THE EFFECTS OF RESPONSE MAPPING AND CONJUNCTIVE SEARCH ON AUTOMATIC PERFORMANCE IN COMPLEX ENVIRONMENTS

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ABSTRACT

Complex tasks in the world ranging across fields such as aviation, military and healthcare require operators to develop highly skilled and automatic levels of performance in response to critical stimuli in the environment. This research extends the findings from the dual-process theory of automaticity by considering two aspects that are common in realistic search-and-respond tasks: the consistency of responding and the conjunction of cues. Results revealed that inconsistent mapping of responses disrupted performance, and that the more variably responses are mapped, the worse is the effect on detection time. In addition, results showed that the mapping of each of the cues that confirm a target had an effect on the development of automatic behavior. When all the cues that defined a target were variably mapped, performance deteriorated, compared to situations in which at least one of the cues was consistently mapped. Potential implications for design and training of complex systems are discussed.

INTRODUCTION

One of the more relevant theoretical developments of automaticity is the dual-process theory (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). A classic finding from this theory is that automatic processing develops with extended practice when targets are consistently mapped (they are always targets and never appear as distractors). Such automatic processing is assumed to be fast and parallel, requiring little attention or awareness. Thus, performance under automatic processing is unaffected by workload. On the other hand, under varied mapping conditions wherein stimuli may be targets in one instance but distractors in another, performance occurs under controlled processing, which is voluntary, serial, requires attention, and is significantly affected by workload.

Several complex tasks in the world today require participants to develop highly skilled and automatic levels of performance to achieve fast and accurate responses to critical stimuli in the environment. In target detection tasks, ranging across fields such as aviation, military and healthcare, such automatic detection processes are relevant to situations such as that of a pilot detecting the presence of an enemy aircraft among ‘friendly’ aircraft, a physician detecting the presence of a tumor in x-rays, or a luggage screener detecting a presence of a hidden weapon among objects in passenger luggage. The development of automaticity in such contexts is particularly important as these complex tasks are characterized by multiple target stimuli and distractors, and environmental variables such as time pressure and workload make these tasks extremely difficult to perform in the absence of a practiced skills.

Despite the clear relevance of the dual-process theory to complex tasks, this theory has seldom been shown to provide concrete prescriptions for design and training of these tasks (Schneider & Shiffrin, 1985). The general conclusions drawn were that optimal detection and response times in target detection tasks can be obtained when keeping targets and distractors consistently mapped. However, real-world complex tasks are replete with multiple and heterogeneous stimuli, often requiring that we make decisions based on varied or inconsistent conditions. For example, in the field of military aviation, pilots must be able to distinguish the attributes of friendly aircraft from those of their enemy, in order to select the appropriate response. The nature of visual search is often *conjunctive*: detection must combine multiple attributes; and *dynamic*: characteristics of the environment keep changing over time while a decision is being made (consider for example, speed and altitude). Further, in real-world complex tasks, a consistently mapped target may require different responses depending on the situation and context. For example, the same target identified as enemy may be attacked with different weapons depending on contextual variables such as visibility or target trajectory.

Our goals in this research are to test the dual-process theory of automaticity in complex tasks and to determine concretely how the dual-process theory can provide prescriptions for design and training. This paper accomplishes these goals as follows. First, we present what we call “An ecological account of the dual-process theory of automaticity.” In this section, we identify sources of complexity to which this research applies. Then, we present two experiments to test two particular sources of our ecological account of automaticity: (1) the consistency of responses and (2) conjunctive search. Finally, results from these experiments are discussed for their relevance and their implications for design and training.

An Ecological Account of the Dual-process Theory of Automaticity

Although there are many ways in which a complex task could be characterized (Gonzalez, Vanyukov, & Martin, 2005), the dual-process theory of automaticity has been studied in search-and-respond tasks, and the approach shown here focuses on this family of tasks.

Search-and-respond tasks are pervasive in the real-world. They are as common as looking for fruit defects at the grocery store or finding an open teammate on the basketball court. Also, some of these tasks are important and relevant for our health and society, such as a doctor identifying a tumor on an X-ray image, a soldier determining the presence of a combatant in unfamiliar terrain or an airport security officer looking for dangerous items in passenger luggage. Although ubiquitous and important to our daily life, it is unclear what makes this family of tasks complex.

The complexity of search-and-respond tasks can be determined by at least two general factors: (1) stimulus and response mappings, and (2) temporal and spatial characteristics of the task.

Stimulus and response mappings

Traditionally, in the dual-process theory of automaticity, mapping is seen as a one-to-one relationship between a visual item and the "target" category to which the item may belong. But in complex search-and-respond tasks, there can be two types of mappings: the stimulus and the response. Further, these mappings are often not one-to-one but many-to-many relationships. Items to be identified as targets or distractors are often defined by the combination of multiple attributes (conjunctive attributes) rather than one, and may be classified as multiple possible targets. For example, an airplane defined by multiple attributes (i.e., size, color, model, altitude, and speed) may be classified as belonging to one of multiple categories of targets (i.e., very aggressive, moderately aggressive or minimally aggressive). In the tasks used to develop the dual-process theory of automaticity, the response is the same when an item is identified as target. But in the real world, mapping between the category (i.e., a target or a distractor) and the response can be again a many-to-many relationship. For example, multiple actions such as ignore, damage, or destroy can be applied to the same enemy target.

