The role of working memory in tactile selective attention

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Abstract

Load theory suggests that working memory controls the extent to which irrelevant distractors are processed (e.g. Lavie et al., 2004). However, so far this proposal has only been tested in vision. Here, we examine the extent to which tactile selective attention also depends on working memory. In Experiment 1, participants focused their attention on continuous target vibrations while attempting to ignore pulsed distractor vibrations. In Experiment 2, targets were always presented to a particular hand, with distractors being presented to the other hand. In both experiments, a high (vs. low) load in a concurrent working memory task led to greater interference by the tactile distractors. These results establish the role of working memory in the control of tactile selective attention, demonstrating for the first time that the principles of load theory also apply to the tactile modality.

The role of working memory in tactile selective attention

The ability to respond to target stimuli while ignoring distractors is important for the successful performance of many everyday tasks. A great deal of research has therefore focused on the factors affecting the successful rejection of distractors. This research began with studies of auditory selection (e.g. Broadbent, 1958; Cherry, 1953; see Driver, 2001, for a review) but from the 1970s onwards has tended to focus on vision (see Lavie & Tsal, 1994, for a review). However, despite the wealth of information received through the sense of touch, relatively little research has addressed the processes involved in determining the success of tactile selective attention (see Spence, 2002). Nevertheless, the issue of distractor processing would appear to be particularly relevant for tactile attention given that we continuously receive large amounts of tactile information, much of which we typically choose to ignore (e.g. the feel of the clothes on our bodies; e.g. Graziano, Alisharan, Hu, & Gross, 2002; Holmes & Spence, 2006).

Indeed, previous research has shown that the presence of tactile distractors can impair the detection and discrimination of tactile targets presented at the same time. For example, participants in a study by Evans and Craig (1992) had to respond according to the direction of a moving tactile stimulus presented to one finger while ignoring a moving distractor presented to a different finger. Participants were slower to respond when the movement of the distractor was incongruent (vs. congruent) with that of the target (see also Horner, 1997, 2000). More recently, Soto-Faraco, Ronald, and Spence (2004) established a tactile response competition task using static (rather than moving) tactile stimuli. Participants responded to the elevation of a continuous target vibration while ignoring a pulsed distractor vibration presented to the other hand at an elevation that was either congruent or incongruent with that of the target. In line with Evans and Craig's results, Soto-Faraco et al. found distractor interference effects for vibrotactile distractors presented at an elevation that was incongruent (vs. congruent) with that of the target (see also Driver & Grossenbacher, 1996). Thus the evidence now agrees that tactile distractors can interfere with the processing of tactile targets. However, the factors determining the extent to which such tactile distractors can be ignored have yet to be investigated.

By contrast, a significant amount of research has addressed the mechanisms involved in the rejection of visual distractors. It is now well-established that distractors are ignored more effectively when the target task is more perceptually demanding (i.e., when the 'perceptual load' is higher) than when it is less demanding (e.g. Lavie, 1995). More recently, it has also been shown that people are more susceptible to interference by distractors when they are unable to use their full working memory capacity on the task at hand (e.g. de Fockert, Rees, Frith & Lavie, 2001; Lavie, 2000; Lavie & de Fockert, 2005; Lavie, Hirst, De Fockert & Viding, 2004). For example, Lavie et al. (2004) had their participants respond to the identity of a target letter (X or Z) while ignoring a distractor letter which could either be congruent with respect to the target letter (e.g. an 'X' when the target was also an 'X') or incongruent (e.g. a 'Z' when the target was an 'X'). Distractor interference effects (also referred to as congruency effects) were measured as the difference in performance between congruent and incongruent trials. Participants in Lavie et al.'s study carried out the visual letter task under either high working memory load (when they were asked to remember six randomly-chosen digits) or low working memory load (when they only remembered one digit). Incongruent distractors produced greater interference (indicated by larger congruency effects) under conditions of high working memory load than under low load conditions. These findings, among others, suggest that the availability of working memory is important for minimizing interference by low-priority distractors, presumably through the active maintenance of current stimulus-processing priorities (see also Lavie, 2005).

