Working Memory Load and Stroop Interference Effect

A thesis submitted in partial fulfilment of the

requirements for the Degree of Masters of Science

in Psychology

By

Quan Ying Gao

University of Canterbury

2006

Acknowledgements

I would like to thank my two supervisors, Dr. Zhe Chen and Paul Russell. They have worked with me tirelessly, ever so tolerant, given me advice and support throughout this research.

Thank you my most lovely friend, Elizabeth Kyonka. Thank you for your assistance and encouragement. Thank you Robyn Daly for your help and advice. I would also like to thank everyone in the Psychology Department who has encouraged me every step of the way.

Finally, but most improtantly, I thank my husband, Fred. Without your encouragement and love, I would not have been able to complete this study.

Table of Contents

Abstract

Although the effect of working memory (WM) load on the magnitude of distractor interference has been studied extensively, a common characteristic in prior research is that the target and distractors belong to different objects The present experiments investigate the effect of WM load on distractor interference when the relevant and irrelevant information is part of the same object. In two experiments, participants saw stimulus displays that consisted of a memory set followed by a Stroop color stimulus. The tasks were to respond to the color of the stimulus first and then to a memory probe. The principal manipulations were the relationship between the color and meaning of the Stroop stimulus (neutral vs. incongruent) and the level of WM load (high vs. low). The results show that WM load had little effect on the magnitude of Stroop interference. These results were consistent with previous research which shows that WM load plays a limited role in the efficiency of selective attention when the extent of attentional focus was held constant across different WM load conditions. They also emphasize the importance of stimulus structure in understanding selective attention in general, and distractor processing in particular.

Introduction

A fundamental question in visual attention is concerned with how and when to prevent processing of task irrelevant distractors. An important debate is on whether attentional limitations occur before or after stimulus identification. Early selection views, which were proposed by Broadbent (1958) and further developed by Treisman (1969), assume that perception is a limited resource process. Analyses of the physical features of stimuli can proceed without attention; however, semantic analysis and identification require full attention. Thus irrelevant distractors can be efficiently prevented early. Selection is based on spatial location and other properties of the stimuli (e.g. colour and orientation). In contrast, late selection views, which were proposed by Deutsch and Deutsch (1963), assume that perception is an automatic process; stimulus identifications are processed in parallel, and the selection occurs after stimuli are identified.

Lavie and her colleagues (Lavie, 1995; 2005; Lavie & Tsal, 1994; Lavie, Hirst, de Focket, & Viding, 2004) recently proposed the load theory of attention that integrated the early selection and the late selection approaches. According to Lavie, perceptual resources are limited at any given moment, and perception proceeds automatically until all resources are used up. Whereas early selection occurs under high perceptual load due to the lack of resources, late selection takes place under low perceptual load because of the availability of resources. Furthermore, two mechanisms are involved in selective attention: a passive perceptual selection mechanism and an active cognitive control mechanism (Lavie et al., 2004). The perceptual selection mechanism is considered a passive mechanism because distractor interference does not occur under situations of high perceptual load. When the perceptual load involved in a task is high, distractors are not perceived because the perceptual capacity is fully engaged by the relevant stimuli. However, when the perceptual load involved in a task is low, distractors are perceived because resources remain available to process them. The cognitive control mechanism is required to actively inhibit distractors under conditions of low perceptual load. If the cognitive control mechanism is occupied (e.g., when participants have to carry out a high working memory load task), large distractor interference will result due to the lack of available resources to actively maintain stimulus processing priorities.

Lavie's (1995; 2005) load theory has received much empirical support (e.g., Huang-Pollock, Carr & Nigg, 2002). For example, Lavie and Cox (1997) carried out a study in which participants were required to search for one of two targets among five Os (easy search) or among five different nontarget letters (hard search) while ignoring an additional irrelevant distractor letter presented peripherally. The peripheral distractor could be compatible (the same letter), incompatible (the other target letter), or neutral (a letter with no-response associations) with respect to the target. The results indicated that although participants were slower in the hard task than in the easy task, they showed a significantly greater compatibility effect in the easy task than in the hard task. This result suggests that there was greater distractor interference when the target was among five Os than when it was among five different letters. In a subsequent experiment, Lavie and Cox further tested whether the low distractor compatibility in the hard task of the previous experiment was caused by the unavailability of attentional resources. They varied the number of nontarget letters, and found that the compatibility effect remained constant at a higher level until set size four, and then it dropped significantly. These results are consistent with Lavie's load theory. They suggest that the distractor interference could be prevented only when the perceptual capacity was exhausted. Whereas distractor interference was minimal under high perceptual load, it was substantial under low perceptual load.

In more recent experiments, Lavie and her colleagues tested the cognitive control mechanism by focusing on the role of the frontal cortex in selective attention tasks (Lavie et al., 2004). The frontal cortex is known to be associated with various cognitive control processes, such as working memory (Courtney, Ungerleider, Keil, & Haxby, 1997). Therefore, when perceptual load is low, greater distractor interference should result when working memory load is high rather than when it is low due to the lack of resources to actively inhibit the distractors in the high working memory load condition. This hypothesis has been supported by several studies (Lavie et al., 2004; Lavie & de Fockert, 2006; Lavie & de Fockert, 2005).