Thus, the concept of consistency from the dual-process theory of automaticity can be defined in multiple ways in complex search-and-response tasks: between stimuli and categories (i.e., stimulus mapping or *consistency of attending*) or between categories and responses (i.e., response mapping or *consistency of responding*). These two types of consistency have been previously identified in the literature of automaticity in generic task contexts. For example Fisk and Schneider (1984) investigated whether both consistency of attending and responding (i.e., total task consistency) are necessary for the development of automatic detection in a memory task. They found that performance was better when stimulus mapping was consistent. Interestingly, response mapping had a negligible processing cost when stimuli were consistently-mapped to categories. They concluded that response mapping was not necessary for the development of automatic detection, and was less crucial for skill acquisition than stimulus mapping. Similarly, Kramer, Strayer and Buckley (1991) showed a smaller increasing trend in event-related potentials for consistent-attending conditions than for varied-attending conditions with practice, but no interaction with response mapping. They concluded that consistency of responding was unnecessary for the development of automatic detection and that the processing costs of inconsistent responding were small.

Past findings clearly indicate that total task consistency is not necessary for the development of automatic detection in relatively simple single-cue tasks (Durso, Cooke, Breen, & Schvaneveldt, 1987; Fisk & Schneider, 1984; Kramer et al., 1991). However, we believe that total consistency in general, and response mapping in particular, are important in complex tasks. The reason for this can be illustrated with the following example. In the military field, soldiers often face situations where they need to choose a course of action based on the perceived severity of the threat posed by an enemy aircraft. Specifically, they may have to decide whether to use guns, bombs or lasers to attack the enemy depending on whether the hostile aircraft needs to be destroyed, captured or merely ‘frightened away’. The challenge in a situation such as this arises from the fact that an enemy aircraft might appear similar on more than one occasion. Yet, the required response varies depending on the pilot’s weighting of the situation at hand. This inconsistency in the mapping of responses to the same stimuli poses a significant challenge to operators in complex systems.

Temporal and spatial dynamics

In addition to stimulus and response mappings, the complexity of search-and-respond tasks is also determined by the temporal and spatial dynamics of the task. Most complex tasks are dynamic in time and space. Decisions are often made while the conditions of the decisions are changing (Edwards, 1962) and thus, decision-makers must act in real-time (i.e., when the situation demands a decision, not just when a decision maker is ready to act) (Brehmer, 1992). Thus, *when* a decision is made is essential in these tasks. In addition, the spatial location of items involved in the decision making process often changes in real-time while the situation in being evaluated (consider for example, speed and altitude in the airplane example above).

Most research involving search-and-respond tasks in the study of automaticity are static. Items to be identified do not change in time and space. The fact that complex search-and-respond tasks are dynamic means that relationships between stimulus and response can change in time and space. Related research in the automaticity literature indicate that the selection of consistently-mapped cues becomes increasingly efficient with practice (Rogers & Fisk, 1991). In other words, cues that are always associated with targets increase their attentional strengths relative to distractors; it is also known that people learn to search the smallest set of features that distinguish targets from distractors (Fisher & Tanner, 1992; Kramer et al., 1991). But in complex search-and-respond tasks, we find not only various levels of mapping but also the complication of dealing with dynamic complexity, which involves time constraints and spatially moving targets.

Next, we present two experiments to test two sources of our ecological account of automaticity: the consistency of responses and conjunctive search. The focus of the first experiment is to investigate the processing costs of inconsistent responding. The second experiment then investigates the effect and search costs of complex targets, those defined by the combination of multiple cues.

THE RADAR TASK

Both experiments conducted used a complex search-and-respond task with real-world counterparts, called Radar. This task is dynamic in time and space, involving moving items and time constraints in effect during the identification of an item.

The Radar task is a single-user control task in which the goal is to detect and eliminate a hostile enemy aircraft by selecting an appropriate weapon system. Radar is similar to military target visual detection devices, in which a moving target needs to be identified as a potential threat and a decision is made on how to best destroy the target under time constraints. The development of this task was inspired by the theatre defense program created by (Bolstad & Endsley, 2000).

The Radar task has two components: (1) search-and-respond and (2) decision-making. Due to the nature of the two experiments reported in this paper, only the search-and-respond component of Radar is described here. In the methods section of each of the experiments, we will explain how this component of Radar was adapted to address the two manipulations studied in this paper. A complete description of Radar including the decision-making component can be found in Gonzalez and Thomas (in press).

The search-and-respond component is illustrated in Figure 1. This component requires the user to memorize a set of targets and then look for the presence of one or more targets on a radar grid. This component essentially reproduces the goals of Schneider and Shiffrin's (1977) task, except that the visual elements in Radar are dynamic in time and space. In Schneider and Shiffrin's (1977) task, all stimuli appear within foveal vision, they are static and there is no time constraint to respond. In contrast, in the Radar task, the stimuli move on the screen, and thus rapid eye movements and visual scanning are required to find a target. A target threat may or may not be present among a set of moving blips that represent incoming aircraft. The blips—in the form of symbols, digits, consonants, or blank masks—begin at the four corners of the radar grid and approach the center at a uniform rate. The detection of an enemy aircraft must occur before the blips collapse in the middle of the grid. Using the search-and-respond component of Radar, it is possible to manipulate the consistency of mapping, workload (the number of items memorized and the number of items on the radar screen), and the time constraints (called the frame time, measured as the time taken by the blips to collapse in the middle of the grid).

