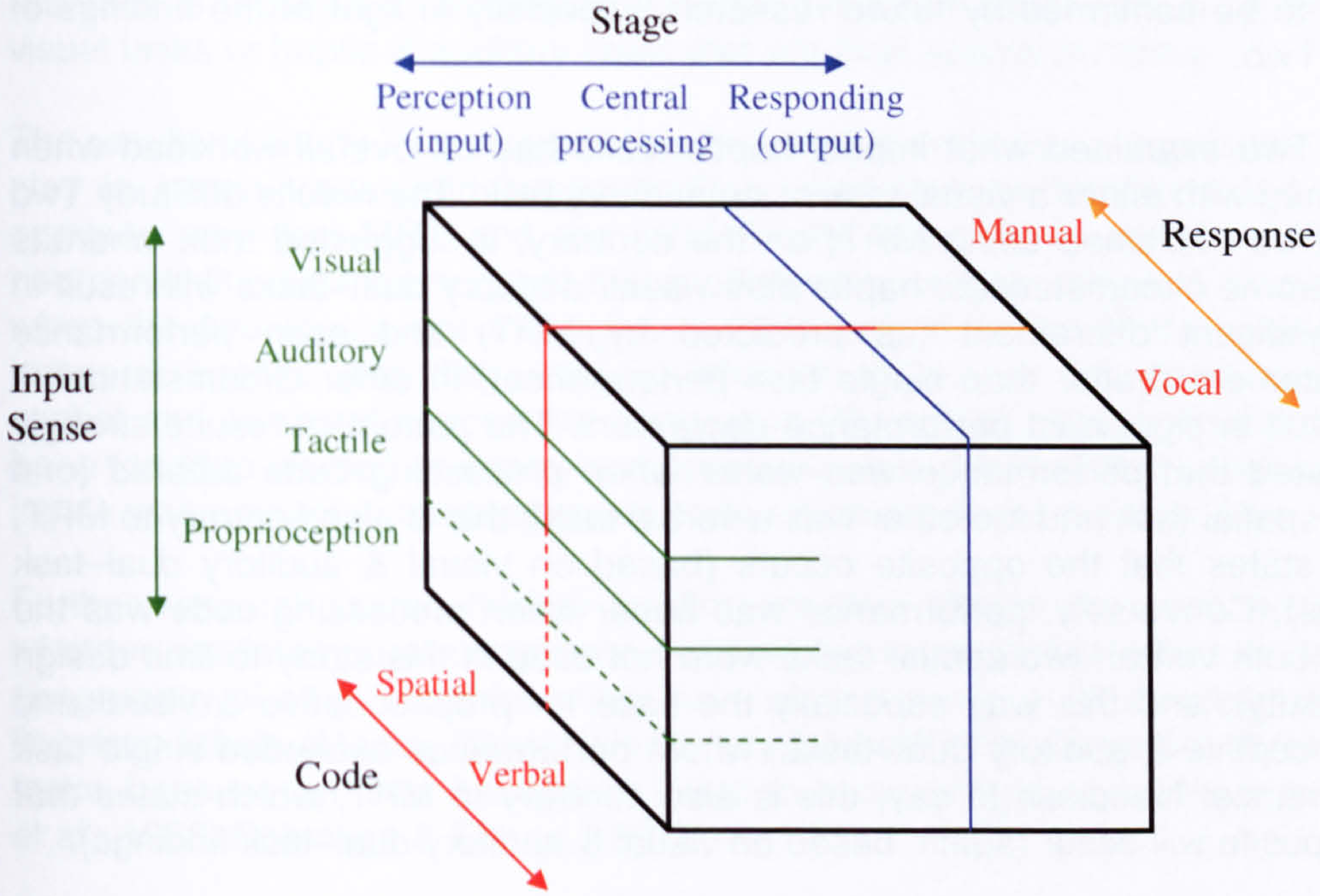


Figure 61: Modification to Wickens's MRT Model (1980) based on the Results of Study One

As explained in the Discussion of Study One, although most of the different–sense (tactile & proprioceptive) conditions yielded reasonably good dual–task performance, one in particular did not do so well. This may be an anomaly but more research needs to be conducted to investigate the reasons behind this. Therefore, the overall thrust of the results suggests separation of tactile and proprioceptive 'resources' but the modification to Wickens's model is a tentative one.

Nevertheless, the results from Study One strongly suggest that two tactile tasks or two proprioceptive tasks are significantly more difficult to perform at the same time than one tactile and one proprioceptive task, and this indicates that the modification to the model in Figure 61 is justified so that this finding can be highlighted.

More research is needed to confirm what role (if any) processing code plays in haptic workload, as although this was not the focus of this thesis, these results were inconclusive in that respect; it was not clear whether better performance was associated with different processing codes or same processing codes. This is represented by the red dashed line dividing the processing codes in the haptic 'boxes'. Note, however, that the two same–haptic–sense conditions had different processing codes; because MRT suggests that this should lead to better performance than if processing codes were the same; one could argue that the dual–task decrement associated with two same–haptic–sense tasks would only increase if processing codes were also the same. However, this needs to be confirmed by future research, especially in light of the findings of Study Two.

Study Two examined what impact haptic tasks had on overall workload when combined with either a visual task or an auditory task. The results of Study Two cannot be explained using MRT; on the contrary, it suggested that, whereas under some circumstances, haptic plus visual/ auditory dual–tasks will result in no significant decrement (as predicted by MRT) and even performance enhancement (better than single task performance), in other circumstances it will result in significant performance *decrement*. The pattern of results strongly suggested that performance was worse when processing code *differed* (one was a spatial task and the other was a verbal task); this is also contrary to MRT, which states that the opposite occurs (based on visual & auditory dual–task findings). Conversely, performance was better when processing code was the *same* (both verbal; two spatial tasks were not used in this study to limit design complexity), and this was especially the case for proprioceptive & visual and proprioceptive & auditory dual–tasks, where performance exceeded single task performance. Needless to say, this is also contrary to MRT, which states that the opposite will occur (again, based on visual & auditory dual–task findings).

Therefore, the results of Study Two reveal exceptions to two MRT 'rules'; the sensory resource rule and the processing code rule, where the exact opposite effects were shown to occur. These results are summarised in Figure 62.

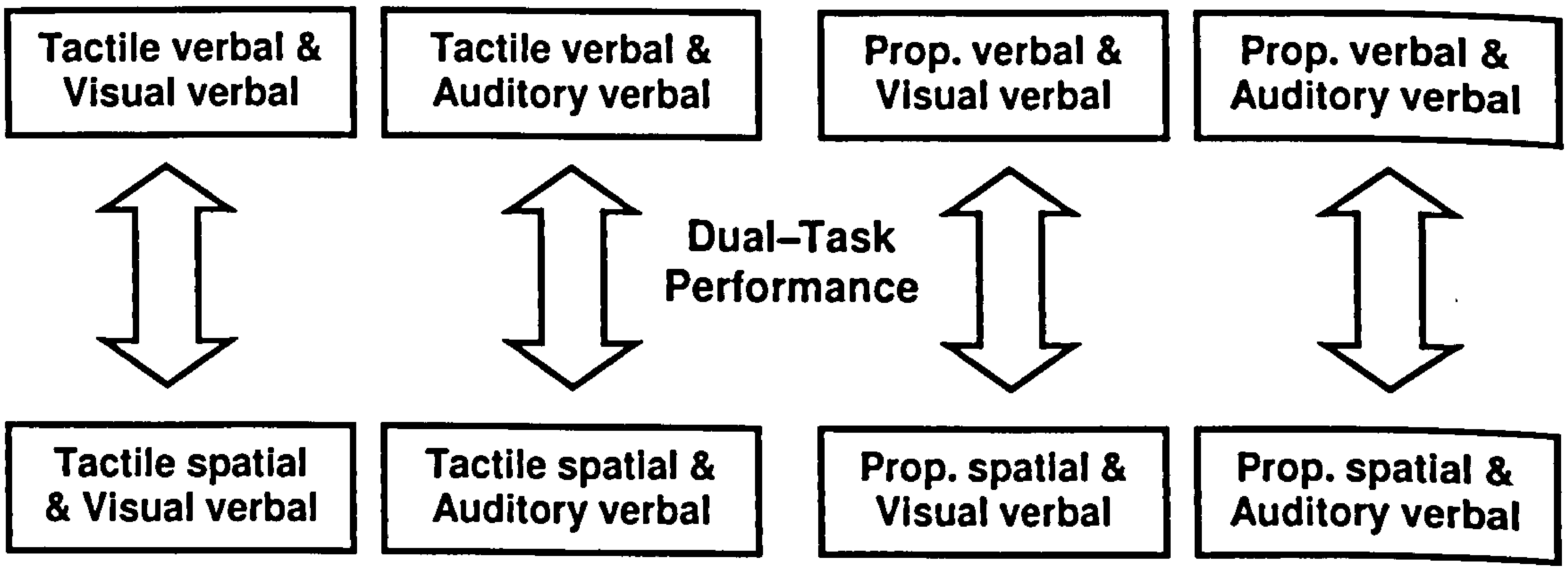


Figure 62: The Results of Study Two Summarised (note Prop. refers to Proprioceptive)

The practical implication of these findings is that, whereas one would expect workload to improve when visual or auditory tasks are offloaded onto the haptic sense, sometimes the opposite will occur and workload will not improve or it could even deteriorate. More specifically, these findings suggest that if a haptic task is verbal in nature (for example, the TSAS targeting task) and a concurrent visual or auditory task is also verbal in nature (for example radio communication), then performance will be better than if one of the tasks being performed is spatial in nature (for example, the TSAS navigation task). Further research is required to investigate whether the same effect occurs for haptic & visual tasks or haptic & auditory tasks that are both *spatial* in nature.

The results of Study Two suggest that processing code has a significant role to play in haptic–visual and haptic–auditory dual–task performance but in the opposite way that MRT and the MRT Model would have predicted. Recent neuroscientific findings suggest that multisensory cellular output is 'dampened' when the two inputs are incongruous (different) in terms of the spatial and temporal spaces that they occupy, whereas output is enhanced when the spatial and temporal spaces are congruous (the same), and performance has been found to worsen or improve, respectively. It is possible that congruency of inputs was a factor in the processing code effect observed in Study Two.

Further research is required to confirm whether this is the case and if so, whether spatiotemporal congruency was at the heart of this effect or whether congruency of other variables might have played a role, such as congruency of linguistic labels (Marks, 2004), which may be particularly relevant to symbolic tasks, because symbols have been found to access linguistic labels (e.g. Potter et al., 1980; Robinson & Eberts, 1987).

It is also unclear whether the congruency effects observed by neuroscientific research occurs instead of or in addition to the processing code effects observed in previous dual–task research; if it occurs in addition to the processing code effect, then it is important to know whether the two effects occur independently or in concert with each other.

As mentioned, Study Two revealed exceptions to the MRT rules regarding sensory resources and processing code resources, and although it is a fairly isolated dual–task finding against the backdrop of decades of dual–task research, one could argue that this is in some way related to the fact that previous research was almost exclusively limited to visual and auditory inputs. In addition, in previous dual–task research, the verbal tasks involved speech or the visual equivalent of verbal tasks (e.g. text or other symbology), whereas in this study the verbal tasks involved the communication of information through haptic symbology. Although research suggests symbolic tasks use the same processing resource as strictly verbal tasks (see Section 6.2), this difference may have played a part in revealing the exception. Nevertheless, future research should also investigate why this effect has emerged in this study but not in the past for the dual–tasks limited to visual and auditory inputs.

An hypothetical 'input congruency matrix' (see Figure 63) has been drawn to amalgamate some of the principles of MRT with those of the neuroscientific findings on congruency mentioned earlier.

Congruous Inputs (C)/ Incongruous Inputs (I)

	C	I	C	I	C	I
VISUAL						
AUDITORY						
TACTILE						
PROPRIOCEPTIVE						
	VV	VV	VS	VS	SS	SS

VERBAL (V) / SPATIAL (S)

Figure 63: Input Congruency Matrix

In this matrix, tactile and proprioceptive inputs are treated as separate sensory inputs to emphasise the same–sense results of Study One. MRT spatial versus verbal processing codes are represented in three combinations of processing code (verbal & spatial, verbal & verbal, and spatial & spatial). However, in line with the results of Study Two and recent neuroscientific findings, it is suggested that performance within these combinations will be affected by whether the concurrent inputs are congruous or incongruous, with the latter associated with greater performance decrement than the former. Note that more research is required to understand the conditions when congruency is a factor and when it is not.

In essence, when multi–sensory inputs appear to be related to the same event (i.e. they are congruous) then it is believed that the natural tendency of the brain is to preferentially select these inputs over incongruous inputs (as mentioned in Section 3.1.1 with reference to selective attention) and then integrate these congruent inputs (as mentioned in Section Four). This integration of congruous inputs is reflected firstly at the single cell level by summation of congruous multisensory inputs (Stein et al., 2004), resulting in cellular output enhancement and secondly by subsequent performance enhancement (Stein et al., 2004). The rationale is probably that if more than one sense appears to corroborate the details of an event then greater importance is be placed upon those inputs. However, the brain must make choices when it comes to apparently incongruous inputs, choices over which sense is likely to be correct and the degree to which overall output is dampened (i.e. to reduce the level of importance placed upon the inputs) (King, 2004; Stein et al., 2004).

It is clear that Wickens's MRT Model is over simplistic and that greater complexity is required to account for situations where different–sense and different–code inputs may result in significant decrement and vice versa. The matrix in Figure 63 improves on Wickens's MRT Model (1980) by taking into account the importance of input congruency in concurrent multisensory input processing. It is not suggested that the results of Study Two can be explained by the congruency effect, but simply that, because this is an effect that has been shown to exist in multisensory processing, then it is one possible explanation for the results and any model of dual–task processing must take it into account. Naturally, further research is required to understand the exception to the MRT rules revealed in Study Two and confirm whether congruency of inputs had anything to do with it.

An important area for future research is the question mark about the definition of congruous versus incongruous inputs. However, although spatial and temporal congruency has been highlighted as important by recent neuroscientific research, the congruency of other factors may also be important in determining whether multisensory inputs are associated with performance decrement or enhancement.