In the present study, we reasoned that the executive control functions involved in maintaining current task priorities in working memory should not be modality-specific and should therefore also be important in controlling selective attention in sensory modalities other than vision. Thus we designed the present experiments to investigate the role of working memory in tactile selective attention.

Experiment 1

In Experiment 1 we assessed the effects of working memory load on distractor interference in the tactile response-competition task recently developed by Soto-Faraco et al. (2004). A memory set consisting of digits either in ascending numerical order (low working memory load condition) or in random order (high working memory load condition) was presented at the start of each trial. The participants were asked to memorize these digits in their order of occurrence until a memory probe appeared at the end of the trial. Interleaved between the memory set and memory probe was a tactile selective attention task in which the participants responded to the elevation of a continuous target vibration while ignoring a pulsed distractor vibration in the other hand. The distractor vibration was presented at an elevation that was either congruent or incongruent with that of the target, and distractor interference was measured as the difference in performance between congruent and incongruent trials. If working memory serves to control tactile selective attention, then a high (vs. low) working memory load during performance of the tactile selective attention task should result in greater interference by the irrelevant tactile distractors.

Method

Participants. Twenty right-handed participants (12 female), aged between 18-35 years, received a £5 gift voucher in return for their participation in this study. A further four participants were excluded from the analysis due to chance or near-chance performance on incongruent trials (M accuracy = 47%, 49%, 53% and 59%), indicating that they could not reliably distinguish between the vibrotactile target and distractor stimuli. An additional participant was excluded due to an overall accuracy that was over two standard deviations below the group mean (group M = 91%, excluded participant M = 81%, SD = 4.8%).

Apparatus and stimuli. Figure 1 shows the experimental set-up. Participants sat at a table holding two foam cubes, one in either hand (30 cm apart and equidistant from the midline) while looking at a computer screen (at a distance of 60 cm). They were asked to hold the cubes in such a way as to keep their fingers in contact with the vibrotactile stimulators fixed within the cubes. As shown in Figure 1, one vibrator was situated at the top outside edge of each cube (which participants held with their index fingers) and another at the bottom outside edge (which participants held with their thumbs). The target vibration consisted of a continuous 350 ms presentation of a white noise signal from one of the four vibrotactile stimulators. The distractor vibration consisted of three short bursts of the same signal, each lasting 50 ms and separated by 100 ms empty intervals (giving a total duration of 350 ms). Throughout the experiment, participants wore headphones through which white noise was presented at a level that was sufficient to mask the noise produced by the vibrators. Participants responded by lifting one of the four foot pedals placed on the floor underneath the table, under the toes and heels of both feet. Stimulus presentation and response collection were controlled by a PC running E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA).

Design and procedure. Each trial started with a black fixation point presented at the center of a white screen for 500 ms. This was followed by a 1500 ms presentation of a memory set consisting of a row of six black digits, separated from each other by .05° and centered at fixation. Each digit subtended a visual angle of 0.25° x 0.3°. In the low load blocks, the six digits were always 1-6 presented in ascending numerical order. In the high load blocks, six digits (taken from the digits 0-9) were presented in a different random order on each trial. Participants were requested to remember these digits for report at the end of the trial. Following the memory set display, a visual mask consisting of six '#' signs remained on the screen for 200 ms. Next there followed an unpredictable series of either two, three or four continuous vibrotactile targets, each accompanied by a pulsed distractor (Note 1). Targets were equally likely to appear in any of the four stimulus locations. Participants made speeded elevation discrimination responses (high vs. low) regarding the elevation of each target (regardless of whether it was presented to the left or right hand). A pulsed distractor, which participants were instructed to ignore as far as possible, was simultaneously presented to the non-target hand, either at the same elevation (congruent trials) or at the opposite elevation (incongruent trials). Response measurement began immediately following the first offset of the pulsed distractor stimulus (i.e. 50 ms after the start of stimulus presentation) because this was the first moment at which participants would have been able to distinguish the target from the distractor. Participants were instructed to respond as rapidly and accurately as possible, lifting the toes (for upper targets) or the heel (for lower targets) of whichever foot they were using to respond to the tactile task. Half of the participants responded to the tactile targets with the left foot and to the memory probe with the right foot, whereas the other half of participants responded to the tactile targets with the right foot and to the memory probe with the left foot. A feedback screen was presented for 500 ms after each tactile task, either following a response or after 5000 ms if no response had been made. This consisted of a blank screen if the response was correct; the word incorrect (written in red) if the response was incorrect; or the word missed (written in red) if no response had been detected. A 1000 ms blank screen was then presented before the next tactile task (or the memory test). After the final tactile task, a warning screen was presented for 1000 ms, containing the words ‘MEMORY TEST’. This was followed by two probe digits, presented one after another at the centre of the screen for 500 ms each. A question mark was then presented at the center of the screen, which constituted the participants’ cue to respond to the memory probe. The task was to report whether the two probe digits were presented in the same order (raise toe) or reversed order (raise heel) as they had been in the initial memory set. A feedback screen identical to that used for the tactile task was also presented following the memory test.