EXPERIMENT 1

The purpose of Experiment 1 is to determine the influence of response mapping in automatic performance. In this experiment, we manipulated the response mapping by varying the number of possible responses (only one or more than one) and the consistency of the responses (the same responses or changing responses) throughout practice. The stimulus mapping was consistent throughout practice. We also manipulated the time constraints, i.e., the time available for target detection. We predicted that response mappings would have a significant effect on performance despite the consistency of stimulus mapping. We also expected the frame time to influence performance, specifically in the cases where response mapping became more complex (one-to-many mappings and inconsistency).

Method

Participants

Eight students (two females and six males) with the average age of 20 participated in the study. All participants were right-handed, had normal color vision, and had normal or corrected-to-normal visual acuity. All participants were recruited from local universities and were paid $11.00 per hour for their participation. Each participant completed six experimental sessions of approximately 3 hours each, for a total of 18 hours of task practice.

Experimental design

We designed a 4X2 within-subjects experiment. Two independent variables were manipulated in the experiment: (1) response mapping (at 4 levels) and (2) frame time (at 2 levels). Thus, the experiment consisted of 8 conditions. Each condition was presented twice during the experiment. Each condition was presented in a block of 30 frames and each frame had 14 trials (detections). A set of targets to remember (memory set) was shown before each frame. Thus, a total of 6,720 trials were distributed in six experimental sessions. The dependent variables were the proportion of correct detections and the average detection time for correct detections.

Response mapping. An illustration of the four levels of response mapping is shown in Figure 2. Four keys corresponding to the four corners of the numeric keypad were used for possible responses: 1, 7, 9, and 3. The keys were color coded with a color sticker on the key (1 = red, 7 = blue, 9 = green, and 3 = yellow). The participant's goal was to respond by pressing the correct key depending on the response mapping condition:

1) *Fixed mapping*: participants responded with one and the same key every time a target was detected. All axes on the radar grid were the same color. The color of the axis was randomly selected, shown to the participant and remained constant in each frame. Thus, any time the participant detected a target he/she was to respond by pressing the same key, regardless of where the target was detected.

2) *Full mapping*: participants responded with one of the four possible keys according to the color of the axes in which the target was detected. For example, if the target was detected in the bottom-left corner axes, the correct response was to press the 1 key (red). Each of the four axes of the grid were color-coded with the same color as the response keys (bottom-left=red, top-left=blue, top-right=green, bottom-right=yellow).

3) *Partial mapping*: participants responded with one of the four possible keys. However, in this condition two of the axes were consistent with the colors of the numeric keys and the other two axes were randomly assigned one of the four colors.

4) *Random mapping*: participants responded with one of the four possible keys, but in this condition, the color of each of the four axes was randomly assigned to one of the four colors. Thus, the consistency between spatial layout and the color coding of the responses and radar axes was random.

Frame Time. The time between the onset of one frame and the next was manipulated in two ways: the "slow" condition was 2,050 ms and the "fast" condition was 1,050 ms. For both frame time conditions, the radar grid was presented to the participants for 1,000 ms before each trial and the inter-trial interval was 1,500 ms.

Procedure

Before the onset of each frame, participants were asked to memorize a set of 4 targets (either digits or letters). Then they were presented with a sequence of 14 trials. Each trial displayed four moving blips. The participant's task was to detect any member of the memory set that appeared in the sequence of trials. Targets could appear in any trial except the first two and last two trials. At the end of each frame, participants received feedback on their performance. In case of an error in detection, a tone sounded at the end of the relevant frame. Participants were also provided with textual feedback at the end of each trial which detailed the type of error made (false alarm, miss, etc.). Stimulus mapping was always consistent and members of the target set never appeared as distractors. For example, when the targets were digits (1–9) the distractors were letters (C, D, F, G, H, J, K, L, M) and vice versa.

Results

Figure 3 shows the proportion of correct detections (Panel A) and the detection times (Panel B) averaged by response mapping condition (stimulus, full, partial, random) and frame time condition (slow, fast).

The repeated measures analysis of variance revealed main effects of response mapping and frame time only for detection time, and no significant effects for the proportion of correct detections. The interactions between response time and frame time were not significant.

The proportion of correct detections remained relatively stable across mapping conditions, particularly in the slow condition. However, although Figure 3 (Panel A) shows a different pattern across response mapping conditions for the fast frame times, the interaction between response mapping and frame time was not statistically significant.