Possible Shortcomings of the Research

It is important to note that dual-task decrements may not always be due to resource-sharing, but may indicate inadequate quantity or quality of information available to the participant (i.e. data limitations) (Norman & Bobrow, 1975). The performance operating characteristic (POC) method described in Section Five enables the researcher to judge whether it is the former or the latter that is the main cause of the dual-task decrement. This method demands that the participant allocate a specific proportion of their resource(s) to each task, and in this research the proportions were 25% to task one and 75% to task two, then 50% to task one and 50% to task two, and finally, 75% to task one and 25% to task two. This produces a series of data points along a curve (the POC curve) and it is the overall shape of this curve that suggests whether performance decrements occurred as a result of resource limitations (where a performance trade-off between the two tasks will exist) or data limitations (where task one performance will be independent of task two performance), as mentioned in Section Three.

The problem with this is how allocation of resources can be controlled. Resource allocation feedback (described in Section Five) was used to try to counter this problem; this feedback was crucial as it enabled the participant to adjust his/ her effort to each task so that allocation of resources could be controlled as much as possible. However, even with this technique, which required monitoring of and responding to the on-screen resource allocation feedback, complete control was not possible; participants seemed to lapse focus now and again, which sometimes led to less than ideal proportional resource allocation and this is revealed in the results. For example, the proprioceptive spatial and proprioceptive verbal dual-task (PSPV), Figure 11, shows that the 50% and 50% data point is very close to the 75% and 25% data point. The position of these two data points suggests that participants allocated 50% to each task in both circumstances, despite the feedback they received. This does not alter the overall thrust of the results for this dual-task, because each data-point suggests a performance trade-off that is explicable in terms of resource sharing rather than data-limitations. This is further supported by the fact that both the tactile verbal and proprioceptive spatial dual-task (TVPS), Figure 15, and the tactile verbal and proprioceptive verbal dual-task (TVPV), Figure 16, are associated with significantly better performance than the PSPV dual-task, suggesting that the decrement in the PSPV dual-task is probably not due to data-limitations. The same can be said for other dual-tasks that reveal imperfect proportional allocation of resources, when, despite this, overall trade-offs are apparent and comparisons to other dual-tasks also suggest resource sharing. However, imperfect allocation of resources does highlight the challenge that researchers and participants face when it comes to controlling resource allocation and it emphasises the need for more research into understanding and tackling this issue.

Single tasks were presented with resource allocation feedback so that any interference caused by the presence of the feedback was controlled. Any interference from the on–screen feedback would not come from the act of allocating and controlling resources, which in itself has not been found to require any workload 'resources' (De Shon et al., 1996). However, what was not present during the single task trials was the *need* to allocate and control resources and therefore to a great extent, less attention needed to be paid to the feedback, thereby reducing the potential for interference in the single task conditions anyway. This would be an issue to investigate in future research.

Because the resource allocation feedback relied upon single task scores, single tasks were always performed before dual-tasks and it is worth acknowledging that trial order may have been a potential confounding variable. However, (a) it was decided that the potential benefits of using the resource allocation feedback outweighed the potential benefits of counterbalancing the single and dual tasks and (b) with the single to dual-task order the same across all of the dual-tasks, it did not remove from the key issue of interest, the *relative differences between each dual-task compared with each other and their respective single task scores.* However, as mentioned in the Method to Study One, the order of tasks within the single task condition was counterbalanced, as was the order of dual-tasks and this was the key to minimising the effects of fatigue and practice. The same counterbalancing applied in Study Two.

It was not possible to measure the exact forces exerted by the proprioceptive device (the Force Feedback Two joystick by Microsoft) but the forces exerted were undoubtedly above detection threshold in the pilot trials and this is not surprising given the very low detection threshold of the force sensors in the joints and tendons (Tan et al., 1994). It is worth pointing out that the purpose of the experiments was to measure difference in performance from the single task to the dual–task condition and that, because participants were able to detect targets in the single task conditions, then this was taken as indication that forces were above minimum threshold, which would obviously also apply to the dual–task condition. However, readers may like to know the range of forces exerted by the device and this would probably be straightforward to find out by contacting the makers of the joystick (Microsoft) for this information.

The input devices available for this research were positioned optimally to enable the various combinations of tasks to be performed in the most practical and comfortable way. This meant that, for example in Study Two, one device occupied the space in front (visual), one task occupies space to sides of head simultaneously (auditory) and the others occupy either the right or left space somewhere between directly in front and directly to the sides (tactile and proprioceptive tasks). Neuroscientific evidence suggests that the spatial relationship (as well as temporal relationship) between concurrent inputs is important in determining whether performance suffers or is enhanced. Therefore this aspect would need to be controlled in future research to determine the importance of congruency of inputs in dual–task performance.

All responses were made manually (rather than vocally and manually) so that this aspect of the design was controlled. The most practical way of making responses was using the joystick. For most dual–tasks this meant that one joystick was used per task. The exception to this was when participants were presented with two tactile tasks at the same time. In this circumstance, all feedback came via the same glove and, because of the configurations necessary to realise each combination of tasks, responses to both tactile tasks were made using the same joystick (albeit through three different thumb buttons, one for the tactile spatial task and two for the tactile verbal task). This was not necessarily ideal but was unavoidable as only one glove was available and this happened to be a left–hand glove. This may have contributed the difficulty in performing the two tactile tasks at the same time and would need to be investigated in future research. However, in the pilot trials, two different tactile devices were tested and responses were made using different hands; yet the same effect was observed. Note that it was not possible to use this additional tactile device in the two studies because it would have resulted in too many occasions where different hands were used for the same devices, many more practise and single task conditions and the introduction of another variable.

15.2 Summary

The two aims of this thesis were to (a) establish whether the performance of two haptic tasks at the same time would exceed haptic workload capacity and (b) to establish whether the performance of a haptic task and a visual or auditory task at the same time would exceed overall workload capacity. The aims of the thesis have been satisfied and the predictions that one could make from the results of Study One and Study Two are as follows:

(a) Concurrent same–haptic–sense tasks (two tactile or two proprioceptive tasks) result in significantly greater performance decrement than concurrent different–haptic–sense tasks (a tactile task and a proprioceptive task). This is in line with MRT regarding concurrent same–sense visual or auditory tasks versus concurrent different–sense (visual and auditory) tasks.

(b) Concurrent different–sense tasks (a tactile or proprioceptive task with a visual or auditory task) may result in either no performance decrement or significant performance decrement, depending upon processing code. However, contrary to MRT, these results suggest that worse performance is associated with different–processing–codes (verbal and spatial) and better performance is associated with same–processing–codes (verbal and verbal). This could be related to the principle of input congruency highlighted by recent neuroscientific findings.

VI: CONCLUSION

This research has been prompted by the recent surge of interest in the benefits of haptic displays and their potential to off–load the visual and auditory senses within multi–display environments such as the cockpit. Aircrew are susceptible to visual overload in particular, as modern aircraft place great emphasis on their ability to extract and interpret information from multiple visual displays and visual display modes. Overload is a causal factor in loss of situation awareness, which can have very serious consequences, including 'controlled flight into terrain' (CFIT) accidents, which occur when pilots inadvertently fly their aircraft into terrain. Haptic displays already exist that provide continuous situation feedback to the pilot, to prevent loss of situation awareness and to free up the visual system (see: McGrath et al., 1998; McTrusty & Walter, 1997; Raj et al., 1998; 2000; Rochlis & Newman, 2000; Rupert, 2000; Rupert et al., 1999; 1994; 1990). It could therefore be expected that installing such a device into the cockpit would reduce the occurrence of CFIT accidents.

There are essentially two types of haptic display, tactile and proprioceptive displays. Tactile displays provide feedback in the form of vibrations and proprioceptive displays provide feedback in the form of force–feedback. For pilots, tactile devices such as TSAS (NAMRL) can offer real solutions to the challenges of overload, spatial disorientation and ensuring situation awareness at all times. On the other hand, proprioceptive displays have been shown to improve control accuracy (for example, the turbulence control stick developed at AFRL, WPAFB) during extreme weather conditions.

The premise that haptic displays could reduce workload is very much based on the MRT of dual–task performance, which was encapsulated in Wickens's MRT Model (1980). MRT argues that within– but not between–sense dual–task interference will occur when tasks compete for the same sensory resource (visual or auditory). Similarly, the theory also argues that within– but not between–processing–code dual–task interference will occur when tasks compete for the same processing code resource (spatial or verbal). Therefore, in theory, because haptic tasks will not be competing for the same sense resource as visual or auditory tasks, then the haptic sense could represent an untapped resource that can be used to off–load these other senses.

The principles behind MRT (i.e. separate resources), can be traced to the traditional hierarchical and modular view of information processing. This is the view that information is processed in increasingly more complex centres, and that sensory inputs are processed in unisensory brain areas before converging at multisensory brain areas towards the end of the process. However, it is possible that current theories of dual–task performance are oversimplistic. Recent neuroscientific findings suggest that multisensory processing can influence processing in 'unisensory' areas of the brain (e.g. Schroeder & Foxe, 2004) and that, whereas multisensory processing often leads to better performance, sometimes it leads to poorer performance (for example, when the inputs are spatially or temporally incongruous) (e.g. Stein et al., 2004). Therefore, one cannot assume that by spreading tasks across different senses to reduce workload, this will in itself always lead to better performance.

Virtually no studies have addressed concurrent performance of two haptic (tactile or proprioceptive) tasks before, which has left the issue of haptic workload capacity and the impact of haptic displays on visual and auditory workload open to speculation. In addition, because haptic tasks have been almost completely left out of research into dual–task performance, theories (including MRT) have been based solely on visual and auditory dual–task findings. However, the haptic sense is a major contributor to information processing and therefore must be considered in the development of any theory of dual–task performance. This research aimed to address this gap in knowledge.

If the point of introducing haptic displays into environments such as the cockpit is to off–load other senses, then it is important to know that:

(a) The haptic sense will not itself become overloaded.

(c) The haptic sense does not share workload processes with the other senses.

This programme of work addressed these concerns through the following two research objectives:

1. To examine whether multiple haptic inputs can be processed at the same time without performance decrement — Study One

2. To examine whether haptic inputs can be processed at the same time as visual or auditory inputs without performance decrement — Study Two

This knowledge is important to have so that sensible decisions can be made regarding what and how many haptic displays can be presented to the user at the same time and what affect these haptic displays may have upon visual and auditory information processing.

The objectives of the thesis were satisfied and the conclusions that have been made from the results of Study One and Study Two are as follows:

1. Concurrent same–haptic–sense tasks (two tactile or two proprioceptive tasks) result in significantly greater performance decrement than concurrent different–haptic–sense tasks (a tactile task with a proprioceptive task). This is in line with MRT regarding concurrent same–sense visual or auditory tasks versus concurrent different–sense (visual and auditory) tasks.

2. Concurrent different–sense tasks (a tactile or proprioceptive task with a visual or auditory task) may result in either no performance decrement or significant performance decrement, depending upon processing code, which cannot be explained by MRT. Also contrary to MRT, these results strongly suggest that worse performance is associated with different–processing–codes (verbal and spatial) and better performance is associated with same–processing–codes (verbal and verbal). This could be related to the principle of input congruency highlighted by recent neuroscientific findings.

Therefore, this research suggested that two different haptic displays can be used at the same time with significantly less decrement in performance than two haptic displays of the same type (either both tactile or both proprioceptive in nature). This will be of interest to human factors and engineering practitioners.

In addition, the fact that the brain appears to treat tactile versus proprioceptive tasks as different types of tasks (in the same way as visual versus auditory tasks are treated), may be of interest to psychologists and neuroscientists involved in research into the haptic sense and multisensory information processing in general.

However, the results of Study Two suggest that on the introduction of haptic displays into environments such as the cockpit, overall workload will be determined by other task related factors and not just input sense. The pattern of results revealed that workload was improved when processing code was the same for both tasks, and worse when processing code was different for both tasks.

Conventional task analysis or cognitive task analysis would identify whether inputs are tactile, proprioceptive, visual or auditory in nature as well as whether the tasks themselves involved spatial or verbal processing. This would enable the designer or engineer to pinpoint any potential conflicts in terms of shared resources.

To be specific, the following guidelines can be offered regarding the sharing of haptic tasks:

1. **It is recommended that the concurrent performance of two tactile tasks (utilising vibration feedback) be avoided.** If this is unavoidable, then significant performance decrements on both tasks should be expected and, therefore, it is suggested that baseline performance on both tasks be their dual-task performances rather than their single task performances. The amount of performance decrement on both tasks in the dual-task condition during this research was around 50% on both tasks compared with their single task performances. However, more research is needed to add weight to these recommendations and findings. There may be circumstances where this decrement would not occur but, in the absence of such findings at present, it is clearly safer to assume that significant decrements would occur.

2. **It is recommended that the concurrent performance of two proprioceptive tasks (utilising force feedback) be avoided.** As above, if this is unavoidable, then significance performance decrements on both tasks should be expected and, therefore, it is suggested that baseline performance on both tasks be their dual-task performances rather than their single task performances. The amount of performance decrement on both tasks in the dual-task condition during this research was between 40% and 50% compared with their single task performances. However, as above, more research is needed to add weight to these recommendations and findings. Again, there may be circumstances where this decrement would not occur but, in the absence of such findings at present, it is clearly safer to assume that significant decrements would occur.

3. **It is tentatively suggested that the concurrent performance of one tactile task and one proprioceptive task (i.e. one vibration task and one force-feedback task respectively) is acceptable.** However, in this research, this combination resulted in some dual-task performance decrements (between 10% and 30%) and more research is needed to confirm the reasons for these decrements as it is suspected that this may be related to other factors such as processing code or input congruency.

4. **It is tentatively suggested that the concurrent performance of one haptic task (either tactile or proprioceptive) and one visual task is acceptable where processing codes are the same for both tasks (specifically, they are both verbal in nature as opposed to one verbal and one spatial).** However, it should be noted that, where haptic and visual tasks are concerned, the term verbal is used to denote tasks that are symbolic or 'emblematic' of verbal labels. More research is needed to confirm whether similar findings occur when the same processing code tasks are both spatial in nature. It should also be noted that these findings are not consistent with previous processing code research utilising only non haptic tasks and that more research is required to add weight to this recommendation and to confirm that it is processing code and not another factor such as congruency of inputs that determines performance decrements in these multisensory tasks. More research is required to understand why these findings were revealed using haptic tasks when they have not been revealed using only non haptic tasks.