Participants were given several examples of pulsed and continuous vibrations, followed by eight practice tactile target trials in which there were no distractors and a further eight tactile target trials with distractors. They were then given two short practice blocks of the entire task including the memory set, one of high working memory load and one of low load. This was followed by four experimental blocks, two of high working memory load and two of low load. Each experimental block included five trials containing two tactile targets, six trials containing three tactile targets, and five trials containing four tactile targets, so that each block contained 48 tactile target trials in total. (Note 1). The order of presentation of the blocks was counterbalanced across participants (with half the participants receiving blocks in the order: low, high, high, low and the other half of participants receiving the reverse order: high, low, low, high).

Results and Discussion

Working memory task

Participants were significantly slower to respond to the working memory task under high load (M = 2124 ms) than under low load (M = 1573 ms, t(19) = 8.31, $p < .01$). Similarly, percentage accuracy on the memory task was significantly lower under high load (M = 86%) than under low load (M = 98%, t(19) = 4.80, $p < .01$). Together, these results indicate that the working memory manipulation used here was successful, such that the high load task was significantly more demanding than the low load task.

Tactile task

In both of the experiments reported here, trials in which incorrect memory responses were made were ruled out of the tactile task analyses. In addition, trials in which incorrect tactile responses were made were ruled out of the RT analyses, as were trials with RTs longer than 1300 ms. Table 1 presents mean tactile task RTs from Experiments 1 and 2 as a function of distractor congruence (congruent vs. incongruent) and working memory load (high vs. low). Figure 2 presents mean tactile task percentage accuracy from Experiment 1 as a function of the same two factors.

RTs. A within-participants ANOVA with the factors of distractor congruency (congruent vs. incongruent) and working memory load (high vs. low) revealed a significant main effect of congruency, $F(1,19) = 54.41$, $MSE = 2540.13$, $p < .01$, such that responses were slower on trials where the distractor was incongruent ($M = 719$ ms) than on trials where the distractor was congruent ($M = 636$ ms). There was no main effect of load and no interaction between the two factors ($p > .15$ for both comparisons).

Accuracy. A similar ANOVA on the accuracy data also revealed a significant main effect of congruency, $F(1,19) = 46.46$, $MSE = 57.18$, $p < .01$. Performance accuracy was worse when the distractor was incongruent ($M = 85\%$) than when it was congruent ($M = 96\%$). There was also a significant main effect of working memory load, $F(1,19) = 6.67$, $MSE = 24.82$, $p < .05$, such that there was a small, yet reliable, difference in tactile task accuracy between the high ($M = 89\%$) and low ($M = 92\%$) working memory load conditions. However, this pattern was in fact only found for the incongruent conditions (see Figure 2). Thus this main effect appears to have been driven by the significant interaction between the factors of working memory load and distractor congruency, $F(1,19) = 6.51$, $MSE = 18.80$, $p < .05$. This interaction indicated that although the distractor congruency effect was significant under low working memory load (M effect = 8%, $t(19) = 5.31$, $p < .01$), it was significantly increased by high working memory load (M effect = 14%), as predicted. The significant increase in distractor interference under high working memory load indicates the involvement of working memory in the control of tactile selective attention.