On the other hand, detection time of correctly detected targets was clearly influenced by both, the response mapping $F(3, 21) = 20.31$, $p < .001$, and the frame time $F(1, 21) = 54.95$, $p < .001$, independently. Detection time increased with the difficulty of the response mapping condition. Detections were fastest in the mapped-to-stimuli condition (M = 1056 ms, SD = 78.14) and slowest in the random-mapping condition (M = 1425 ms, SD = 61.49) as expected. Detection time was also fastest in the fast condition (M = 1173 ms, SD = 73.97) and slowest in the slow condition (M = 1391 ms, SD = 68.15).

Summary

The results of Experiment 1 indicated that response mapping significantly affected the detection time of correctly detected targets despite the consistency of stimulus mapping. The results however, also indicated that response mapping did not have an effect on the proportion of correct detections. Furthermore, time constraints also significantly affected detection time, but the effects were constant across response mapping conditions. These results and their implications for design and training are analyzed in the general discussion and conclusions section.

EXPERIMENT 2

This experiment tests the dual-process theory of automaticity when targets are formed by the conjunction of two cues and stimuli are dynamic. Once again, we used the search-and-respond component of Radar.

Rather than using one cue (symbol type) as traditionally it is done in the dual-process theory of automaticity (Schneider & Shiffrin, 1977), we used two cues (symbol type and color) and we either kept the mapping consistent or varied the mapping over practice. We also used a workload variable, the memory set size (the number of items to remember and search for), to test whether performance under automatic processing was unaffected by workload. We expected that the mapping of both cues together rather than the mapping of only one of the cues would affect performance. Specifically, we expected consistent mapping of both cues to result is best performance. Also, we expected that the consistent mapping of the conjunction of the two cues would result in performance that would be unaffected by workload.

Method

Participants

Five participants (one female and four males) with an average age of 22 years participated in this study. Participants were right-handed, had normal color vision, and had corrected or normal acuity. All participants were recruited from local universities and were paid $11.00 per hour for their participation. Each participant took part in six experimental sessions (each lasting approximately 3 hours) over six different days, for a total of 18 hours of task practice.

Experimental design

This experiment was a 2X2X2 within-subjects design. Three variables were manipulated in this experiment: (1) the mapping of the color (consistent or varied), (2) the mapping of a symbol (consistent or varied), and (3) the memory set size (1 or 4 items to remember and search for). The conjunction of two cues, type of symbol and color, determined the target set. The symbols used in the experiments were digits (1, 2, 3, 4, 5, 6, 7, 8) and letters (K, H, D, G, J, L, M, C). The colors used in the experiment were gold, gray, green, orange, peach, red, yellow, purple, cyan, and blue; these colors were selected from the Visual Basic 6.0 color palette because they are most distinct from each other. It has been shown that the amount of information that can be gleaned through human color perception is maximized at 10 colors (Flavell & Heath, 1992).

Each of the 8 possible conditions was randomly assigned to a block of 16 frames and each frame had a total of 14 trials (detections). The memory set was shown before ach frame. The symbols and colors were either consistently mapped (randomly selected symbols and colors were kept as targets within a frame) or variably mapped (the symbols in a target set could appear as distractors in another target set within a block). A target was defined by a conjunction of color and symbol. The memory-set size was set to either 1 or 4 as it was manipulated in the initial experiments of the dual-process theory of automaticity (Schneider & Shiffrin, 1977). When the memory-set size equaled 1, there was only one possible target (defined by the conjunction of a single color and a single symbol). When memory-set size was 4, there were 4 targets (out of 16 possible unique conjunctions of the four colors and four symbols).

The dependent variables were the proportion of correct detections and the average detection time for correct detections.

Results

Proportion of correct detections. The repeated measures analysis of variance on the proportion of correct detections shows significant main effects of color mapping, $F(1, 4) = 7.99$, $p < .05$, symbol mapping, $F(1, 4) = 44.31$, $p < .01$, and memory set size, $F(1, 4) = 7.82$, $p < .05$. The proportion of correct detections was higher under consistent color mapping (M = .94, SD = .05) than varied color mapping (M = .86, SD = .09); higher under consistent symbol mapping (M = .96, SD = .05) than varied symbol mapping (M = .84, SD = .08); and higher under memory set size of 1 (M = .93, SD = .06) rather than 4 (M = .87, SD = .07).

The two-way interactions were also significant for color mapping and symbol mapping, $F(1, 4) = 7.99$, $p < .05$, for color mapping and memory set size, $F(1, 4) = 7.99$, $p < .05$, and for symbol mapping and memory set size, $F(1, 4) = 7.99$, $p < .05$. These interactions are shown in Figure 4.

Detection Time. The analyses of variance showed significant main effects of color mapping, $F(1, 4) = 35.75$, $p < .01$, symbol mapping, $F(1, 4) = 16.35$, $p < .05$, and memory set size, $F(1, 4) = 178.87$, $p < .001$. The correct detections' responses were faster under consistent color mapping (M = 756 ms, SD = 177) than varied color mapping (M = 1030 ms, SD = 210); faster under consistent symbol mapping (M = 820 ms, SD = 155) than varied symbol mapping (M = 967 ms, SD = 233); and faster under memory set size of 1 (M = 756 ms, SD = 172) rather than 4 (M = 1031 ms, SD = 215).