For example, Lavie & de Fockert (2005) recently carried out a study in which a single-task condition and a dual-task condition were used to compare capture by an irrelevant singleton, which is a stimulus containing a unique feature. In the single-task condition, participants were required to search for a circle among diamonds and to make a speeded response to the orientation of a line within the circle. In the dual-task condition, participants were required to hold in memory a set of six digits while performing the search task, and to determine the presence or absence of a digit afterwards. In all conditions, the stimulus displays were sometimes accompanied by an irrelevant colour singleton distractor. The results showed that the irrelevant singleton caused significantly greater interference under the dual-task condition than under the single-task condition. In the next experiment, the researchers further tested the effect of working memory load on visual search tasks under the dual-task condition. A four-digit memory set was presented at the beginning of each trial. Whereas the digits were presented in a different random order under the high working memory load condition, the same ordered set appeared on every trial under the low load condition. The results again indicated significantly less distractor interference under the low working memory load condition compared with the high working memory load condition. Comparable results were found in Experiment 3 in which the working memory load was manipulated by requiring participants to hold different number of digits (4 vs. 1) in the high and low working memory conditions. These findings are consistent with Lavie's cognitive load theory of attention in that the magnitude of distractor interference was negatively correlated with the availability of working memory resources.

However, despite the empirical support from the experiments reviewed above, other studies have shown that the effects of perceptual load and working memory load on distractor processing are more complex than was proposed by the load theory (e.g., Chen, 2003; Chen & Chan, in press; Eriksen & St. James, 1986; Logan, 1978; Miller, 1987; Paquet and Craig, 1997; Woodman, Vogel, & Luck, 2001; Yantis and Johnston, 1990). For example, the effect of perceptual load on distractor interference appears to depend on the spatial relationship between the relevant and irrelevant information. Whereas perceptual load modulates the degree of distractor interference when the relevant and irrelevant information belong to different objects, the effect reversed when they are part of the same object as in Stroop stimuli (Chen, 2003). In one experiment conducted by Chen (2003, Experiment 3), participants were required to identify the colour of a Stroop word or a letter string only when certain conditions were met: the line presented with the Stroop task was either black or white (low perceptual load condition), or the line was either black and in an upper position or white and in a lower position (high perceptual load condition because processing feature conjunctions requires more attentional resources than processing single features (e.g. Treisman & Gelade, 1980). The results indicated that although participants responded significantly faster in the low load condition than in the high load condition, Stroop interference was greater under high loads than under low loads. These results are inconsistent with Lavie's hypothesis of perceptual load, in which low perceptual load would result in greater interference. The result of this experiment suggests that an increase in perceptual load does not necessarily decrease the magnitude of distractor interference when the relevant and irrelevant information are different dimensions of the same object.

Chen (2003, Chen & Chan, in press) also noted that there was a potentially important confound in many previous load experiments (e.g., Lavie & Cox, 1997; Lavie et al., 2004). The level of perceptual load and/or memory load was confounded with the spatial extent of attentional focus. Chen suggests that the effect of load might be different when the extent of the attentional focus is controlled because the extent of attentional focus is known to influence the degree of distractor interference (Chen, 2003, Experiment 4; LaBerge, Brwon, Cater, Bash, & Hartley, 1991). In a recent study (Chen & Chan, in press, Experiment 3), Chen and Chan reported no effect of the level of working memory load on the degree of distractor interference. Their participants saw a memory array (one digit or six digits), followed by a cue. The cue was made of either one square (narrow attentional focus) or four identical squares that formed a rectangle (wide attentional focus). The spatial extent of the cue was much smaller in the narrow attentional focus condition than in the wide attentional focus condition. Upon the offset of the cue, a target (H or S) surrounded by four identical distractor letters (H, S, or X) was presented. The participants were required to respond to the target while holding digits in memory. There were three experimental conditions: a high working memory load/narrow attentional focus condition (the high-load/narrow-focus condition), a low working memory load/narrow attentional focus condition (the low-load/narrow-focus condition), and a low working memory load/wide attentional focus condition (the low-load/wide-focus condition). If greater distractor interference was found in the high than the low working memory load condition, cognitive control would be the major determinant of performance, and the result would be consistent with Lavie's cognitive load theory. However, the attentional focus account would be the major determinant if greater interference was observed in the wide-focus condition than in the narrow-focus condition. The results showed that working memory load had little effect on distractor interference. There was no significant difference in the magnitude of Stroop interference between the high-load/narrow-focus condition and the low-load/narrow-focus condition. Instead, a significantly greater Stroop interference effect was found in the low-load/wide-focus condition than in the low-load/narrow-focus condition. These results are inconsistent with Lavie's memory load theory, which predicts a larger compatibility effect in the high-load/narrow-focus condition compared with the low-load/narrow-focus condition. They suggest that controlling the spatial extent of attentional focus could reduce or eliminate the effect of working memory load on distractor interference.