5. **It is tentatively suggested that the concurrent performance of one haptic task (either tactile or proprioceptive) and one auditory task is acceptable where processing codes are the same for both tasks (specifically, they are both verbal in nature as opposed to one verbal or one spatial).** However, all the same caveats apply as above.

These results reveal an exception to two key MRT rules, the sensory resource rule and the processing code rule. The conclusion was that MRT and the Wickens's MRT Model (1980) may be oversimplistic and that other factors, such as the principle of congruency highlighted by recent neuroscientific research, should be taken into account in any theory and model of dual–task processing. It is beyond the scope of this thesis to offer a definitive explanation for these findings but it is the starting point for long–term investigation into why these exceptions have been revealed using haptic inputs after decades of auditory and visual dual–task research.

With these findings in mind, it is crucial to choose haptic displays where benefits have been demonstrated and human factors issues fully explored. Conversely it is equally important that the potential benefits of haptic devices are not ignored simply because there is much work to be done in the process of confirming their effectiveness and safety. This is especially important in light of research findings into the primary causes of aviation fatalities, and the potential preventative benefits of haptic displays and multi–sensory information presentation.

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APPENDIX A: PILOT TRIALS

METHOD FOR PILOT TRIALS

DESIGN

The overall design was repeated measures with counterbalancing. Participants were asked to perform a multitude of different tasks. First of all, each task was performed by itself (single task condition) and then each task was performed with other task in pairs (dual–task condition). The goal was to see if certain dual–task combinations were easier to perform than other dual–task combinations. In order to measure performance, performance on each task within the dual–task pair was compared to respective single task performance.

INDEPENDENT VARIABLES

Independent Variable One: Task

- Task one — left–hand side
- Task two — right–hand side

Independent Variable Two: Priority

- 0%
- 25%
- 50%
- 75%
- 100%

Independent Variable Three: Input Sense

- Proprioceptive
- Tactile

Independent Variable Four: Input Processing Code

- Spatial
- Verbal

Independent variable three and four meant that there were the following task conditions:

- Proprioceptive Verbal
- Proprioceptive Spatial
- Tactile Verbal
- Tactile Spatial

Independent Variable Five: Task two *Input Sense Difficulty*

- Easy
- Difficult

Independent Variable Six: Task two *Input Coding Difficulty*

- Easy
- Difficult

Independent Variables five and six meant that there were the following variations for task two:

- Input Modality (easy) _ Coding (easy)
- Input Modality (easy) _ Coding (difficult)
- Input Modality (difficult) _ Coding (easy)
- Input Modality (difficult) _ Coding (difficult)

One example is as follows:

- Tactile (easy) _ Verbal (easy)
- Tactile (easy) _ Verbal (difficult)
- Tactile (difficult) _ Verbal (easy)
- Tactile (difficult) _ Verbal (difficult)

The tasks were as follows:

Tactile Verbal (using the glove)

The aim was to respond in the correct way to information that has been coded into vibrations from the glove 'tactors' that differed in terms of their rhythm and number of choices. Responses were made using the joystick, which was gripped whilst wearing the glove.

There were four variations:

Tactile (easy) Verbal (easy)
Easy to discriminate between rhythms (very different wave–forms)
Only two choices (friend and enemy)

Tactile (easy) Verbal (difficult)
Easy to discriminate between rhythms (very different wave–forms)
Four choices (friend one, friend two, enemy one and enemy two)

Tactile (difficult) Verbal (easy)
Difficult to discriminate between rhythms (very similar wave–forms)
Only two choices (friend and enemy)

Tactile (difficult) Verbal (difficult)
Difficult to discriminate between rhythms (very similar wave–forms)
Four choices (friend one, friend two, enemy one and enemy two)

Tactile Spatial (using the glove)

The aim was to respond in the correct way to vibrotactile information that represents spatial reference points. Responses were made using the joystick, which is gripped whilst wearing the glove.

To be more specific, the gloved hand gripped the joystick so that a specific tactor referred to forward, back, left and right. The idea was to move the joystick away from the vibrating tactor until the vibrations stopped. The participant was told that the vibrations represented distance from the target and the intensity increased the further away he/she was from it. When the vibrations stopped the participant pressed the 'fire' button on the joystick. This process continued until time was up.

There was only one variation as this task was only ever used for Task One:

Tactile (easy) Spatial (easy)
Easy to detect intensities
Intuitive spatial reference points.

Tactile Verbal (using the mouse)

The aim was to respond in the correct way to information that had been coded into vibrations that represented, in 'Morse Code' terms, either a 'dot' or a 'dash'. Vibrations were felt through the mouse and responses were made using the left mouse button for dots and right mouse button for dashes.

There was only one variation as this task was only ever used as Task One

Tactile (easy) Verbal (easy)
Easy to discriminate between dots and dashes (very different durations)
Only two choices (i.e. dot or dash)

Tactile Spatial (using the mouse)

The aim was to respond in the correct way to vibrotactile stimuli through the mouse that represented different shapes superimposed on the desktop (i.e. in 2–dimensional space). The task varied in terms of the complexity of shapes and discriminability of shape 'edges' against the background noise.

Responses were made by pressing the left mouse button for squares, right mouse button for circles and the 'wheel' for triangles.

There were four variations:

Tactile (easy) Spatial (easy)
Easy to discriminate between background 'noise' and shape 'edges'
Two choices between very different shapes (square and triangle)

Tactile (easy) Spatial (difficult)
Easy to discriminate between background 'noise' and shape 'edges'
Two choices between very similar shapes (square and circle)

Tactile (difficult) Spatial (easy)
Difficult to discriminate between background 'noise' and shape 'edges'
Two choices between very different shapes (square and triangle)

Tactile (difficult) Spatial (difficult)
Difficult to discriminate between background 'noise' and shape 'edges'
Two choices between very similar shapes (square and circle)

Proprioceptive Verbal (using the joystick)

The aim was to respond correctly to information that had been coded into forces using the force–feedback joystick. The task varied on discriminability of 'codes' and number of choices. Responses were made using the joystick, by pressing the button that corresponded with that warning.

There were four variations:

Proprioceptive (easy) Verbal (easy)
Easy to discriminate between forces (very different force profiles)
Only two choices (collision and puddle)

Proprioceptive (easy) Verbal (difficult)
Easy to discriminate between forces (very different force profiles)
Three choices (collision, puddle, and fog)

Proprioceptive (difficult) Verbal (easy)
Difficult to discriminate between forces (very similar force profiles)
Only two choices (collision and puddle)

Proprioceptive (difficult) Verbal (difficult)
Difficult to discriminate between forces (very similar force profiles)
Three choices (collision, ramp and gusts)

Proprioceptive Spatial (using the joystick)

The aim was to find a target using force–feedback from the joystick. The forces differed in terms of intensity of feedback against background noise and the task differed in terms of spatial complexity. Feedback came in the form of resistance and nudges. Responses were made by pressing the joystick 'fire' button once the target was found.

There were four variations:

Proprioceptive (easy) Spatial (easy)
Easy to discriminate between feedback against the background noise.
Large target, which was easy to find. Single 'path' then target

Proprioceptive (easy) Spatial (difficult)
Easy to discriminate between feedback against the background noise.
Small target, which was hard to find. Choice of two 'paths' then target

Proprioceptive (difficult) Verbal (easy)
Hard to discriminate between feedback against the background noise.
Large target, which was easy to find. Single 'path' then target

Proprioceptive (difficult) Verbal (difficult)
Hard to discriminate between feedback against the background noise.
Small target, which was hard to find. Choice of two 'paths' then target

DEPENDENT VARIABLE

Dependent Variable: Dual–Task Performance (number of hits)

- Task one number of hits
- Task two number of hits

Task one and Task two could be any of the four main tasks listed in Table 100 below, in which the associated dependent variable is also listed. Note that, each of these tasks varied on difficulty but the dependent variables for these tasks remained the same throughout.

Table 100: dependent variables for the Pilot Trials

Task Condition (IV 3 & IV 4)	Dependent Variable
Proprioceptive Spatial	Number of targets correctly positioned (referred to as hits) using force feedback
Proprioceptive Verbal	Number of correct responses (referred to as hits) to warning–related information pertaining to aircraft flying handling, presented through force feedback
Tactile Spatial	Number of times the aircraft is correctly oriented (referred to as hits) towards a target, using vibration feedback
Tactile Verbal	Number of correct responses (referred to as hits) to target–related information presented using vibration feedback

CONDITIONS IN DETAIL

Single task Conditions

The single task conditions (listed below) were performed in order to have a control by which to compare dual–task performance. They were performed by themselves and therefore allow 100% resource allocation. Note that the single task condition is different from the dual–task condition where resource allocation is 100_0 or 0_100, because, in the latter, two tasks are presented at the same time despite 100% allocation towards one of the tasks. In the latter case, distraction may occur and this cannot be said to be a fair representation of single–task performance. It was important to use true single tasks as the comparison to the dual–tasks so that a true reflection of any dual–task decrement or enhancement could be obtained.

Each numbered line represents one experiment lasting one minute.

Proprioceptive Verbal Tasks

1. Proprioceptive (easy) Verbal (easy) – 100% RA
2. Proprioceptive (easy) Verbal (difficult) – 100% RA
3. Proprioceptive (difficult) Verbal (easy) – 100% RA
4. Proprioceptive (difficult) Verbal (difficult) – 100% RA

Proprioceptive Spatial Tasks

5. Proprioceptive (easy) Spatial (easy) – 100% RA
6. Proprioceptive (easy) Spatial (difficult) – 100% RA
7. Proprioceptive (difficult) Spatial (easy) – 100% RA
8. Proprioceptive (difficult) Spatial (difficult) – 100% RA

Tactile Verbal Tasks

9. Tactile (easy)	Verbal (easy)	– 100% RA
10. Tactile (easy)	Verbal (difficult)	– 100% RA
11. Tactile (difficult)	Verbal (easy)	– 100% RA
12. Tactile (difficult)	Verbal (difficult)	– 100% RA

Tactile Spatial Tasks

13. Tactile (easy)	Spatial (easy)	– 100% RA
14. Tactile (easy)	Spatial (difficult)	– 100% RA
15. Tactile (difficult)	Spatial (easy)	– 100% RA
16. Tactile (difficult)	Spatial (difficult)	– 100% RA

Dual task Conditions

The dual–task conditions required two tasks to be performed at the same time and therefore potentially required a certain amount of resource division. The task combinations include:

1. PV_PV — Proprioceptive Verbal & Proprioceptive Verbal
2. PS_PS — Proprioceptive Spatial & Proprioceptive Spatial
3. TV_TV — Tactile Verbal & Tactile Verbal
4. TS_TS — Tactile Spatial & Tactile Spatial
5. PV_PS — Proprioceptive Verbal & Proprioceptive Spatial
6. TV_TS — Tactile Verbal & Tactile Spatial
7. PV_TV — Proprioceptive Verbal & Tactile Verbal
8. TS_PS — Tactile Spatial and Proprioceptive Spatial
9. TV_PS — Tactile Verbal & Proprioceptive Spatial
10. PV_TS — Proprioceptive Verbal & Tactile Spatial

However, each combination had to vary on policy and on difficulty (although note that only task two varies on difficulty). The following table is a sample from the above list of dual–tasks. Each of the numbered points (1.a.; 1.b.; 1.c.; and 1.d.) within the table represents one dual–task at one difficult level but within that table it varies on resource allocation policy. Because each resource allocation policy was presented for one minute, there were five minutes worth of resource allocation policies (one minute per policy) per individual table. Because there were four difficulty levels per dual–task, the total time taken per dual–task was four difficulty levels by five minutes of policies, i.e. twenty minutes per dual–task. There were ten dual–tasks and therefore total dual–task time came to two hours. Coupled with the sixteen minutes worth of single tasks (one minute per single task), total experimental time required by each participant came to two hours and sixteen minutes. This did not include practice time.

Table 101: A sample of the dual–tasks for the Pilot Trials in more detail – Proprioceptive Verbal (Task One) & Proprioceptive Verbal (Task Two)

1.a.	Task one	Proprioceptive (easy)	Verbal (easy)	100% RA
	Task two	Proprioceptive (easy)	Verbal (easy)	0% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	75% RA
	Task two	Proprioceptive (easy)	Verbal (easy)	25% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	50% RA
	Task two	Proprioceptive (easy)	Verbal (easy)	50% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	25% RA
	Task two	Proprioceptive (easy)	Verbal (easy)	75% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	0% RA
	Task two	Proprioceptive (easy)	Verbal (easy)	100% RA
1.b.	Task one	Proprioceptive (easy)	Verbal (easy)	100% RA
	Task two	Proprioceptive (easy)	Verbal (difficult)	0% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	75% RA
	Task two	Proprioceptive (easy)	Verbal (difficult)	25% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	50% RA
	Task two	Proprioceptive (easy)	Verbal (difficult)	50% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	25% RA
	Task two	Proprioceptive (easy)	Verbal (difficult)	75% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	0% RA
	Task two	Proprioceptive (easy)	Verbal (difficult)	100% RA
1.c.	Task one	Proprioceptive (easy)	Verbal (easy)	100% RA
	Task two	Proprioceptive (difficult)	Verbal (easy)	0% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	75% RA
	Task two	Proprioceptive (difficult)	Verbal (easy)	25% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	50% RA
	Task two	Proprioceptive (difficult)	Verbal (easy)	50% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	25% RA
	Task two	Proprioceptive (difficult)	Verbal (easy)	75% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	0% RA
	Task two	Proprioceptive (difficult)	Verbal (easy)	100% RA
1.d.	Task one	Proprioceptive (easy)	Verbal (easy)	100% RA
	Task two	Proprioceptive (difficult)	Verbal (difficult)	0% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	75% RA
	Task two	Proprioceptive (difficult)	Verbal (difficult)	25% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	50% RA
	Task two	Proprioceptive (difficult)	Verbal (difficult)	50% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	25% RA
	Task two	Proprioceptive (difficult)	Verbal (difficult)	75% RA
	Task one	Proprioceptive (easy)	Verbal (easy)	0% RA
	Task two	Proprioceptive (difficult)	Verbal (difficult)	100% RA

CONTROLS

Control Comparison

The baseline from which to compare dual–task scores was single task scores.