The two-way interactions were also significant: color mapping and symbol mapping, $F(1, 4) = 35.75$, $p < .01$, color mapping and memory set size, $F(1, 4) = 35.75$, $p < .01$; and symbol mapping and memory set size $F(1, 4) = 35.75$, $p < .01$. In detection time the triple interaction color mapping, symbol mapping, and memory set size was also significant, $F(1, 4) = 41.67$, $p < .01$. These interactions are shown in Figure 5.

Summary

The results of Experiment 2 revealed that participants were more accurate and faster in detecting targets when each of the cues that formed a target was consistently mapped, than when the cues were variably mapped. More importantly, the mapping of both cues in conjunction also determined performance. Performance was worst when both cues were variably mapped. On the other hand, mapping at least one of the cues consistently had a significant advantage on performance. Furthermore, when any of the two cues was consistently mapped, performance was unaffected by workload. In contrast, when at least one of the cues was variably mapped, performance was affected by workload. The significant three-way interaction on detection time shows that worst performance appears when both cues were variably mapped and individuals worked under conditions of high workload.

GENERAL DISCUSSION AND CONCLUSIONS

The dual-process theory and the current studies show that optimal performance after extended practice occurs when targets are consistently mapped. However, this research extends this traditional view of automaticity by considering the multiple ways in which consistency may occur in complex, real-world search-and-respond tasks.

In the first experiment, we demonstrated that response mapping can be critical for skill development above and beyond the consistency of attending. The more inconsistent the responses are, the longer it takes to detect targets. This extends research that has reported negligible effects of response mapping (Fisk & Schneider, 1984; Kramer, Strayer, & Buckley, 1990). Our results revealed that, on average, the difference in response times between consistent responding (the Fixed response mapping condition) and the Full condition was 184 ms; between the Fixed and the Partial condition was 298 ms; and between the Fixed and Random mapping condition was 421 ms. These processing costs associated with inconsistent responding were considerably higher than in past research by Fisk and Schneider (1984), that found a processing cost of 64 ms for inconsistent responding and concluded that consistency of responding was less important than consistency of attending in the development of automaticity. Also, Kramer et al. (1991) concluded that consistency of responding was unnecessary for the development of automatic detection and that the processing cost of inconsistent responding was small (17 ms). However, as our results demonstrate, when tasks are complex and dynamic, the consistency of responding is equally important. Therefore, we would expect that in real-world, complex search-and respond tasks, consistency of responding as well as the time constraints in the task can be important factors for effective performance. Although our results did not reveal a statistically significant interaction between response mapping and time constraint, the data suggest that there might be an increasingly detrimental effect of time constraints on performance as the inconsistency of responses (or the complexity of response mapping) increases. Testing this possibility will require further research.

In the second experiment, we demonstrated the importance of dynamic, conjunctive search. Our results indicated that the consistency of mapping of each of the cues that defined the targets, independently, resulted in better performance. But, most importantly, our study indicates that the inconsistency of both cues together produced the most detrimental effect on performance. Research on attention indicates that a target defined by multiple cues results in a serial search (Treisman & Gelade, 1980). That is, search time can increase with the number of cues and the number of levels of cues that are needed to search. Also, research shows that cues are processed in serial order (e.g., colors then symbols or symbols then colors) (Fisher & Tanner, 1992). Thus, previous research suggests that an increased number of cues may involve increased serial search. Our results demonstrate that if at least one of the cues is consistently mapped, this search can become more accurate especially when compared with cues that are all variably mapped.

Implications for design and training

As discussed in our ecological account of the dual-process theory of automaticity, ‘consistency’ is a multi-dimensional concept. Thus, rather than solely analyzing a task in terms of consistency of attending, which often results in obvious and simplistic implications to systems design and training, we suggest that performance on a search-and-respond task needs to be analyzed on at least two additional possible dimensions: the mappings of stimuli and responses and the temporal and spatial dynamic characteristics of the task.

As demonstrated by the results of these experiments, analyzing a search-and-respond task in terms of the consistency of responding and the conjunction of search cues helped identify some important impediments in skill acquisition. For example, when the spatial layout of a display and the spatial layout of the response keys are redundant (i.e., location compatibility) it capitalizes on people's natural tendency to move toward stimuli (Simon, 1969; Wickens & Hollands, 2000). When the spatial location of the stimulus and the response location are inconsistent (for instance, a target is preset on the northwest axis, but the appropriate response is the 9 key or the northeast response key), Wickens and Hollands' (2000) collocation and movement compatibility principles are violated. However, even when these principles are not violated (when the spatial location of the stimulus and the response key are redundant), there are still processing costs over inconsistent responding. Thus, when possible, system designers should consistently map stimuli and responses, to attenuate the processing costs associated with response selection.

Another implication of this research involves a recommendation for training. If extensive training is provided with a wide range of stimuli in simulated tasks, it is possible to develop automatic detection if at least one of the cues is consistently mapped. Individuals can benefit from automatic detection even when they perform in the presence of other variably mapped cues. Our future research will be directed at exploring the ecological account of the dual-process theory of automaticity in all its dimensions, including the effects of spatial and temporal dynamics and the multiple forms of consistency of attending and responding.