To date the effect of working memory load has been tested only when the relevant and irrelevant information belong to separate entities. The present experiments explore the effect of working memory load on distractor interference when the irrelevant information is part of the same object as the relevant information, such as in Stroop stimuli. The working memory load hypothesis would predict greater

Stroop interference under high working memory loads since fewer working memory resources will be available for the task. In contrast, the attentional focus hypothesis would predict no differential effects of working memory load when the extent of attentional focus is controlled.

Experiment 1 was designed to determine whether distractor interference was influenced by the level of working memory load when the relevant and irrelevant information belonged to the same object. Experiment 2 manipulated both working memory load and the spatial extent of attentional focus.

Experiment 1

Method

Participants. Thirty-six undergraduate students between the ages of 18 and 40, with normal or corrected-to-normal vision were recruited for this study.

Stimuli. Stimuli were presented on a grey background and each trial consisted of a fixation screen, a memory set, a cue, a letter display, and a memory probe. The fixation was a white cross (1.24° of visual angle) presented at the centre of the computer screen. The digits (36 pt Arial font) in the memory set were white coloured, randomly selected from 1 to 9, and always presented at the centre of the screen. There were six digits in the high working memory load and one digit in the low working memory load condition. The cue was made of two white coloured bars (1.34° high) which were separated by a gap of 2.1°. The cue, which was always valid, indicated where the target letter would be presented, either on the left or right side of the screen. The spatial separation between the cue and the centre fixation was 6.21°. The letter display (36 pt Arial font) was either one of “red”, “blue” , “green”, and “yellow” or a string of letters of corresponding length (e.g. “vvv”, “oooo”, “sssss”, “nnnnnn”). For the letter display, there were four colours: red (RGB: 100, 0, 0), blue (RGB: 0, 0, 100), green (RGB: 0, 100, 0), and yellow (RGB: 100, 100, 0). Each word (or its corresponding letter string) was displayed in any of the three colours except the colour that matched the word meaning (e.g. the word “red” and its equivalent “vvv” were printed in blue, green, or yellow, but not in red ink).

Design and Procedure. The experiment was a mixed design: the between-subjects variable was the level of working memory load (high load vs. low load); the within-subjects variable was the response compatibility between the meaning and the colour (neutral vs. incongruent). There were an equal number of incongruent (e.g. “red” was presented in green) and neutral trials (e.g. “vvv” was presented in green) (96 trials for each). Each participant received 48 practice trials. After the practice trials, the participant completed three blocks of 64 trials for a total of 192 trials. The entire experiment took about 30-35 min to complete. The participants were encouraged to take short breaks between the blocks.

E-Prime software was used to present stimuli and to collect responses. The participants were randomly assigned to either the low working memory load condition or the high working memory load condition. Each trial started with a 1,000 ms fixation, followed by a 520 ms blank screen. A memory set was then presented for either 520 ms in the low load condition or 2000 ms in the high load condition (see Figure 1 for details). Upon the offset of the memory set, a cue was presented either on the left or the right side of the screen with equal probability for 120 ms indicating where the target letters would be presented. Immediately after the cue, the letter display was presented for 120 ms. Participants were then required to indicate the colour of the target letters by pressing an appropriately coloured key on the key board as quickly and as accurately as possible. Four different coloured patches, green, yellow, red and blue, were attached to four of the keys on the keyboard, two on the right hand side and the other two on the left hand side ("z" for red, "x" for green, ","for yellow and "." for blue). Both speed and accuracy were emphasized in the colour task. Upon response, a memory probe, which remained visible until participants responded, appeared at the centre of the screen. If the probe digit was one of the digits that appeared in the memory set at the beginning of the trial, participants were required to press a "Yes" key on the key board; otherwise, they pressed a "No" key. There were equal number of probe present and probe absent trials. The "Yes" and "No" keys were labelled, one on the left and the other one on the right hand side ("a" for yes and ";" for no). Accuracy instead of speed was stressed for the memory task.

Results and Discussion

The Stroop task data are shown in Table 1 and Figure 2. Reaction times (RTs) longer than 2000ms were excluded from data analyses (1.0% of the data were excluded). Participants' mean RTs were analyzed by a mixed memory load × congruency analysis of variance. There was a significant Stroop interference effect: faster response times on the neutral trials (730 ms) than on the incongruent trials (755.73ms), $F(1, 34) = 14.26$, $p<0.05$. There was no significant difference between the two memory load conditions, 704.90 ms in the high load condition and 781.25 ms in the low load condition, $F(1, 34) = 1.71$, $p>0.2$. Furthermore, there was no significant interaction between response compatibility and memory load, $F(1, 34) = 1.1$, $p>0.3$. In other words, the interference effect was not significantly different between the low and high load conditions: 32.23ms in the low load condition and 18.38ms in the high load condition.