Counterbalancing:

Counterbalancing was important to counteract any fatigue or practice effects. Practice always took place first, then the single task conditions and finally, the dual–task conditions. However, within those restraints, the following were randomly varied (by pulling a label out of a hat) during the practise, single and dual task conditions:

- Task condition (input sense and input processing code combined) order
- Difficulty order
- Resource allocation priority order

Practice

Before single task scores were recorded, each participant was given practise sessions at the single task conditions without the on–screen resource allocation feedback then practise sessions with the feedback. Practice continued at each of these stages to the point when performance plateaued (ceased to improve).

Output/ Response

Participant responses were always made manually (as opposed to vocally or a combination of the two types of responses) by pressing the buttons on task device, either the joystick or mouse (note that responses to the glove feedback were made using the joystick being held by the gloved hand).

Difficulty Level

Difficulty was manipulated in order to reveal any resource limited performance decrements, which might not otherwise reveal themselves if the difficulty level is too easy. Details of these levels were listed earlier in the Independent Variables section.

Resource Allocation

Resource allocation was essential to ensure participant effort and task prioritisation were controlled. To elaborate, when participants perform a particular task by itself, they would normally allocate 100% of the available resources to that task. However, when they are asked to perform two tasks at the same time (dual–tasking) they will allocate proportions of the available resources to each task (for example, 25% to one task and 75% to the other task). The challenge for researchers is controlling overall effort and division of effort. This was done through resource allocation indicators on a screen in front of the participant, letting the participant know if he/she needed to put more or less effort into each task (this is explained in full in Section Five). This on–screen feedback had the potential to cause interference but because the single task controls were also performed with on–screen feedback, this risk was controlled. For the resource allocation policies used, see the IV Policy in the Independent Variables section.

Finally, this approach lent itself to representation of the results using Performance Operating Characteristic (POC) curves, which was ideal.

Performance Standardisation

Each participant's dual task scores (in terms of number of hits) were converted to percentages (this is not the same as the policy percentages) — Single Task Performance was treated as 100% and Dual–Task Performance on each task was converted into a percentage of the associated Single Task Performance scores.

This was important so that results from different participants could be averaged and so that the average for one dual–task condition could be directly compared to the average from another dual–task condition. For example: If the single task score for Tactile Verbal was ten (hits per minute), and under a particular dual–task condition the Tactile Verbal score was five (hits per minute), then when the dual–task score was converted to a percentage (of the single task score) it would be 50%.

Participant Controls

See below for participant details.

Participants

This was an opportunity sample that was comprised of three male and three female participants. The sample included two left–handed individuals and four right–handed individuals and the age–range was twenty six years to fifty three years.

The same participants performed all the pilot trials. This avoided having to repeat a large proportion of Single and Dual task experiments.

The aim was to repeat these experiments with a sample size of at least thirty. Note, however, that a similar dual–task study used merely six participants (Gopher, D., Brickner, M. and Navon, D., 1982).

Equipment

The equipment, which was the same for both studies, included the following:

- One x 'CyberGlove'
- One x 'Force–Feedback Web Mouse'
- Two x 'Sidewinder Force–Feedback 2' joysticks
- One x 'Haptic Tester' control centre (running two computers)
-

'CyberGlove': tactile and auditory

(Immersion Technologies)

CyberGlove is fitted with CyberTouch 'tactors' to give vibrotactile feedback to the user, which is said to enhance the sense of surface texture, see Figure 10.

There are six tactors in total on the glove and these are located near the end of each finger and thumb and also in the centre of the palm.

In these experiments the vibrotactile feedback was varied in terms of intensity, frequency and rhythm to give spatial directions and 'verbal' codes to the participant.

CyberGlove was worn by participants on their left hand when they were required to perform a tactile task. The participant feels the vibrations and responds accordingly using the joystick.

'Force–Feedback Web Mouse': tactile

(HP and Immersion Technologies)

The mouse was used for tactile tasks where two tactile tasks had to be performed at the same time and was therefore always used in the right hand.

The participant was required to feel his/her way about a pre–specified area of the screen using the mouse and respond to the vibrations they felt. Note that although the term force–feedback is used in the name of the mouse, it actually only provides tactile feedback, in the form of vibrations.

The vibrotactile feedback varied in terms of intensity and frequency to give both spatial and 'verbal' codes to the participant. The vibrations are only felt when the fingers rest over the mouse in the normal way and responses were made using the left and right mouse buttons as well as the central 'wheel'.

'Sidewinder Force Feedback Two' joystick: proprioceptive

(Microsoft)

The two joysticks provided force–feedback to the participant, which was felt as either resistance or 'nudges' to the hand and arm when the stick was held.

Feedback could be configured to give a wide variety of sensations, allowing tasks of both spatial and verbal nature to be conducted. Responses were made using the buttons on the joystick.

The joysticks were used when a proprioceptive task was performed. The joysticks each required one computer in order to be used at the same time. These computers were networked and controlled by Haptic Tester, which is described below. The two joysticks were referred to as joystick local and joystick remote, due to their respective computers.

'Haptic Tester': control centre

(Designed by myself, built by Isca Software Services Ltd.)

Haptic Tester is a program specifically designed to manage every aspect of the experiments, including:

- Equipment configuration and control
- Condition configuration and control
- Equipment & condition 'profile' generation
- Up to four pieces of equipment to be simultaneously controlled
- Individual participant detail records
- Raw results records (hits, misses, response profiles)

- Data files (selected results organised by condition & participant)
- Automatic standardisation of the selected results and calculation of means
- Optional re–formatting of the data into headed columns and rows for SPSS

However, perhaps the key is how Haptic Tester controls resource allocation:

- It allows up to four tasks to be simultaneously performed & monitored
- It gives constant resource allocation priority feedback to the participant. It does this by continuously monitoring and comparing actual number of hits to expected number of hits, given resource allocation priority (100%/ 75%/ 50%/ 25%/ 0%) with reference to single task scores (100%). Then, Haptic Tester displays any discrepancy between actual and expected number of hits on the screen in the form of moving bars, so that effort can be directed where required. The basis for the feedback bars came from Gopher, Brickner & Navon (1982) and permission was given to use this type of display in these experiments.
- Tasks can be split into multiple blocks that run continuously from one to the next. Each block is configurable in terms of resource allocation priority.
- Difficulty is also configurable in terms of the input (proprioceptive/ tactile/ auditory) and in terms of central processing (spatial/ verbal). This means that, for example, a single tactile verbal task may be either:
    - Tactile (easy) verbal (easy)
    - Tactile (easy) verbal (difficult)
    - Tactile (difficult) verbal (easy)
    - Tactile (difficult) verbal (difficult)

Additional features of Haptic Tester include:

- An optional countdown timer that can be displayed during the experiment
- Optional performance feedback in terms of hits and misses that can be displayed for task familiarisation (such as during practise sessions).
- Fully configurable screen size to enable additional windows to be displayed during the experiment if necessary.
- Optional task reference points that can be displayed if necessary (such as for tasks involving the mouse where only a small portion of the screen is used).

Two networked computers (both with Windows 98 and USB) can be managed by Haptic Tester so that two joysticks could be operated at the same time; a Remote and Local computer. All the experiments are set–up and performed at the Local computer. Haptic Tester uses both Microsoft Visual C++ and the Borland C++ Development Suite. The Microsoft Visual C++ libraries were used to handle the joystick and mouse, whereas the libraries to manage the CyberGlove are only available in Borland C++. The results are recorded in ASCII files.

Procedure

The procedure was the same for all the pilot trials.

The experimenter sets up the experiments beforehand by using Haptic Tester to create 'profiles'. These profiles determine the conditions and include equipment configuration and task specification. See the Procedure section on Haptic Tester for details of how this is done.

After a brief verbal overview of the experimental purpose and procedure, the participant was given a demonstration of each task in turn. This was followed by a practise session on each task. Performance was monitored throughout the practise session and practise sessions continued until performance ceased to improve. There were sixteen single tasks (four tasks by four difficulty levels) that were presented for one minute each. Practice was required on each of the sixteen single tasks, firstly without the resource allocation feedback (at least three minutes per task) and then with the feedback (at least one minute per task).

The sixteen single task conditions were then performed, after which the scores were entered into the corresponding dual task profiles in Haptic Tester.

Dual task conditions were then performed. As mentioned earlier, each resource allocation policy was presented for one minute and there were five minutes worth of resource allocation policies. Because there were four difficulty levels per dual–task, the total time taken per dual–task was four difficulty levels by five minutes of policies, i.e. twenty minutes per dual–task. There were ten dual–tasks and therefore total dual–task time came to two hours. The time–breakdown for each participant was as follows (Table 102):

Table 102: The time breakdown per participant for the Pilot Trials

Time Breakdown per Participant for the Pilot Trials		
Practise sessions (sixteen tasks, one minute per task)	Without allocation feedback (at least three times)	Forty eight minutes
	With allocation feedback (at least one time)	sixteen minutes
Single task conditions (sixteen tasks, one minute per task)		sixteen minutes
Dual Task conditions (ten task pairs, four difficulty levels per pair, five allocation policies per difficulty, one minute per policy)		Two hours
TOTAL (Minimum)		**Three hours & twenty minutes**

RESULTS OF THE PILOT TRIALS

Figure 64: PS_PV — Proprioceptive Spatial & Proprioceptive Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

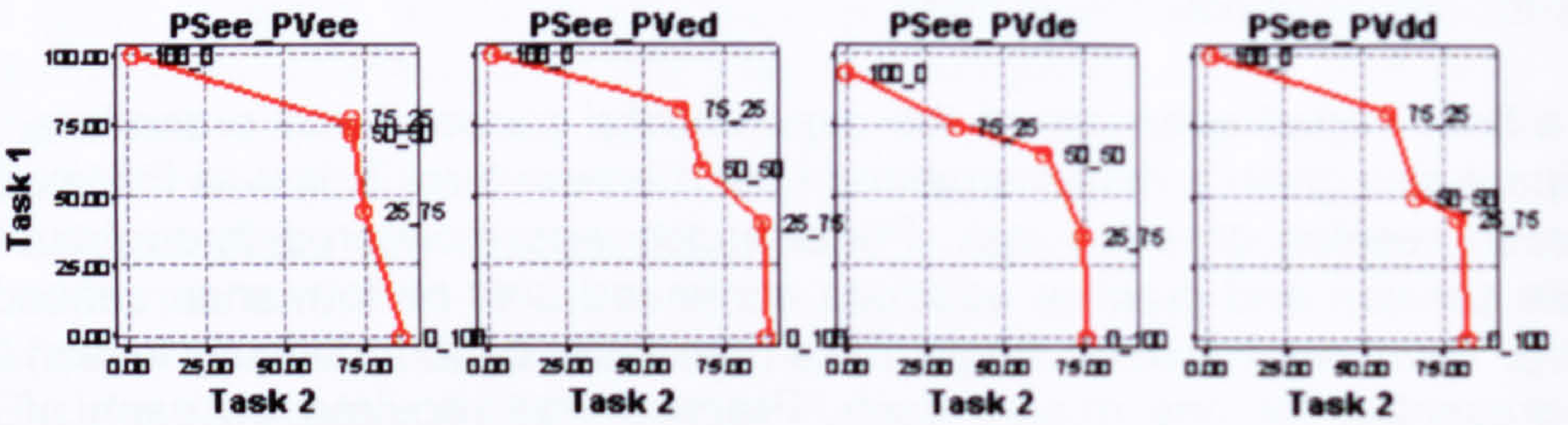


Figure 65: TS_PV — Tactile Spatial & Proprioceptive Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

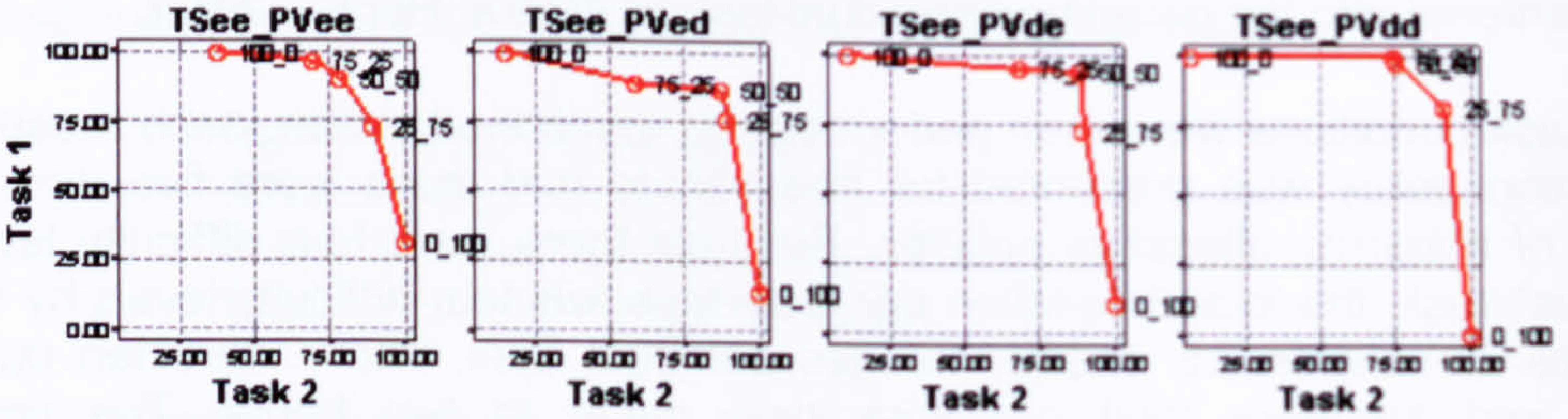


Figure 66: TV_PV — Tactile Verbal & Proprioceptive Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