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FIGURE CAPTIONS

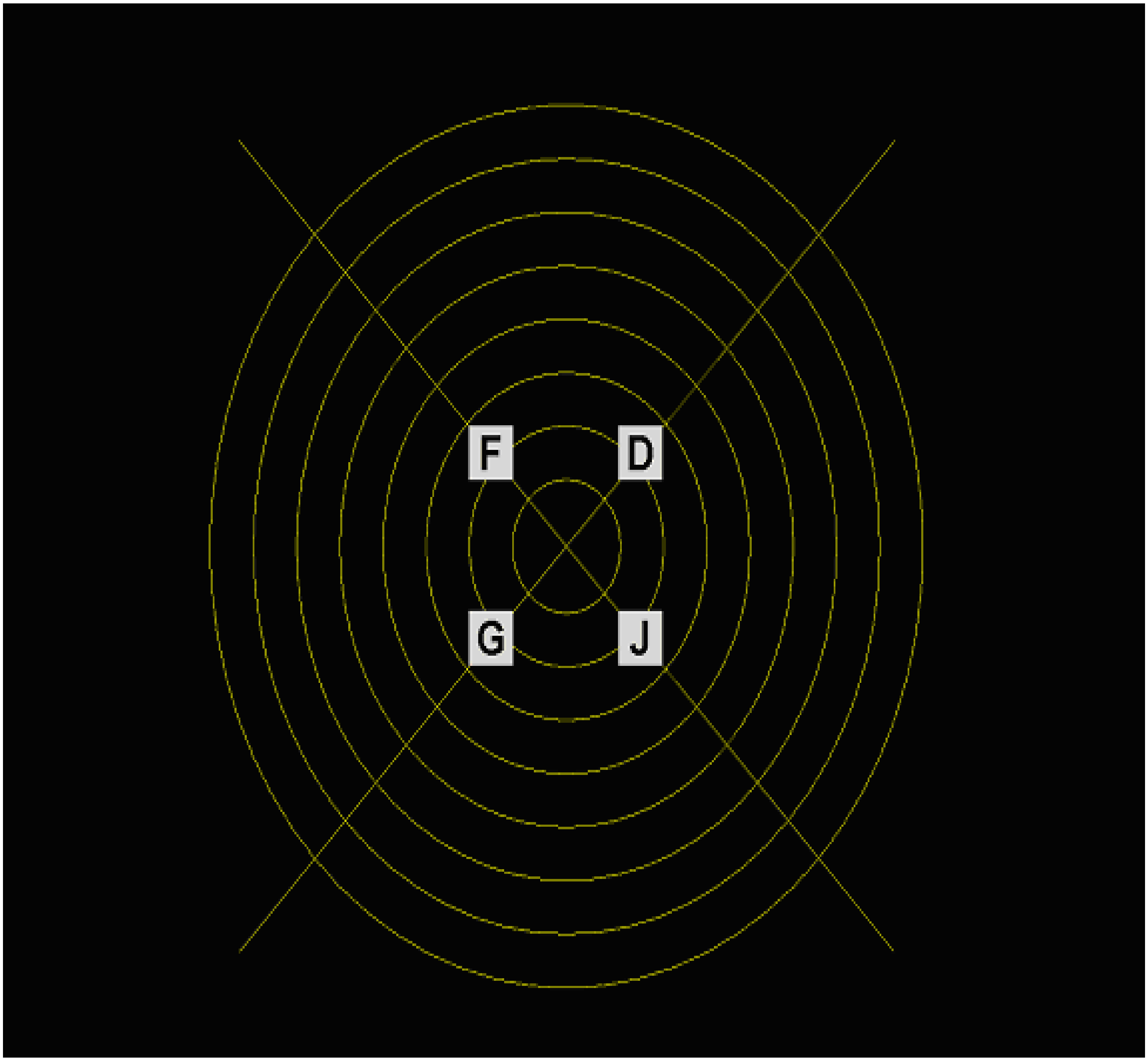
Figure 1.