Participants' mean accuracies were analyzed by a mixed memory load × congruency analysis of variance, which showed that there was no significant difference between the two the high load (6.2% error) and the low load (4.4% error) conditions, $F(1,34)=1.5$, $p>0.2$.

The memory data are shown in Table 2. The effectiveness of the working memory load manipulation was tested. A *t* test for independent means on the accuracy data showed no significant difference between the high and low load memory conditions (7.1% error vs. 5.7% error, for the high and low load conditions, respectively, $t(34) = 0.90$, $p>0.3$. However, a similar test on RT indicated faster responses in the low load condition (908.21ms) than in the high load condition

(1144.08ms), $t(34) = 4.02$, $p<0.001$. Although there was no significant difference in the accuracy data, the result on RT suggest that the manipulation on working memory load was effective.

Overall these results do not support Lavie’s load theory, which predicts that distractor interference is greater with higher working memory load. However, in the present experiment, greater interference was not found in the high than the low memory load condition although Stroop interference effects were evident in the experiment and the memory load manipulation was effective.

One may wonder why the present results differed from those of Lavie’s (Lavie et al., 2004; Lavie & de Fockert, 2006; Lavie & de Fockert, 2005). A possible explanation is the extent of attentional focus in this experiment. The cue that indicated the side of the screen where the next display would appear was equivalent in the two memory load conditions and therefore the extent of attentional focus should have been roughly equivalent in these conditions. The attentional focus, however, was not strictly controlled in many of Lavie’s experiments. In those studies, the attentional focus was typically larger in the high memory load condition than in the low memory load condition

Alternatively, the possibility exists that Experiment 1 was not sensitive enough to detect the effects of memory load predicted by Lavie. After all, there was no difference in memory accuracy in the two load conditions despite longer RT for the high than the low load conditions. To provide converging evidence for the results of

Experiment 1, Experiment 2 used a slightly different paradigm to directly examine the effect of working memory load as well as the effect of attentional extent on distractor interference.

Experiment 2

In this experiment, the level of working memory load was combined with the extent of attentional focus to yield the following three conditions: high memory load and narrow attentional focus (high-narrow condition); low memory load and narrow attention focus (low-narrow condition); and low memory load with wide attentional focus (low-wide condition). This design enables the effects of both memory load (high-narrow vs. low-narrow condition) and the attentional focus (low-narrow vs. low-wide condition) to be explored in the same experiment.

Method

Participants. Seventy-five undergraduate students, between the ages of 18 and 40, with normal or corrected-to-normal vision were recruited for this study.

*Stimuli and Procedur*e. These were the same as in Experiment 1 except for the cue. Unlike Experiment 1, the cue in this experiment was either a small white square (0.57°) or four identical small white squares located at the corners of an imaginary square (8.50°). The cue was presented at the vertical centre of either the left or the right side of the screen (see Figure 3). Participants were equally divided and randomly assigned in equal numbers to one of the three groups: high working memory load with narrow attentional focus, low working memory load with narrow attentional focus, and low working memory load with wide attentional focus. All groups performed a Stroop task followed by a digit memory task.

As in Experiment 1, there were an equal number of incongruent and neutral trials (96 trials for each). Each participant received 48 practice trials. After the practice trials, the participant completed three blocks of 64 trials for a total of 192 trials. The entire experiment took about 30-35 min to complete. The participants were encouraged to take short breaks between the blocks.

Results and Discussion

The results for the Stroop task are shown in Table 3. Data from three participants were not included in the analyses as a large proportion of their RT data were longer than the cut off score of 2000ms.

A mixed groups × response compatibility analysis of variance on participant mean RTs revealed that the only significant effect was the main effect of response compatibility: faster reaction times on the neutral trials (812.04 ms) than on the incongruent trials (839.88 ms), $F(1, 69) = 13.55$, $p<0.001$. There was no significant difference in RTs between groups : 781.76 ms in the high-narrow condition, 805.79 ms in the low-narrow condition and 890.34 ms in the low-wide condition, $F(2, 69) = 2.62$, $p>0.05$. Furthermore, there was no congruency by group interaction, $F(2, 69) =$

1.31, $p>0.2$. The congruency effect in the high-narrow (25.66ms), low-narrow (14.03ms) and low-wide conditions (43.81ms) are comparable.

A mixed groups × response compatibility analysis of variance on participants' mean Stroop error rates showed the responses on these three conditions (3.73% for high-narrow, 4.06% for low-narrow and 2.3% for low-wide) are not significantly different, $F(2, 69) = 1.72$, $p>0.1$.