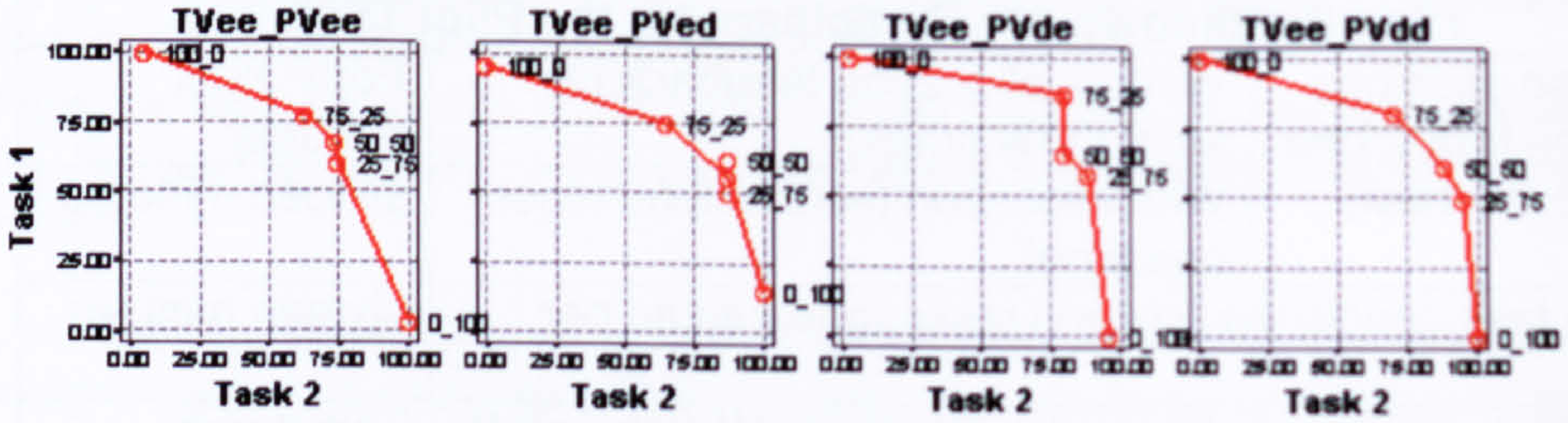


Figure 67: TS_PS — Tactile Spatial & Proprioceptive Spatial at the four task two difficulty levels (from easiest to most difficult, left to right)

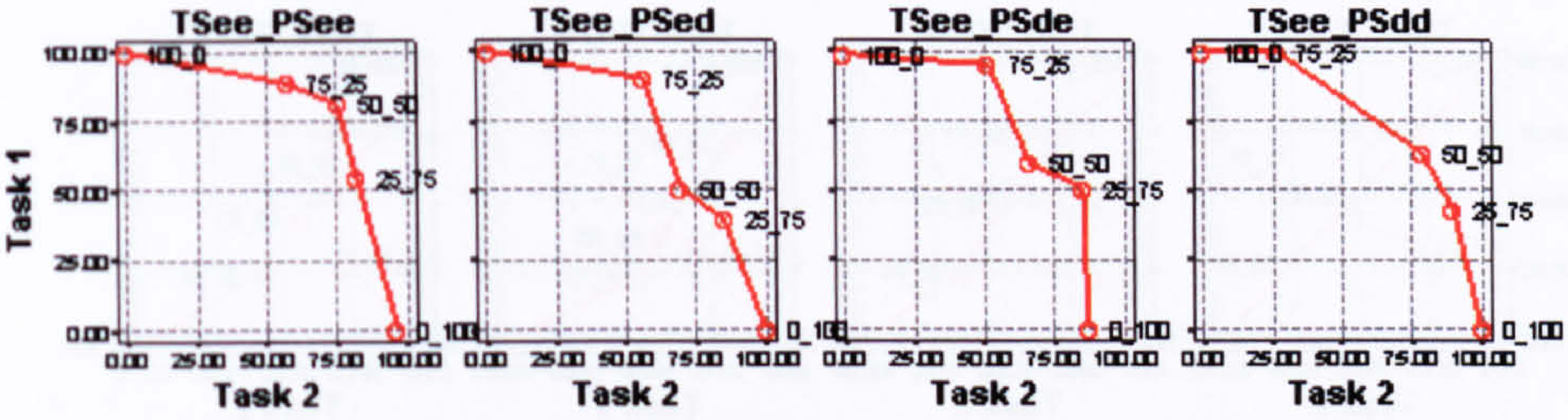


Figure 68: TS_TV — Tactile Spatial & Tactile Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

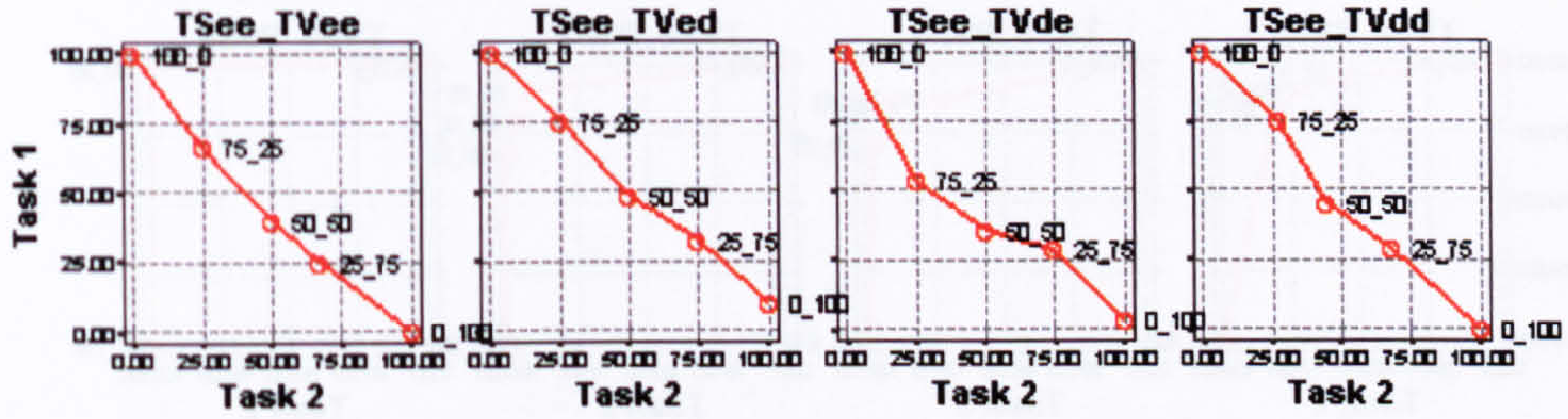


Figure 69: TV_TV — Tactile Verbal & Tactile Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

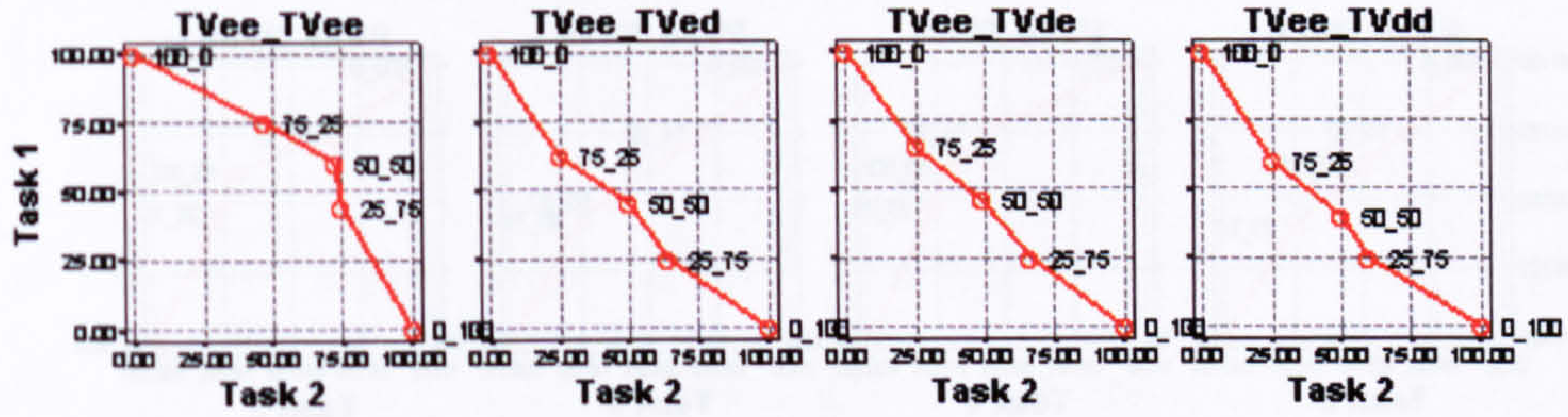


Figure 70: TS_TS — Tactile Spatial & Tactile Spatial at the four task two difficulty levels (from easiest to most difficult, left to right)

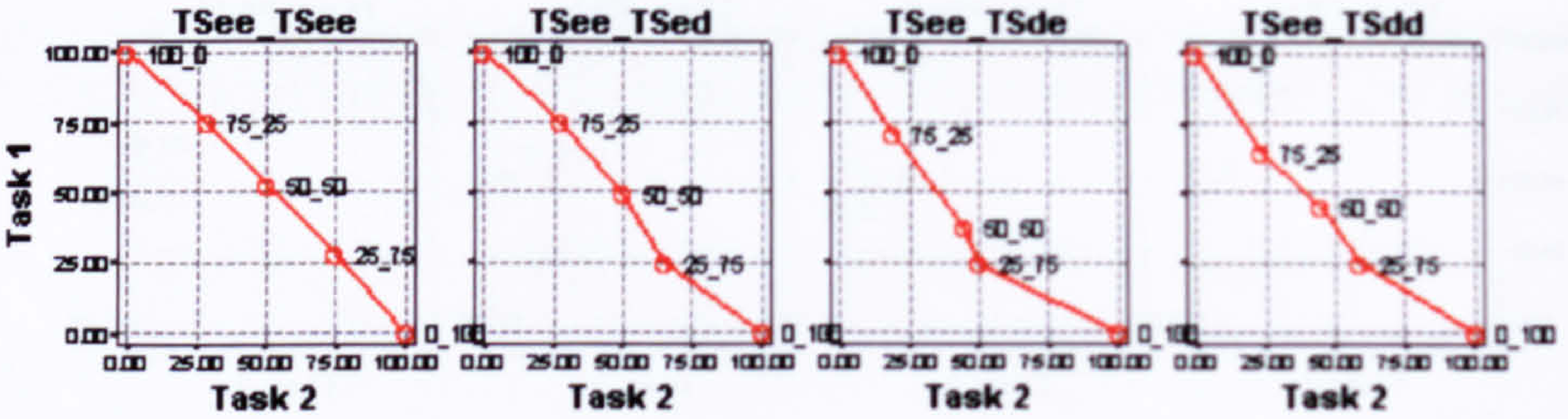


Figure 71: TV_PS — Tactile Verbal & Proprioceptive Spatial at the four task two difficulty levels (from easiest to most difficult, left to right)

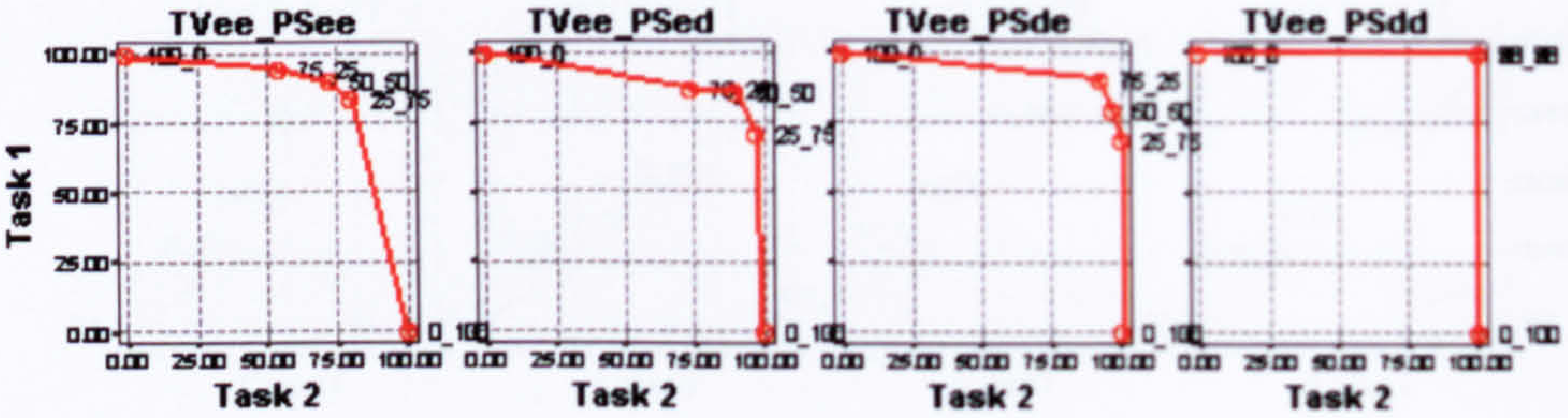


Figure 72: PV_PV — Proprioceptive Verbal & Proprioceptive Verbal at the four task two difficulty levels (from easiest to most difficult, left to right)