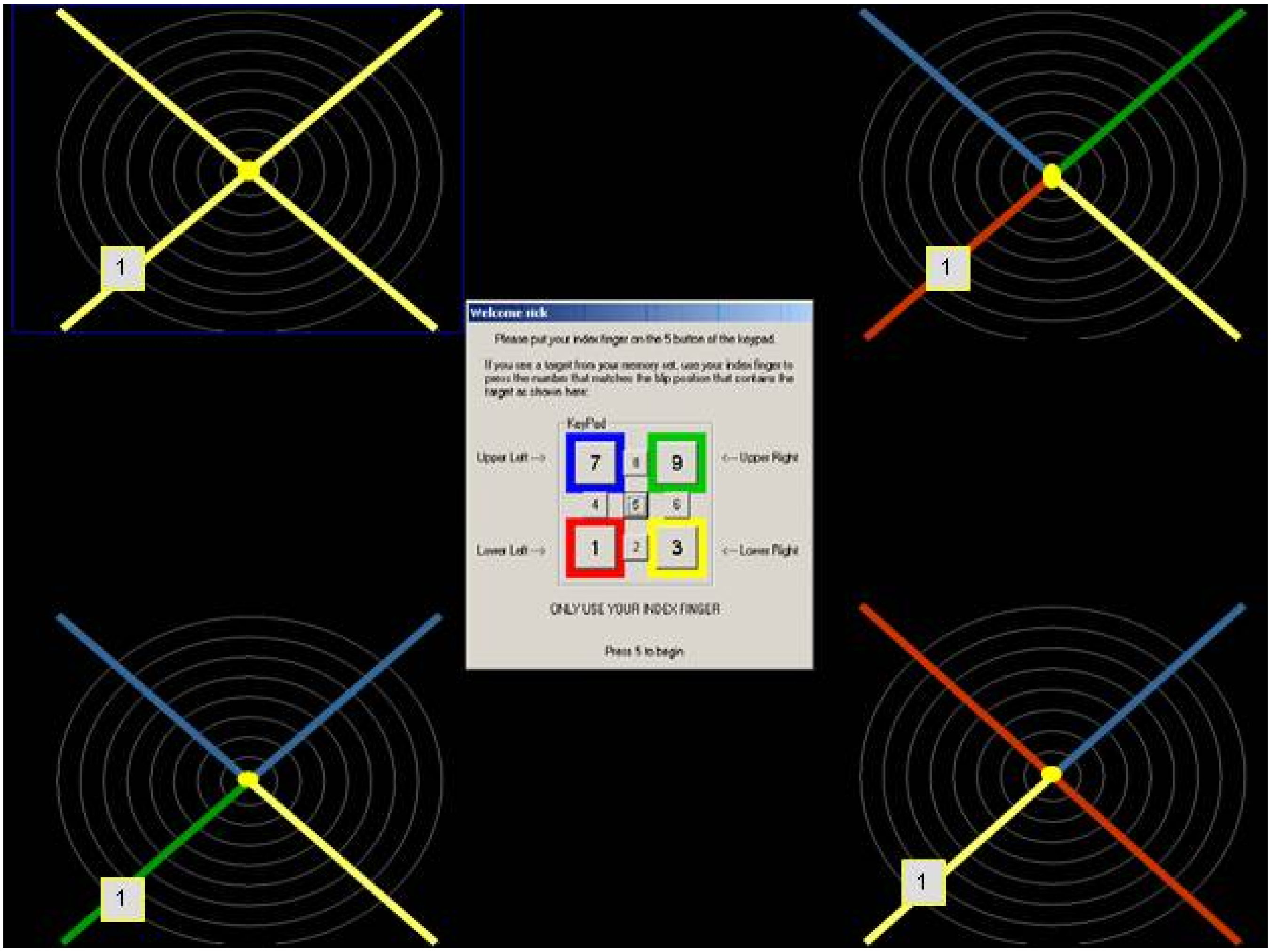
Figure 2. An illustration of the manipulation of the conjunctive search mapping in Experiment 1. The center of the figure shows the keypad instructions to respond according to the color of the axes in the different conditions.

Figure 3. Proportion of correct detections and detection time in Experiment 1.

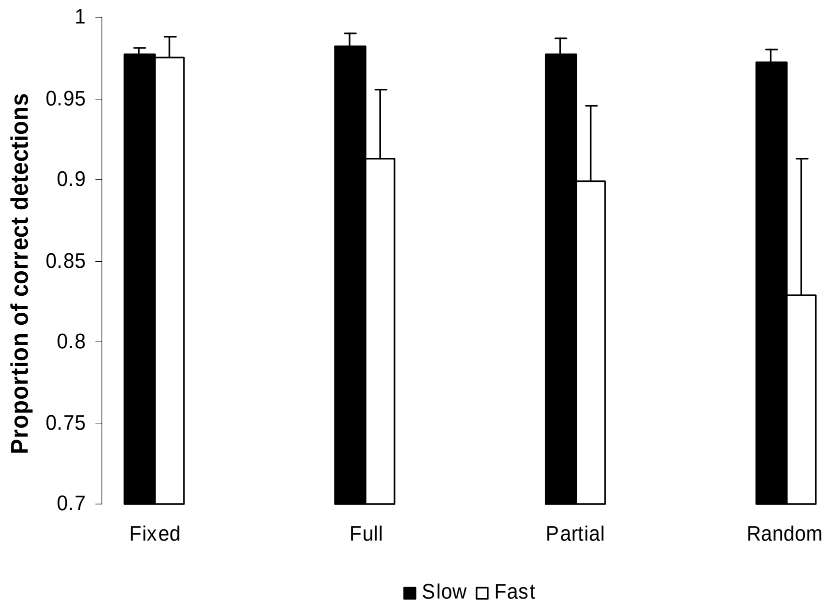
Figure 4. Two-way interactions for the proportion of correct detections in Experiment 2.

Figure 5. Two-way and Three-way interactions for detection time in Experiment 2.