The data for the memory task were illustrated in Table 4. The results of the memory task were analyzed by one-way ANOVAs on mean RT and accuracy, which showed faster and more accurate responses in the two low load conditions (865 ms with 5% error for low-narrow and 817ms with 4% error for low-wide condition) than in the high load condition (1321ms with 9% error), $F(2, 69) = 21.16$, $p<0.01$ for RT and $F(2, 69) = 6.53$, $p<0.01$ for accuracy. These results show that the level of working memory load was manipulated effectively. To clarify the differences between the groups, further *t*-tests (high-narrow vs. low-narrow conditions; high-narrow vs. low-wide conditions; low-narrow vs. low-wide conditions) were conducted. The results indicate that the participants in the high-narrow condition is significantly slower and less accurate than the participants in the low-narrow condition, $t(46) = 4.7$, $p<.001$ for RT and $t(46) = 2.7$, $p<0.01$ for accuracy. The RT in the high-narrow is also significantly longer than that in the low-wide condition, .$t(46) = 5.6$, $p<.001$) and significantly more errors were made in the high-narrow conditions than in the low-wide condition, $t(46) = 2.9$, $p<0.01$. There is no significant difference for RT and error rate in the low-narrow and low-wide conditions, $t(46) = 0.7$, $p>0.2$ for RT and $t(46) = 0.4$, $p>0.3$ for accuracy. These results showed that the manipulation of the memory load was successful.

As the results in Experiment 1, the results from Experiment 2 also contradict the predictions derived from Lavie's cognitive load theory: Higher levels of working memory load did not lead to a greater Stroop interference although the manipulation of the memory load was clearly demonstrated to be effective in Experiment 2.

The results are also inconsistent with Chen's (2003; Chen & Chan, in press) hypothesis regarding the effect of attentional focus on distractor interference. While there was a trend for greater interference to occur with wider attentional extent, the effect failed to reach significance.

General Discussion

The goal of the present study was to investigate the effect of working memory load on distractor interference when the task relevant and irrelevant information were part of a single object. Two experiments are reported. In Experiment 1 levels of working memory load had no effect on the magnitude of Stroop interference, and this was contrary to Lavie's load theory,. Experiment 2 was designed to provide converging evidence to the results of Experiment 1 and to extend it by manipulating the extent of attentional focus in addition to working memory load. As in Experiment 1 manipulations of memory load had no effect on the size of Stroop interference. With the two experiments both showing a load effect in the memory task but no load by congruency interaction in the Stroop task, one can be reasonably confident that the failure to find support for Lavie's theory was not due to a lack of power.

The results of the present experiments are compatible with the findings of Logan (1978), who presented the stimuli in the memory set sequentially, and showed that working memory load did not influence the slope in visual search, suggesting that increasing memory load does not increase interference from distractors. In addition, Woodman, Vogel and Luck (2001) also reported that working memory had no significant influence in performing visual search tasks. In their experiment, participants were required to hold zero (search alone condition), two or four objects (dual task condition) in their memory while performing a visual search task. The search display consisted of 4, 8, or 12 items. The results indicated a linear increase in RTs for the visual search task with the increase of the set size in both search alone and dual task conditions. However, the slopes for these two conditions were comparable. These results suggested that working memory did not play an important role in visual search tasks, which are consistent with the results from the current experiment where there was no significant difference in Stroop interference between the low and high working memory load conditions.

However, the results contradicted the predictions of Lavie's cognitive control theory, in which greater distractor interference results when working memory is loaded (Lavie, 2005). How can we explain these inconsistencies?

One possibility is the difference in attentional focus. In Experiment 1 of Lavie and de Fockert's (2005) study, six digits were presented before the targets in the high memory load condition and no digits in the low load condition. Although the extend of attentional focus could be different between the two load conditions, the fact that a fixation point was presented for 2 seconds before the presentation of the target display made it unlikely that any difference in the effect of the memory load on distractor interference was due to a difference in the extent of attentional focus. .

A more likely possibility is the special relationship between the relevant and irrelevant information in the test array. One common characteristic in prior research is that the target and distractors were separate objects. In the present experiments, the relevant and irrelevant information were part of a single object. It is possible that the availability of working memory resource to the visual task affects the amount of distraction by irrelevant information only when the relevant and irrelevant information are spatially separated; however, when these two pieces of information are overlapped, the effect disappears.

Overall, this current study has found no evidence that the degree of distractor interference varied as a function of working memory load when the relevant and irrelevant information belong to the same object.

The role of attentional focus in visual search tasks is unclear in this present study. Thus, to control the extent of attentional focus for the digits in the memory test, it might be a good idea to present the digit sequentially rather than simultaneously for further study. In addition, with wide and narrow attentional focus, it is important to determine the size of wide and of narrow focus. It is possible that the wide condition in Experiment 2 was not wide enough to encompass the entire Stroop word. Also, the narrow condition might be very concentrated, which is narrower than the area that the word is occupied. Thus, it is possible that not the whole word but only the centre of the word is fully attentional focused. Thus, further study might consider exactly how the size of extent of attentional focus should be manipulated.

Reference

Adleman, N. E., Menon, V,. Blasey, C. M., White, C. D., Warsofsky, I. S., Glover G. H., & Reiss, A. L. (2002). A developmental fMRI study of the Stroop color-word task. *NeuroImage*, *16*, 61-75

Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon Press.