Overall, Experiment 1 demonstrates clear distractor congruency effects in both reaction times and accuracy, indicating that the tactile distractors interfered significantly with tactile target discrimination performance. Importantly, however, the findings also indicate that the tactile distractor interference effect on performance accuracy was more pronounced under conditions of high working memory load than under conditions of low load. Whereas findings of increased distractor processing under high (vs. low) working memory load are now well-established within the study of visual selective attention, the results of Experiment 1 provide the first demonstration that load theory can also be successfully applied to the tactile domain.

However, although these results are encouraging, we note that the influence of working memory load was confined to distractor interference effects on accuracy. The lack of working memory modulations of the distractor interference effects on RTs might have been due to the fact that those effects were already fairly large in the low working memory load condition (M interference effect = 82 ms). This may indicate that tactile distractors are particularly difficult to ignore (for example, in the standard flanker task visual distractors typically elicit congruency effects of around 20-50 ms). However, such flanker tasks tend to provide certainty with respect to the locations of the targets and distractors (e.g. targets are typically presented at the centre of the display, with the distractors at more peripheral locations). By contrast, in the present experiment, the targets and distractors were presented with equal likelihood in any of the possible four stimulus locations. Reduced certainty over target and distractor locations is known to results in increased distractor interference both in visual flanker tasks (Goolkasian & Bojko, 2001) and in tactile flanker tasks (Soto-Faraco et al., 2004). Thus the location uncertainty involved in Experiment 1 may have contributed to the relatively large RT interference effects observed in that experiment. This issue was addressed in the Experiment 2.

Experiment 2

Experiment 2 examined whether the pattern of results found in Experiment 1 would also be observed under conditions where the tactile targets and distractors were clearly separated in space. The design used was similar to that of Experiment 1 except that in the tactile task the target hand was now fixed throughout the experiment, with the distractor always presented to the other hand.

Method

Participants. Twenty new participants aged 18-35 (17 female, of whom three were left-handed) received a £5 gift voucher in return for their participation in this study.

Apparatus and stimuli. The apparatus was the same as that used in Experiment 1. However, in a change from Experiment 1, targets and distractors in the present experiment both consisted of continuous 200 ms presentations of a 200 Hz pure tone signal from one of the four vibrotactile stimulators. The stimuli were now identifiable as targets or distractors depending on the hand to which they were presented.

Design and procedure. The design and procedure were as described for Experiment 1, with the following exceptions. Targets were defined as appearing in one pre-specified hand throughout the entire experiment; left for half of the participants and right for the other half. On each trial, participants made speeded elevation discrimination responses (high vs. low) regarding the elevation of the stimulus presented to the target hand. On some trials, an identical distractor stimulus was simultaneously presented to the non-target hand, either at the same elevation (congruent trials) or from the opposite elevation (incongruent trials). On other trials this distractor was absent. RTs were now measured from target onset, as (in contrast to Experiment 1) targets were now distinguishable from distractors from the moment of their onset. Participants for whom targets were presented to the right hand responded to the tactile task using the right foot (and to the memory task with the left foot). Participants who received targets to the left hand responded to the tactile task with the left foot (and to the memory task with the right foot).

As in Experiment 1, each experimental block included five trials containing two tactile targets, six trials containing three tactile targets, and five trials containing four tactile targets, so that each block contained 48 tactile target trials in total. However, in a change from Experiment 1, these 48 tactile tasks included 16 trials in which the distractor was absent, 16 trials in which the distractor was congruent with the target and 16 trials in which the distractor was incongruent. We included a small number of distractor-absent trials to make the appearance of the tactile distractor less predictable.

Results and Discussion

Working memory task

Performance on the working memory task was worse under high load (M RT = 2201 ms, M accuracy = 85 %) than under low load (M RT = 1674 ms, M accuracy = 95%) and these differences were significant both in the RTs ($t(19) = 5.79$, $p < .01$) and in the accuracy data ($t(19) = 3.53$, $p < .01$). These results replicate those of Experiment 1 in confirming that the working memory manipulation used here was successful.

Tactile task

Figure 3 presents mean tactile task percentage accuracy from Experiment 2 as a function of distractor congruence (congruent vs. incongruent) and working memory load (high vs. low).