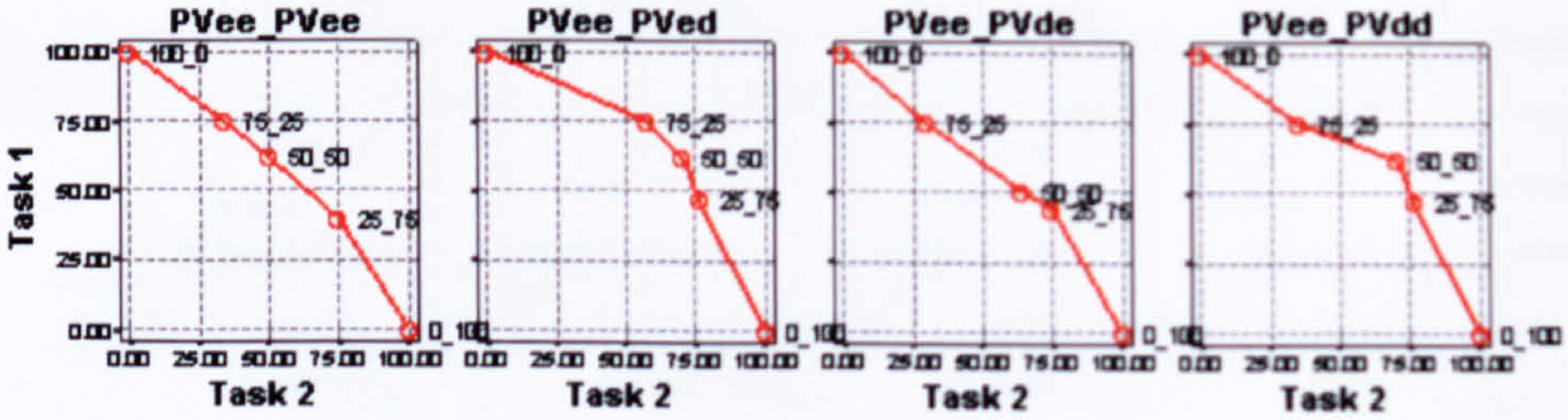
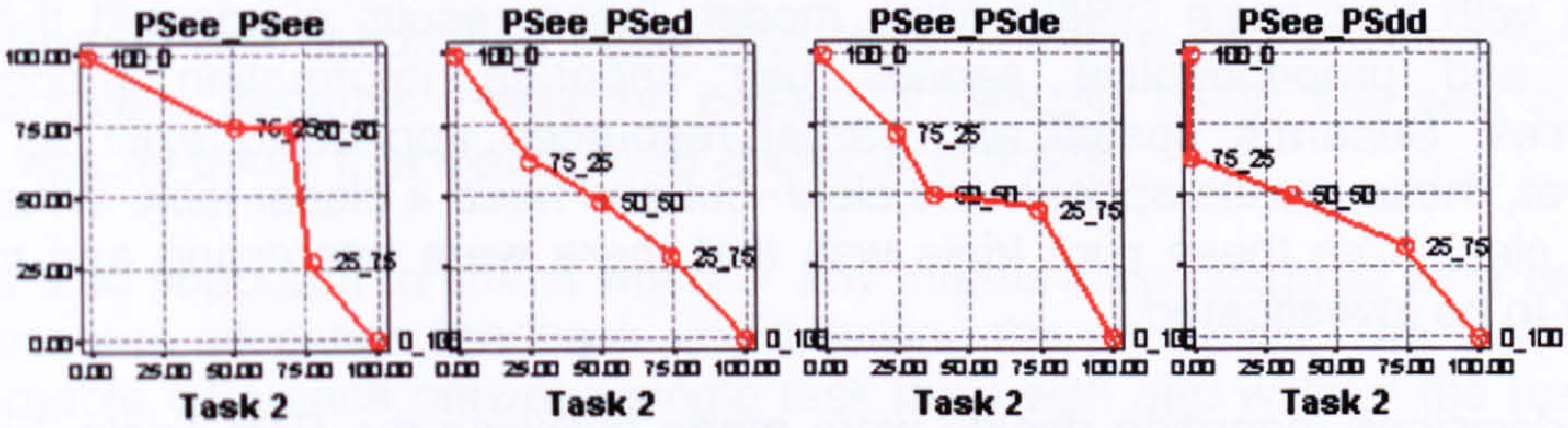


Figure 73: PS_PS — Proprioceptive Spatial & Proprioceptive Spatial at the four task two difficulty levels (from easiest to most difficult, left to right)



DISCUSSION OF PILOT TRIAL RESULTS

In line with Wickens's (1980) MRT model, these results suggested that the tactile and proprioceptive senses use separate information processing resources. Separate spatial and verbal resources appear to exist as well; however, these results appear less clear-cut and need a closer look. What was utterly clear from these pilot trials was that there were interesting and robust effects to be investigated.

Major decisions regarding design were made following the Pilot Trials. First of all it was decided that was possible to reduce the number of resource allocation policies (see the IV Policy under Design). Removing the 0% and 100% policies reduced the number of levels in this independent variable to three levels: 25%, 50% and 75%, which was sufficient to create the POC curves. The single task scores would serve as the 100% point on the POC curve anyway, which meant that removing these policies also removed an element of duplication.

The next major decision was to completely remove Difficulty as an independent variable (see IV Difficulty under Design). The pilot trials indicated which difficulty level was required in order to reveal resource limitations and therefore this difficulty level was chosen in the subsequent studies. In fact there was practically no variation between the easiest and most difficult of levels, suggesting that the effects were quite robust regardless of difficulty level. Because some participants seemed to require a lot more practice on the most difficult levels, it was the easiest of the levels that was chosen for subsequent studies.

Another decision was that it was not necessary to perform certain dual-tasks in order to test the hypotheses. The dual-tasks that would be omitted in subsequent studies included: TSTS, TVTV, PSPS and PVPV. This decision was made because design complexity needed to be reduces and, since the main priority was to look for effects of input sense as opposed to effects of processing code, these dual-tasks were excessive. It would still be possible to make robust inferences about effect of processing code from the remaining dual-tasks. This also meant that all tactile feedback could be delivered through the glove and therefore the other tactile device (the mouse) was dropped. The glove was chosen because it could be used by the same hand that gripped a force-feedback joystick, thereby providing greater flexibility to equipment set-up and it was possible to deliver a tactile spatial and tactile verbal task through the glove at the same time. Removing one of the tactile devices also removed a variable from the equation (i.e different sources and characteristics of tactile feedback). Because there were two identical force-feedback sticks, it was not necessary to drop one of these. It was also not desirable to remove one of the force-feedback sticks because it was possible to perform only one proprioceptive task at a time on one stick and therefore two were required in order to perform the proprioceptive spatial and proprioceptive verbal tasks at the same time.

The Pilot trials also helped establish the intensity thresholds for each task. Participants were able to perform the tasks even at the most difficult level, suggesting that thresholds were well above minimum. However, in the process of setting up and conducting these pilot trials, tweaking of intensity thresholds was possible. Because it was the easiest of difficulty levels that was chosen, there was no doubt that inputs were above thresholds.

It was also important to check whether any interference occurred as a result of the resource allocation feedback and following the pilot trials. The lack of any discernable difference between single task trials with and without the resource allocation feedback, suggested that this was not an issue to be concerned about.

Finally, the pilot trials indicated the practice requirements to reach the point where performance plateaued. As a result of these findings, participants in subsequent studies would be given five practise sessions in total (three without the resource allocation feedback and two with this feedback).

The changes made as a result of these decisions resulted in a significant reduction in the time required per participant. During the pilot trials this time was a minimum of three hours and twenty minutes, which was tiring and tiresome for all involved. The subsequent changes resulted in a total time of between forty and sixty minutes per participant, including time for reading instructions and any questions. This was a dramatic reduction, bringing the time down to an acceptable level. It also meant that a far greater number of participants could be tested overall, as instead of two participants per day, it was then possible to test eight participants per day.

APPENDIX B: HAPTIC TESTER PROGRAM

Haptic Tester:
Originally designed by Heidi Castle for her PhD and built by Iscasoftware Services Ltd (subsequently modified by Heidi Castle and Iscasoftware Services Ltd for BAE Systems into 'BAE Haptics').

Refer to Readme file in Haptic Tester software for installation instructions and upgrade instructions (in case of permission to use BAE Haptics).

For further queries contact:

Heidi Castle:
heidi.castle1@btinternet.com
01348 831 372 / 01249 891 714

OR

Iscasoftware Services Ltd:
steve@iscasoft.co.uk
01672 871 407

Specifications

Overview

Haptic Tester (later modified into BAE Haptics for BAE Systems) is a program specifically designed to manage every aspect of the experiments, including:
- Equipment configuration and control
- Condition configuration and control
- Equipment & condition 'profile' generation
- Up to four pieces of equipment to be simultaneously controlled
- Individual participant detail records
- Raw results records (hits, misses, response profiles)
- Data files (selected results organised by condition & participant)
- Automatic standardisation of the selected results and calculation of means
- Optional re-formatting of the data into headed columns and rows for SPSS

However, perhaps the key is how Haptic Tester controls resource allocation:
- Haptic allows up to four tasks to be simultaneously performed & monitored
- Haptic Tester gives constant resource allocation priority feedback to the participant. Then, Haptic Tester displays any discrepancy between actual and expected number of hits on the screen in the form of moving bars, so that effort can be directed where required.
- Tasks can be split into multiple blocks. Each block is configurable in terms of resource allocation priority.
- Difficulty is also fully configurable.

Additional features of Haptic Tester include:
- An optional countdown timer that can be displayed during the experiment
- Optional feedback on hits, misses, errors etc. can be displayed
- Optional task reference points that can be displayed if necessary.

Equipment Required

For Tactile Feedback

- Cyber Glove by Immersion Technologies

OR

- Force Feedback Web Mouse by HP & Immersion Technologies

For Force Feedback

- Microsoft Sidewinder Force Feedback two joystick (two required)

For Auditory Feedback

- Speakers or headphones

For Visual Feedback

- Monitor

For Haptic Tester to Run

- Two networked PCs with USB capability and Windows '98

To Process the Results

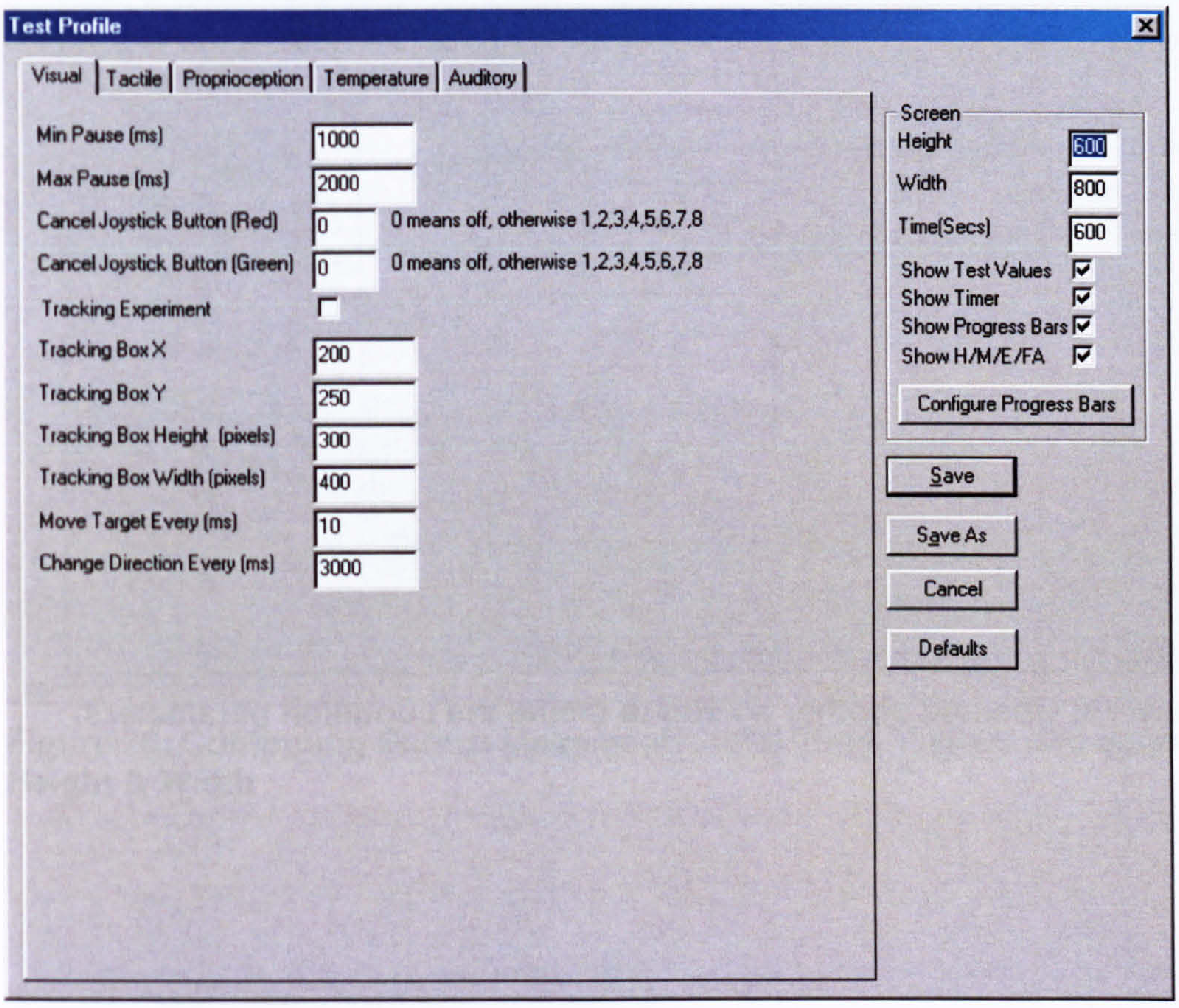
- SPSS version nine or above (this is not essential as the raw data files can be pasted directly into any other statistics package).

Procedure

All of the trials are set up and run by the experimenter using Haptic Tester. Haptic Tester records the participant details and all of the results in their raw format as well as in SPSS format.

Creating a Task Profile

In Haptic Tester, the profiles will contain all the details necessary to create a particular condition and run the equipment correctly. See Figure 74