Chen, Z. (2003). Attentional focus, processing load, and Stroop interference. *Perception & Psychophysics*, *65*, 888-900

Chen, Z., & Chan, C. (in press). Distractor interference stays constant despite variation in working memory load. *Psychonomic Bulletin & Review*

Courtney, S. M., Ungerleider, L. G., Keil, k., & Haxby, J. V. (1997). Transient and sustained activity in a distributed neural system for human working memory. *Nature*, *386*, 6-8-611

Deutsch, J. A., & Deutsch, D. (1963). Some theoretical considerations. *Psychological Review*, *70*, 80-90

De Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attentive. *Science*, *291*, 1803-1806

Eriksen, C. W., & St. James, J. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*, 225-240

Huang-Pollock, C. L., Carr, T. H., & Nigg, J. T. (2002). Development of selective attention: perceptual load influences early versus late attentional selection in children and adults. *Developmental Psychology*, *38*, 363-375

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 451-468

Lavie, N. (2005). Distracted and confused?: selective attention under load. *Trends in Cognitive Science, 9*, 75-82

Lavie, N., & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. *Psychological Science, 8,* 395-398

Lavie, N., & de Fockert, J. (2006). Frontal control of attentional capture in visual search. *Visual Cognition, 14,* 863-876

Lavie, N., & de Fockert, J. W. (2005). The role of working memory in attentional capture. *Psychonomic Bulletin & Review*, *12,* 669-674

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics, 56*, 183-197

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133*, 339-354

Logan, G. D. (1978). Attention in character-classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General*, *107*, 32-63

Miller, J. (1987). Priming is not necessary for selective-attention failures: semantic effects of unattended, unprimed letters. *Perception & Psychophysics*, *41*, 419-434

Paquet, L., & Craig, G. L. (1997). Evidence for selective target processing with a low perceptual load flankers task. *Memory & Cognition*, *25*, 182-189

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643-662

Treisman, A. (1969). Strategies and models of selective attention. *Psychological Review*, *76*, 282-299

Treisman, A. M., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97-136

Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*, 219-224

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin Review*, *11*, 269-274

Yantis, S., & Johnston, J. C. (1990). On the locus of visual selection: Evidence from focused attention tasks. *Journal of Experimental Psychology: Human Perception & Performance*, *16*, 135-149

Table 1

Mean reaction time (in milliseconds) and error rates (percent incorrect) for the Stroop task of Experiment 1. Standard errors are in the parentheses.

	Low Working Memory Load			High Working Memory Load		
	I	N	I-N	I	N	I-N
RT	797 (47.4)	765 (45.9)	32 (11.3)	714 (36.6)	696 (35.1)	18 (7.2)
% Error	4.1 (1.01)	4.7 (0.7)	-0.6 (0.7)	5.8 (1.3)	6.6 (1.3)	-0.8 (0.8)

Note: N = neutral; I = incongruent.

Table 2

Mean reaction time (in milliseconds) and error rates (percent incorrect) for the memory task of Experiment 1. Standard errors are in the parentheses.

	Low Working Memory Load	High Working Memory Load
RT	908 (45.86)	1144 (35.26)
% Error	5.7 (0.79)	7.1 (1.30)

Table 3

Mean reaction time (in milliseconds) and error rates (percent incorrect) for the Stroop task of Experiment 2. Standard errors are in the parentheses.

	High – Narrow			Low – Narrow			Low – Wide		
	I	N	I-N	I	N	I-N	I	N	I-N
RT	794 (27.4)	769 (28.18)	25.66 (10.72)	813 (37.23)	799 (37.61)	14.03 (6.12)	912 (43.78)	868 (37.94)	43.81 (19.04)
% Error	3.76 (0.52)	3.70 (0.65)	0.06 (0.29)	4.19 (1.06)	3.93 (0.56)	0.26 (0.40)	2.37 (0.44)	2.23 (0.28)	0.14 (0.14)

Note: N=neutral; I = incongruent.

Table 4

Mean reaction time (in milliseconds) and error rates (percent incorrect) for the memory task of Experiment 2. Standard errors are in the parentheses.

	High – Narrow	Low – Narrow	Low – Wide
RT	1321 (82.3)	865 (52.8)	817 (39.5)
% Error	9 (1.4)	5 (0.8)	4 (0.9)