RTs. A within-participants ANOVA with the above factors revealed a significant main effect of congruency, F(1,19) = 86.55, MSE = 2627.09, p < .01. In line with the findings of Experiment 1, responses were slower on trials where the distractor was incongruent (M = 661 ms) than on trials where the distractor was congruent (M = 555 ms). Clearly, this distractor interference effect is not smaller than the effect found in Experiment 1 (in fact it is slightly larger), despite the increased location certainty in this experiment. However, as in Experiment 1, there was no main effect of load and no interaction between the two factors (p > .15 for both comparisons).

Responses in the distractor absent condition (M = 499 ms) were faster by 56 ms than responses in the distractor congruent condition, F(1,19) = 30.55, MSE = 2007.34, p < .01). This difference was greater under high load (M difference = 68 ms) than under low load, (M difference = 43 ms), F(1,19) = 6.87, MSE = 453.64, p < .05, possibly as the result of an overall slowing of reaction times under high working memory load (M = 550 ms) compared with low load (M = 504 ms), F(1,19) = 9.29, MSE = 4520.35, p < .01.

Accuracy. A within-participants ANOVA with the factors of distractor congruency and working memory load revealed a significant main effect of congruency, F(1,19) = 29.79, MSE = 150.05, p < .01. Performance was worse when the distractor was incongruent (M = 83%) than when it was congruent (M = 98%). There was a trend for a main effect of working memory load, F(1,19) = 3.98, MSE = 41.63, p = .06, such that accuracy in the tactile task was worse under conditions of high working memory load (M = 89%) than under low load (M = 92%). However, as in Experiment 1, this trend was only found for the incongruent conditions (in fact, the error rates for the congruent conditions were identical across load conditions, see Figure 3). Thus this main effect appears to have been driven by the significant interaction between the factors of working memory load and distractor congruency, F(1,19) = 4.96, MSE = 29.96, $p < .05$. As in Experiment 1, this interaction indicated that although the distractor congruency effect was significant under low working memory load (M effect = 12%, t(19) = 6.04, $p < .01$) it was significantly increased by high working memory load (M effect = 18%, see Figure 3). Finally, accuracy rates were very similar for distractor absent trials (M = 97%) and distractor congruent trials (M = 98%).

Overall, Experiment 2 replicates the findings of Experiment 1, in demonstrating a significant increase in tactile distractor interference on performance accuracy under conditions of high (vs. low) working memory load. (Note 2)

General discussion

Experiments 1 and 2 both demonstrate increased interference by tactile distractors under high (vs. low) working memory load, despite using different tactile tasks that may have involved different spatial orienting processes (i.e. endogenous spatial orienting to the target hand was was precluded in Experiment 1 but permitted in Experiment 2). Together, these findings imply that the availability of working memory is important for the successful control of tactile attention. This provides additional support for the claim that working memory is important for the maintenance of task priorities, regardless of the sensory modality of the task (e.g. Lavie, 2005; Lavie et al., 2004).

Interestingly, in both experiments, the modulation of distractor interference by working memory load was observed in the accuracy data but not in the reaction time data. This observation stands in contrast to previous visual research, which has usually demonstrated working memory load modulations of RT measures of distractor congruency (e.g. Lavie et al., 2004). This apparent discrepancy between the visual and tactile findings raises the intriguing possibility that tactile distractors might be more potent than visual distractors, such that they might cause large interference effects on reaction times regardless of the working memory load. Indeed given the potential importance of information received through the tactile channel (see Gregory, 1967), one might expect tactile attention to be less open to top-down cognitive control than attention in other sensory modalities. According to this account, in the task of ignoring tactile distractors, working memory would serve only to control against the distractors ‘winning’ the competition for control of responses (leading to errors), and would not influence the extent to which the tactile distractors are perceived and are therefore able to influence the RTs.