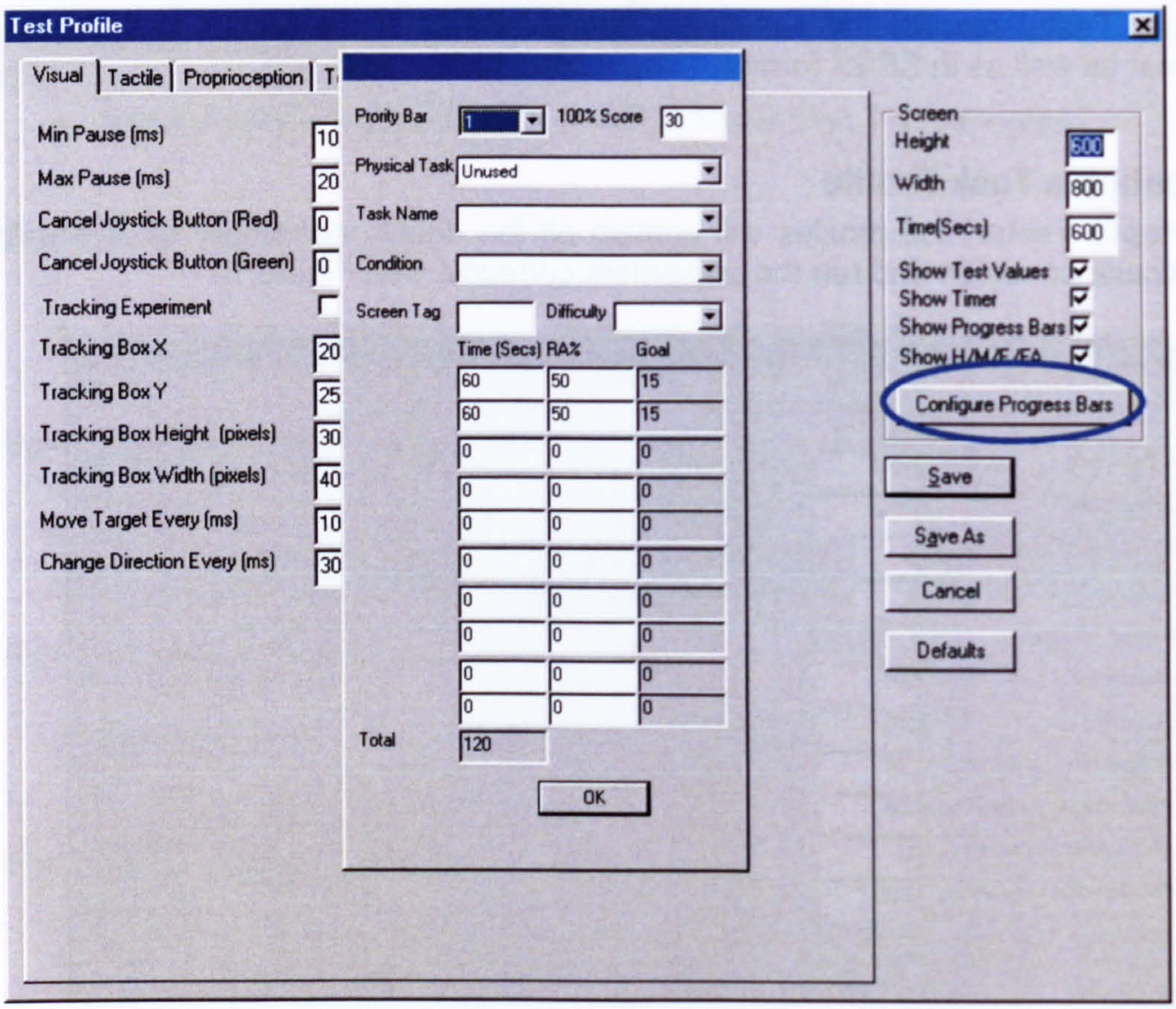
Min Pause (ms) 1000
Max Pause (ms) 2000
Cancel Joystick Button (Red) 0 0 means off, otherwise 1,2,3,4,5,6,7,8
Cancel Joystick Button (Green) 0 0 means off, otherwise 1,2,3,4,5,6,7,8
Tracking Experiment ☐
Tracking Box X 200
Tracking Box Y 250
Tracking Box Height (pixels) 300
Tracking Box Width (pixels) 400
Move Target Every (ms) 10
Change Direction Every (ms) 3000

Height 600
Width 800
Time(Secs) 600
Show Test Values ☑
Show Timer ☑
Show Progress Bars ☑
Show H/M/E/FA ☑

Figure 74: The profile editor screen

In this profile editor screen, each piece of equipment can be turned on or off and each parameter modified to give different feedback to the participant. It was important that each parameter could be fully adjustable so that the tasks could be modified as required in the pilot trials (see Appendix A).

Once the equipment has been configured, the condition parameters are specified by clicking on the Set Progress button, see Figure 75. This brings up another screen, which allows the condition parameters to be specified in detail.



Min Pause (ms)	10
Max Pause (ms)	20
Cancel Joystick Button (Red)	0
Cancel Joystick Button (Green)	0
Tracking Experiment	☐
Tracking Box X	20
Tracking Box Y	25
Tracking Box Height (pixels)	30
Tracking Box Width (pixels)	40
Move Target Every (ms)	10
Change Direction Every (ms)	30

Prority Bar 1 100% Score 30

Physical Task Unused

Task Name

Condition

Screen Tag Difficulty

Time (Secs)	RA%	Goal
60	50	15
60	50	15
0	0	0
0	0	0
0	0	0
0	0	0
0	0	0
0	0	0
0	0	0
0	0	0

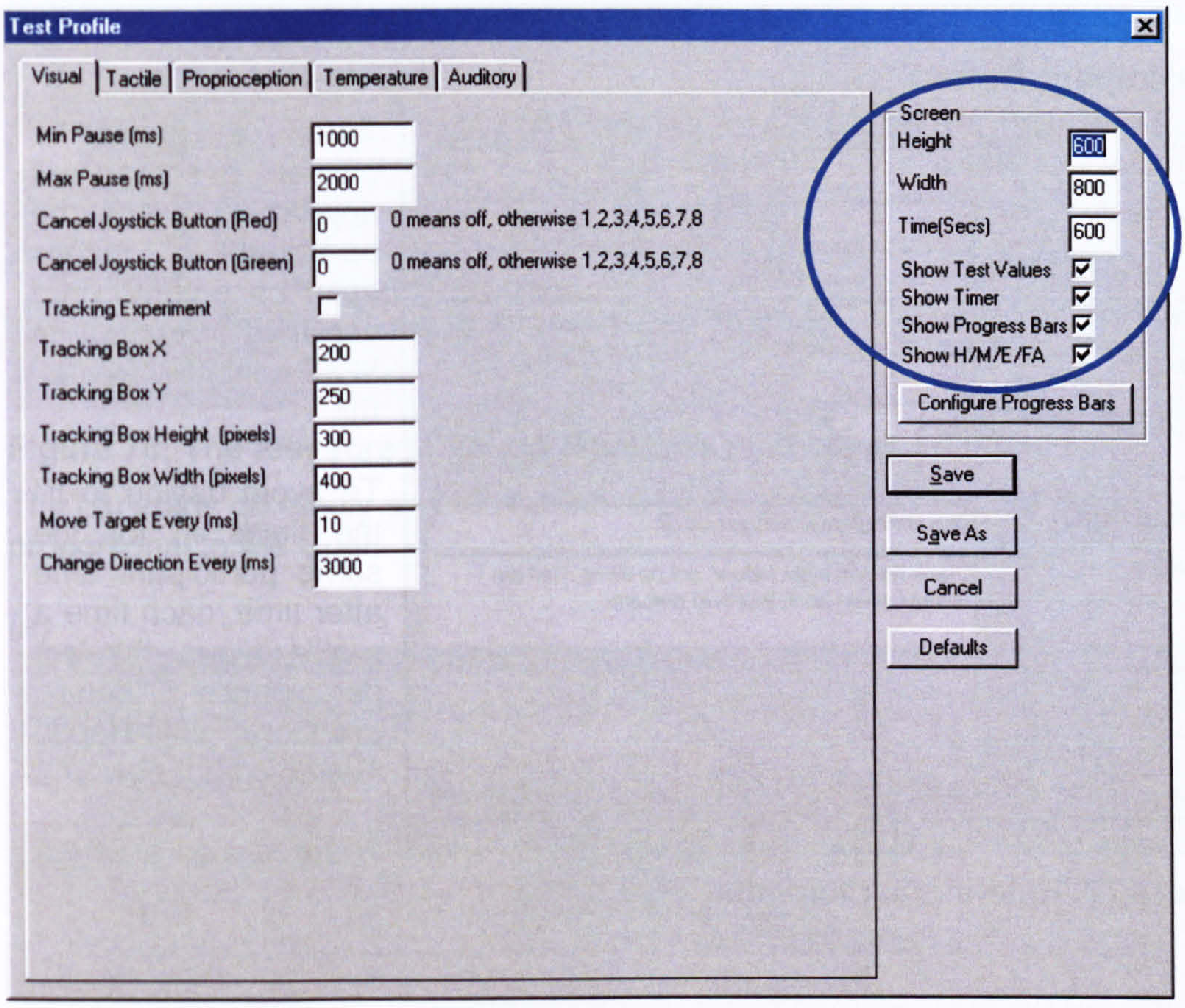
Total 120

Screen

Height	600
Width	800
Time(Secs)	600
Show Test Values	☑
Show Timer	☑
Show Progress Bars	☑
Show H/M/F/FA	☑

Figure 75: Opening another screen to define the condition parameters.

Before exiting the profile editor, a few final details must be specified, see Figure 76. For example, it is important to make sure that the Time field matches the Total time. Haptic Tester will not allow the profile to be saved if these figures do not match up.



Min Pause (ms) 1000
Max Pause (ms) 2000
Cancel Joystick Button (Red) 0 0 means off, otherwise 1,2,3,4,5,6,7,8
Cancel Joystick Button (Green) 0 0 means off, otherwise 1,2,3,4,5,6,7,8
Tracking Experiment ☐
Tracking Box X 200
Tracking Box Y 250
Tracking Box Height (pixels) 300
Tracking Box Width (pixels) 400
Move Target Every (ms) 10
Change Direction Every (ms) 3000

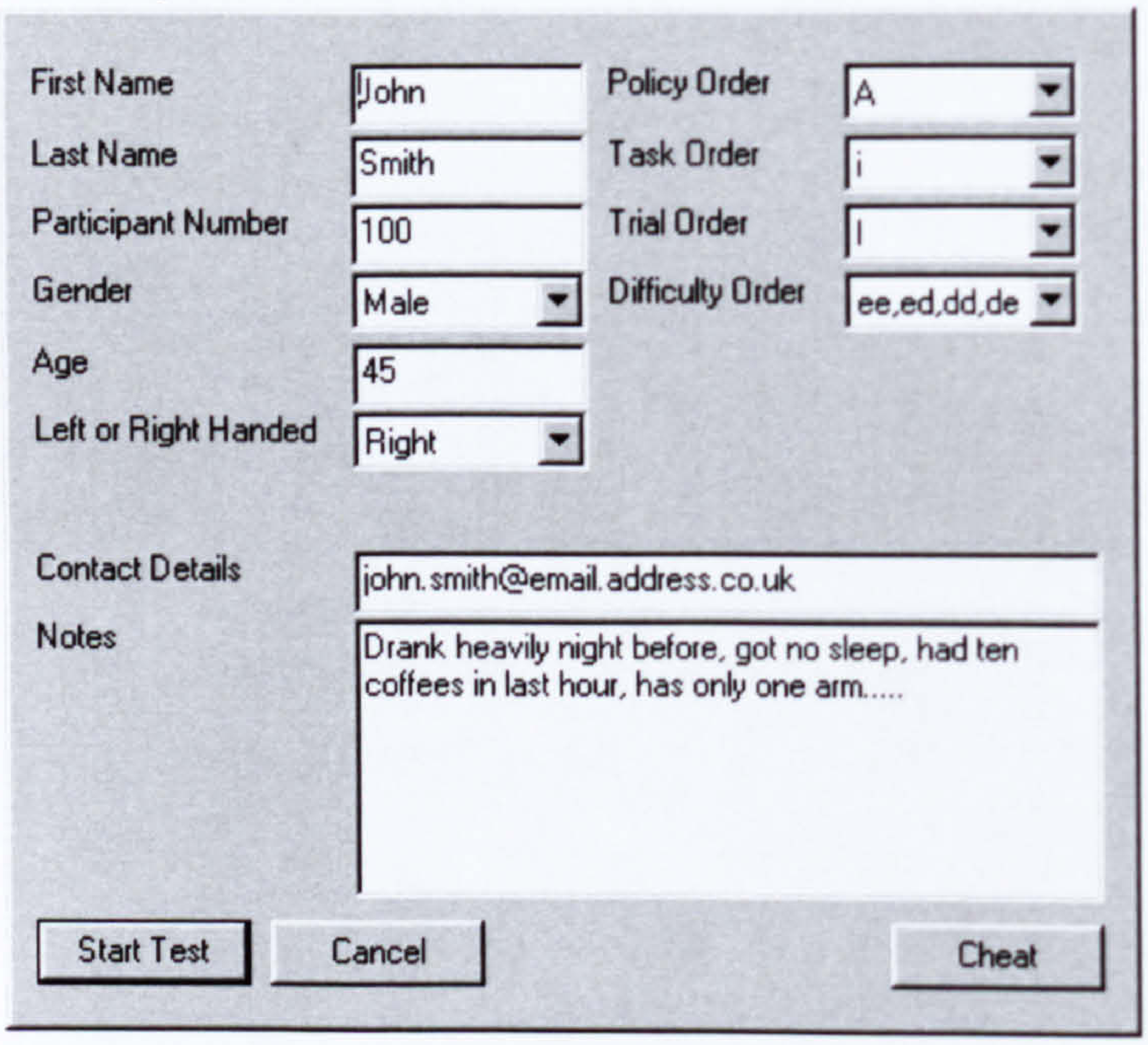
Screen
Height 600
Width 800
Time(Secs) 600
Show Test Values ☑
Show Timer ☑
Show Progress Bars ☑
Show H/M/E/FA ☑

Figure 76: Confirming Screen Movements, total Time, Visuals and screen Height & Width

Running the Test

To run the edited profile, the chosen profile is selected again and Run is chosen from the main toolbar.

Participant Details



First Name: John
Last Name: Smith
Participant Number: 100
Gender: Male
Age: 45
Left or Right Handed: Right
Policy Order: A
Task Order: i
Trial Order: I
Difficulty Order: ee,ed,dd,de
Contact Details: john.smith@email.address.co.uk
Notes: Drank heavily night before, got no sleep, had ten coffees in last hour, has only one arm.....

Figure 77: Entering participant details

When a profile is chosen, a screen will appear, in which the participant details must be entered, see organised results in SPSS using the 'forspss' file

To avoid having to fill the fields in for the same participant time after time, each time a profile is run, the last participant's details are stored until Haptic Tester is shut down.

There is also a Cheat

The Test Screen

See Figure 78 for an example of the test screen during the Dual task with bar condition.