Figure 1

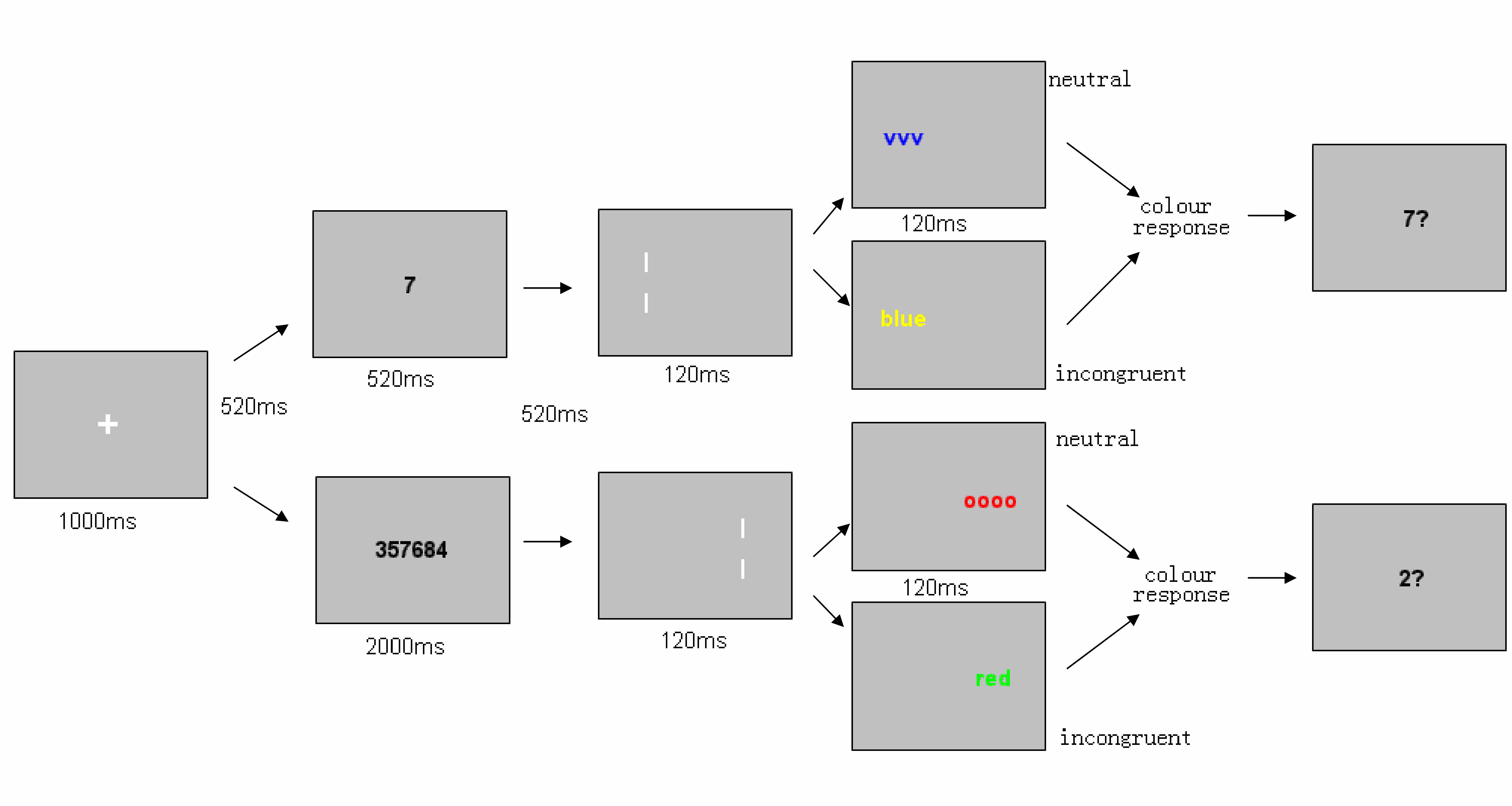
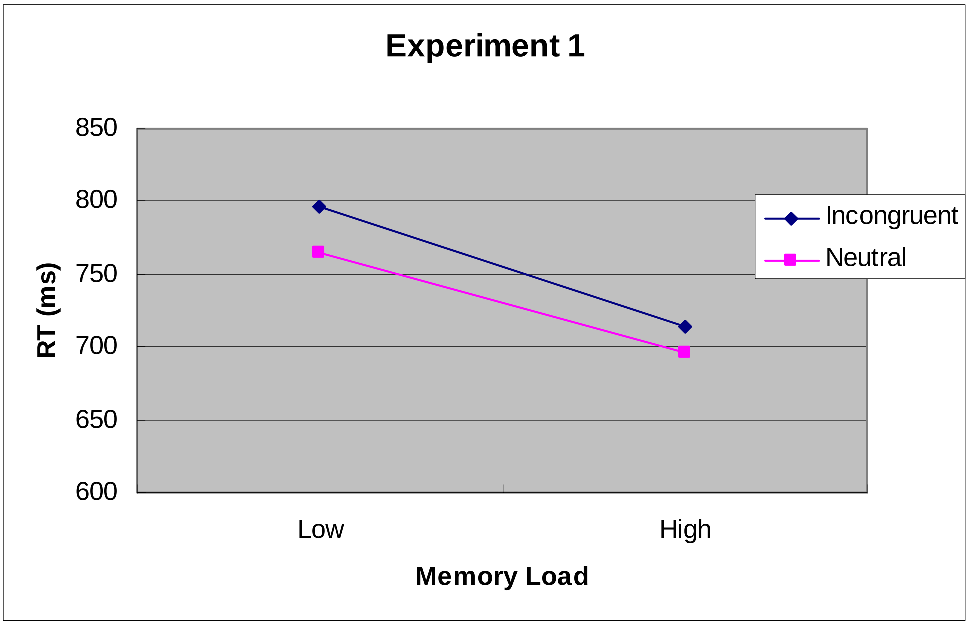
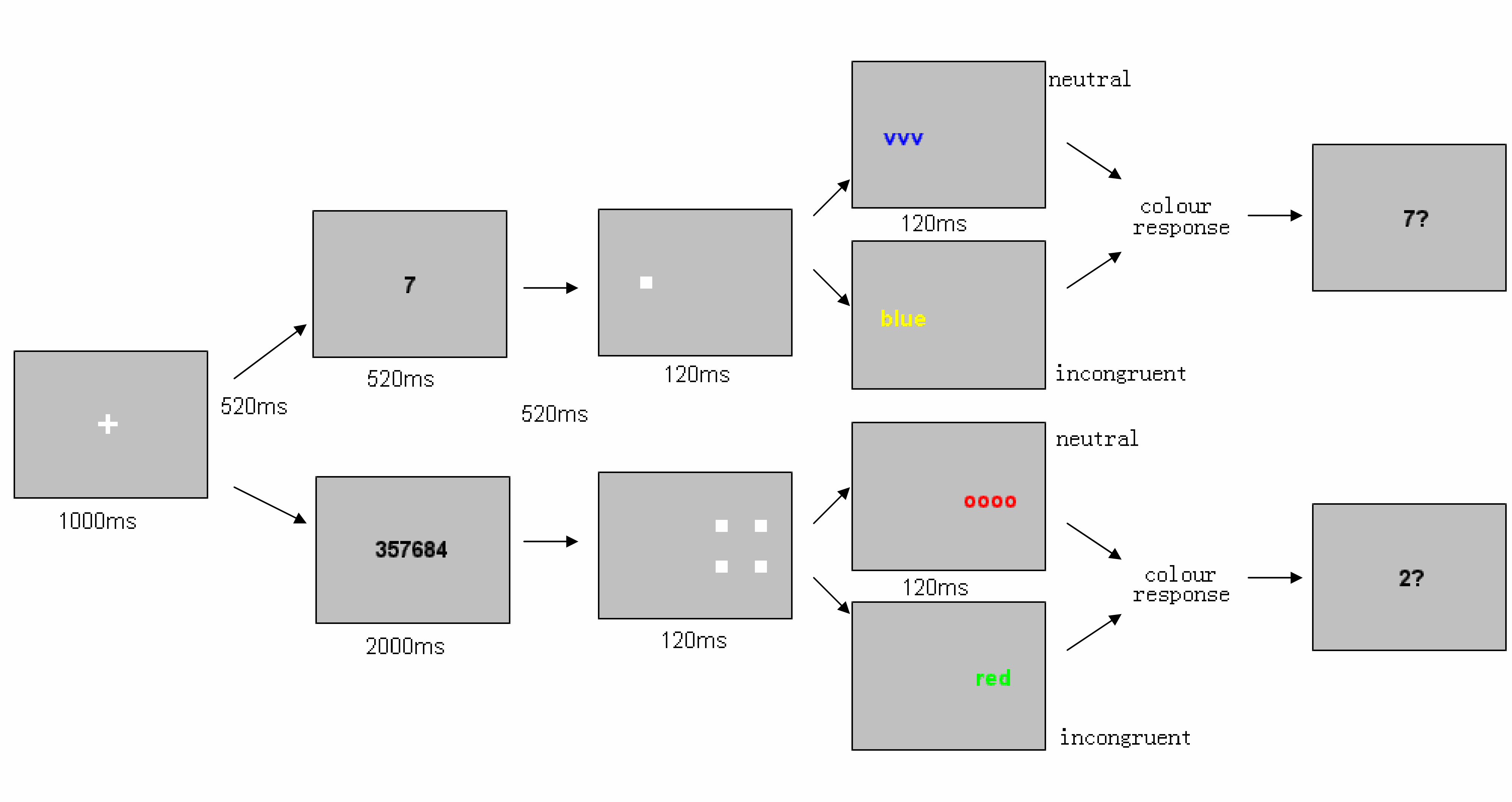

+
1000ms
520ms
7
520ms
520ms
357684
2000ms
120ms
120ms
vvv
120ms
neutral
blue
incongruent
oooo
120ms
neutral
red
incongruent
colour
response
colour
response
7?
2?

Figure 2



Experiment 1
850
800
750
700
650
600
RT (ms)
Incongruent
Neutral
Low
High
Memory Load

Figure 3


+
1000ms
520ms
7
520ms
520ms
120ms
vvv
neutral
120ms
blue
incongruent
colour
response
7?
357684
2000ms
120ms
oooo
neutral
120ms
red
incongruent
colour
response
2?