Nevertheless, our finding that the extent to which tactile distractors can lead to task errors is subject to control by working memory has interesting potential implications in terms of applied settings. For example, with applied psychologists increasingly demonstrating the usefulness of tactile cues in situations of multiple task performance (e.g. Ho, Reed, & Spence, 2006; Ho, Tan, & Spence, 2005; Van Erp & Van Veen, 2005) an understanding of the factors contributing to the processing of these cues is becoming increasingly important. The present results raise the intriguing possibility that tactile cues designed to draw attention away from a primary task and toward a secondary task might actually be less effective if the primary task has a low working memory load than if its load is high.

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Author Notes

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Footnotes

1. We presented an unpredictable number of tactile targets (2, 3 or 4) in order to vary the time of onset of the memory test, with the aim of encouraging participants to maintain the memory set actively throughout the entire trial.

2. One possible criticism of the current findings is that, due to the demanding nature of the high load working memory task, participants may have engaged in sub-vocal articulatory behaviour in the high load blocks but not in the low load blocks. The observed increase in distractor interference under high (vs. low) working memory load could in this case be due to differences in articulation between the two types of block, rather than to differences in working memory load per se. In order to control for this possibility, a group of ten additional participants took part in a modified version of Experiment 2 in which the two high load blocks were replaced by articulation blocks (during which participants were asked simply to repeat the digits 1-2-3-4-5-6 while carrying out the tactile tasks). The data from these participants showed no evidence of an interaction between block type (low load vs. articulation) and distractor congruency (congruent vs. incongruent), either in the error rates or in the RTs ($F < 1$ for both comparisons). This indicates that distractor interference effects were similar both when participants were engaged in articulatory behaviours (M effects = 14% and 87 ms) and when they were not (M effects = 14% and 94 ms). Given that speaking aloud does not appear to increase distractor interference, it seems highly unlikely that the increased distractor effects observed in the present experiments under high (vs. low) working

memory load can be explained by higher levels of sub-vocal articulation processes in high (vs. low) load blocks.

Table 1

Averages of participants' mean RTs in ms (with standard errors in brackets) for Experiments 1 and 2 as a function of working memory load and distractor congruency.

	Low load		High load	
Experiment	Congruent	Incongruent	Congruent	Incongruent
1	626 (22)	708 (28)	644 (21)	730 (24)
2	538 (22)	657 (24)	572 (28)	666 (29)

Figure captions

Figure 1. Schematic outline of the experimental set-up. Responses were made using footpedals beneath the table (not shown here).

Figure 2. Graph to show averages of participants' mean accuracy for Experiment 1 as a function of distractor congruency and working memory load.

Figure 3. Graph to show averages of participants' mean accuracy for Experiment 2 as a function of distractor congruency and working memory load.