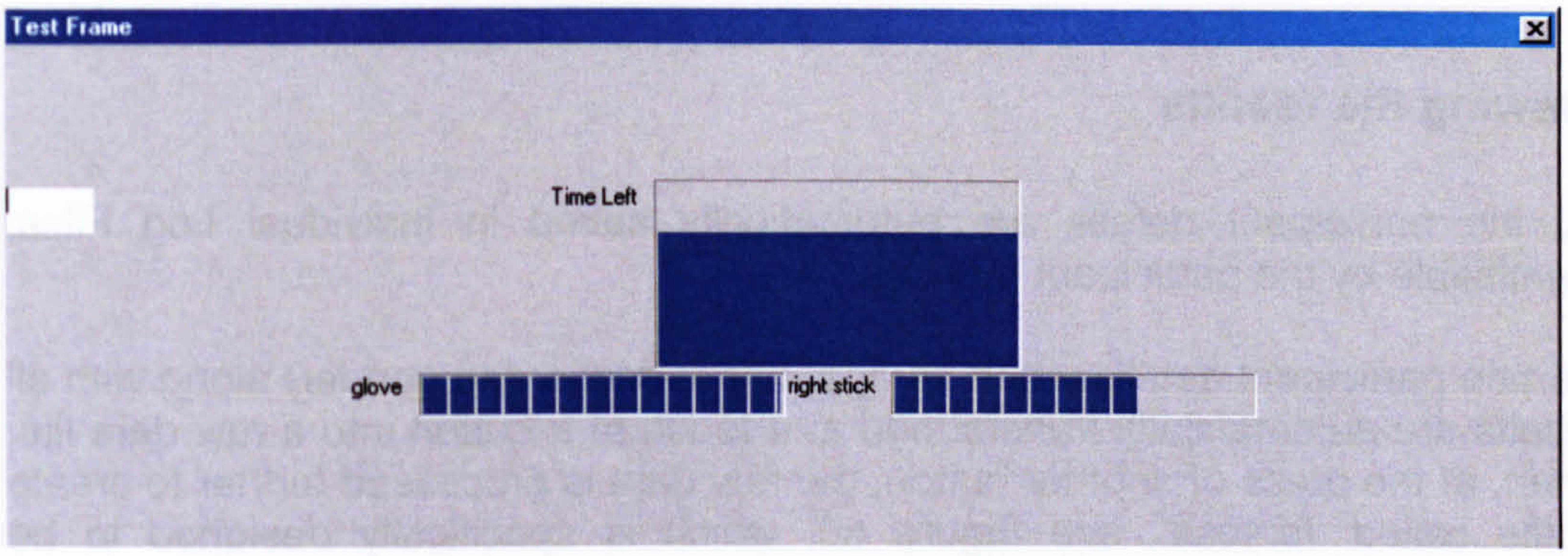
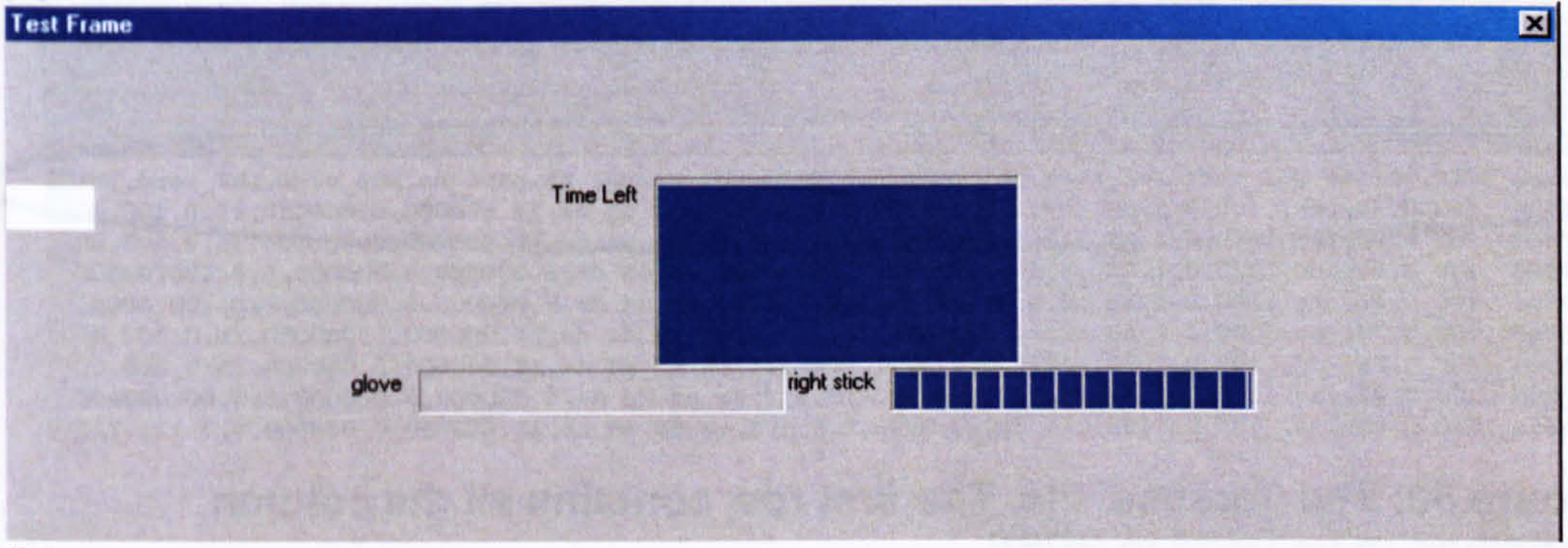


Figure 78: The test screen for the Dual task with bar condition

The bar starts off empty and fills up with a blue colour when hits are made, proportional to the Goal.

(a)



(b)

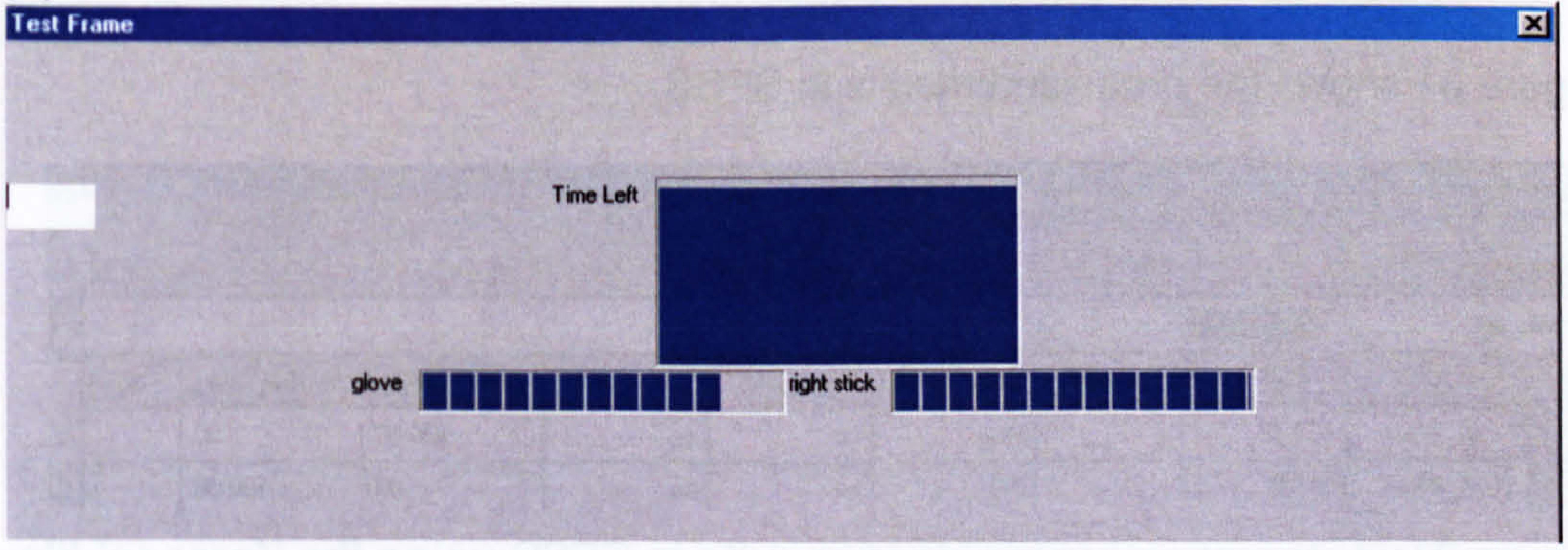


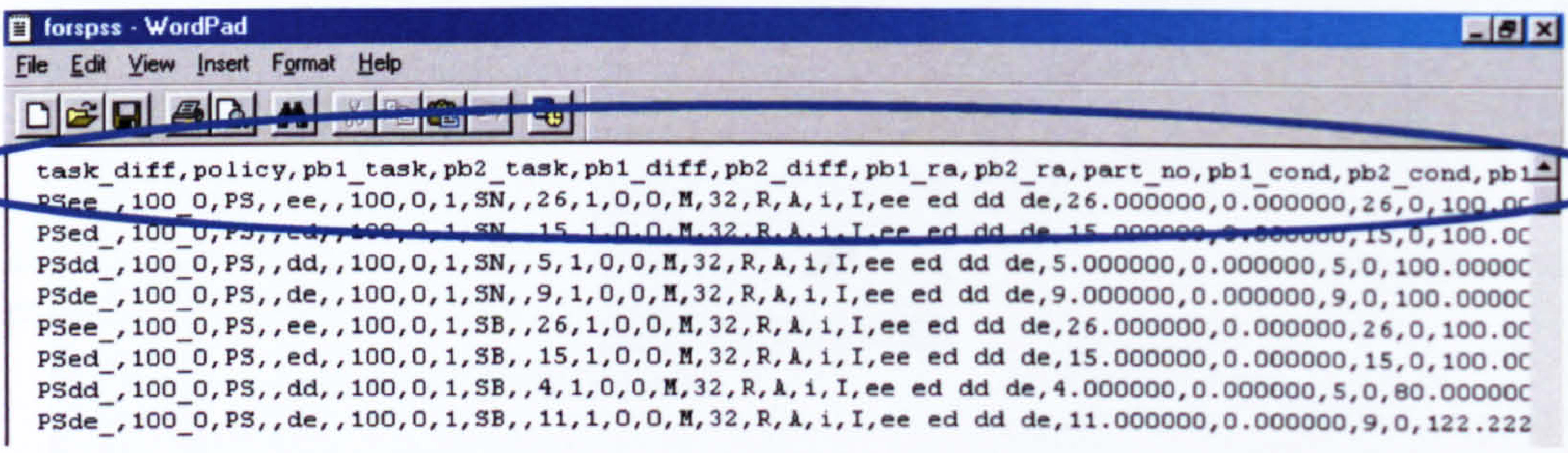
Figure 79: (a) Performance at the start of block one and (b) performance a few seconds later

Figure 79 (a) shows what the participant sees at the start of block 1; the bar for task one (glove) is empty because 100% RA is required, whereas the bar for task two (right stick) is full because 0% RA is required. The bar fills up as effort is applied, see Figure 79 (b).

Viewing the results

All the participant details are automatically saved in individual Log Files, identifiable by the participant number.

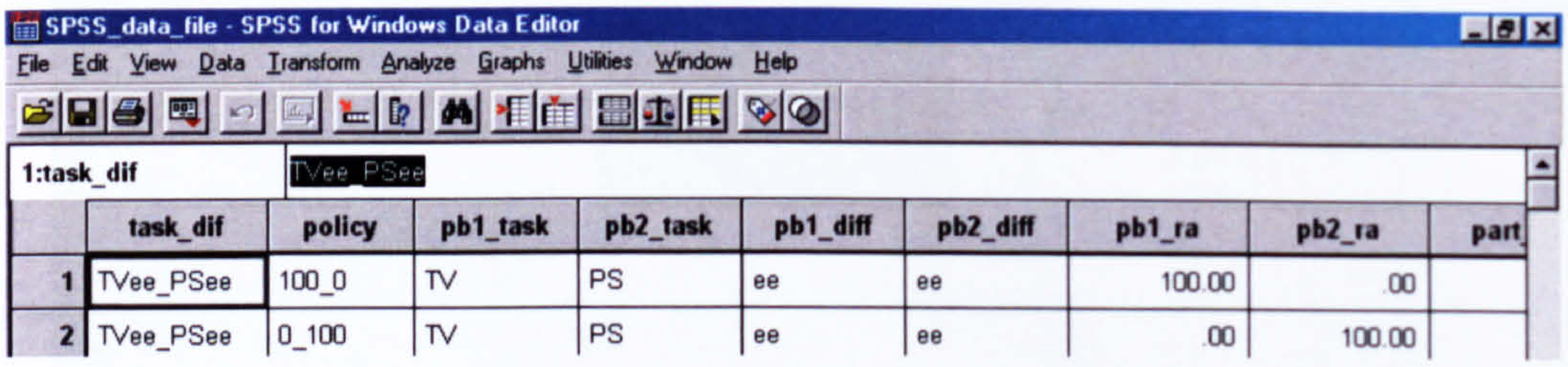
Certain participant details (such as age, handedness and gender) along with all results are automatically transformed at a touch of a button into a raw data file. Then, at the press of another button, the raw data is processed further to create a file called 'forspss', see Figure 80, which is specifically designed to be imported into SPSS for analysis purposes. This is important because potentially tens of thousands of data points would otherwise need to be entered manually. The 'forspss' file organises the raw data into headed columns, a number of additional calculations are made to make analysis easier, including standardised scores (into percentages) and means.



```
task_diff,policy,pb1_task,pb2_task,pb1_diff,pb2_diff,pb1_ra,pb2_ra,part_no,pb1_cond,pb2_cond,pb1
PSee_,100_0,PS,,ee,,100,0,1,SN,,26,1,0,0,M,32,R,A,i,I,ee ed dd de,26.000000,0.000000,26,0,100.0C
PSed_,100_0,PS,,ed,,100,0,1,SN,,15,1,0,0,M,32,R,A,i,I,ee ed dd de,15.000000,0.000000,15,0,100.0C
PSdd_,100_0,PS,,dd,,100,0,1,SN,,5,1,0,0,M,32,R,A,i,I,ee ed dd de,5.000000,0.000000,5,0,100.0000C
PSde_,100_0,PS,,de,,100,0,1,SN,,9,1,0,0,M,32,R,A,i,I,ee ed dd de,9.000000,0.000000,9,0,100.0000C
PSee_,100_0,PS,,ee,,100,0,1,SB,,26,1,0,0,M,32,R,A,i,I,ee ed dd de,26.000000,0.000000,26,0,100.0C
PSed_,100_0,PS,,ed,,100,0,1,SB,,15,1,0,0,M,32,R,A,i,I,ee ed dd de,15.000000,0.000000,15,0,100.0C
PSdd_,100_0,PS,,dd,,100,0,1,SB,,4,1,0,0,M,32,R,A,i,I,ee ed dd de,4.000000,0.000000,5,0,80.00000C
PSde_,100_0,PS,,de,,100,0,1,SB,,11,1,0,0,M,32,R,A,i,I,ee ed dd de,11.000000,0.000000,9,0,122.222
```

Figure 80: The 'forspss' file. The first row contains all the column headings to be used in SPSS

Figure 81 shows the organised results in SPSS.



	task_dif	policy	pb1_task	pb2_task	pb1_diff	pb2_diff	pb1_ra	pb2_ra	part
1	TVee_PSee	100_0	TV	PS	ee	ee	100.00	.00	
2	TVee_PSee	0_100	TV	PS	ee	ee	.00	100.00	

Figure 81: Automatically organised results in SPSS using the 'forspss' file