Figure 1

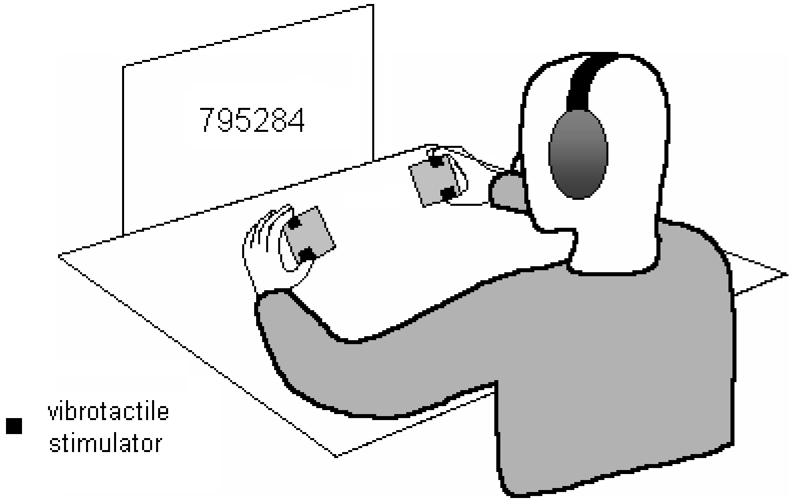


Figure 2

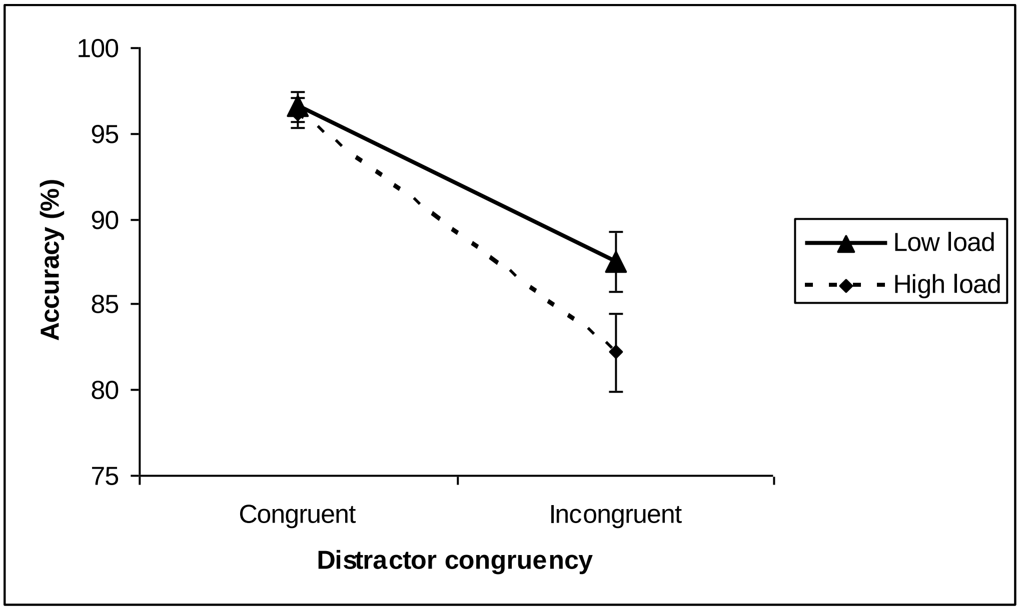
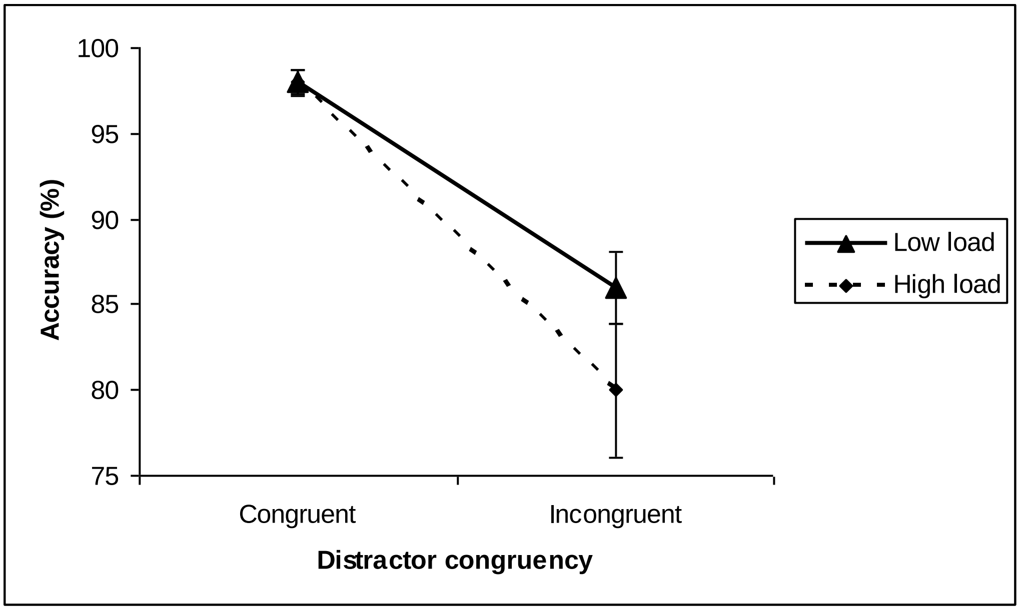

100
95
90
85
80
75
Accuracy (%)
Congruent
Incongruent
Distractor congruency
Low load
High load

Figure 3


100
95
90
85
80
75
Accuracy (%)
Congruent
Incongruent
Distractor congruency
Low load
High load