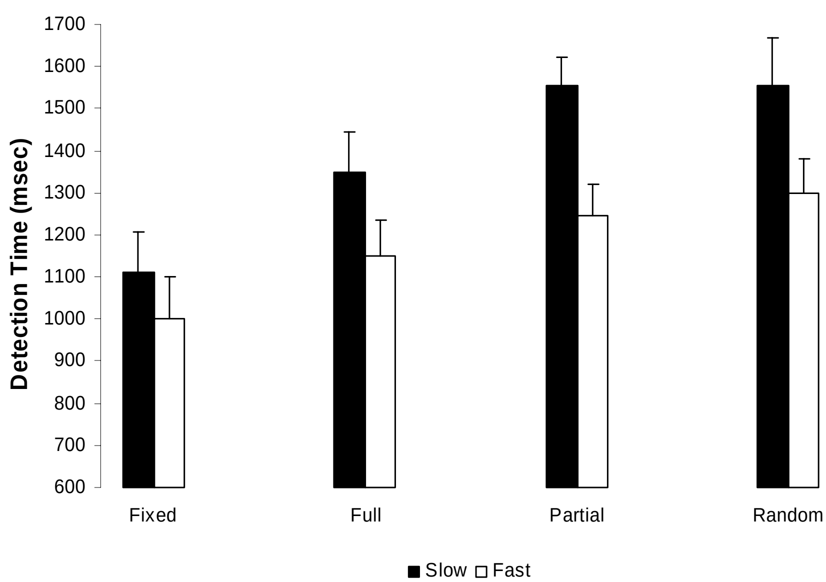

F
D
G
J


Please put your index finger on the 5 button of the keypad.
If you see a target from your memory set, use your index finger to press the number that matches the blip position that contains the target as shown here.
KeyPad
Upper Left -->
<-- Upper Right
Lower Left -->
<-- Lower Right
7
9
1
3
ONLY USE YOUR INDEX FINGER
Press 5 to begin

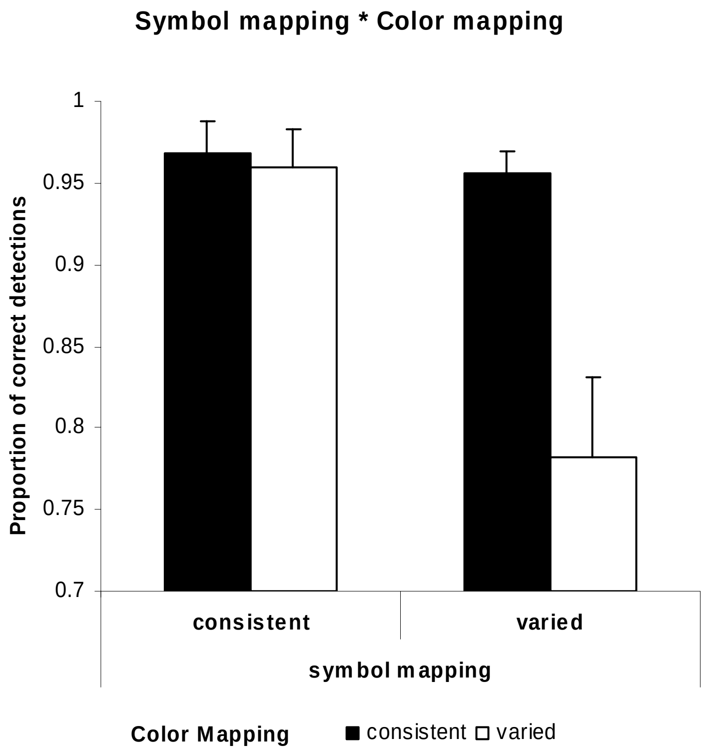
Panel A

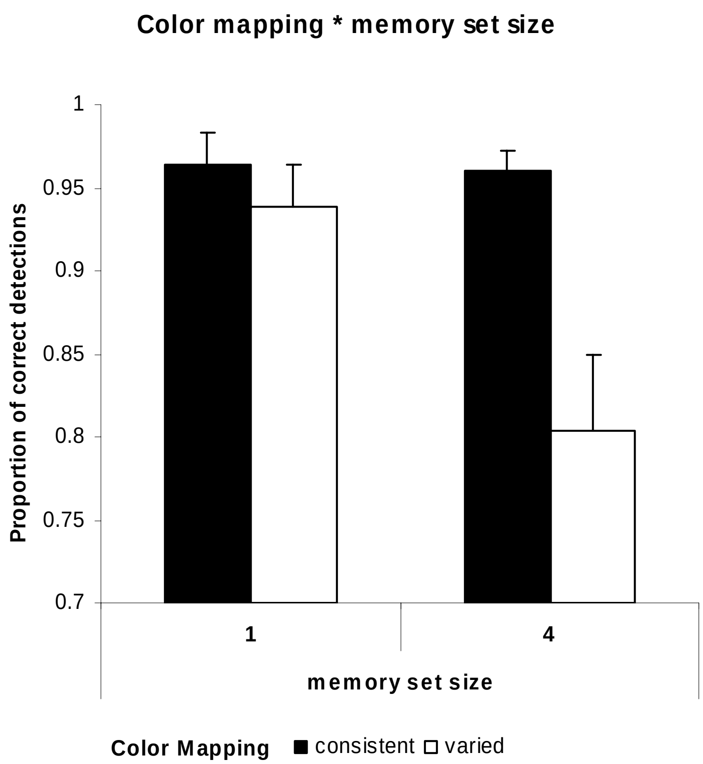


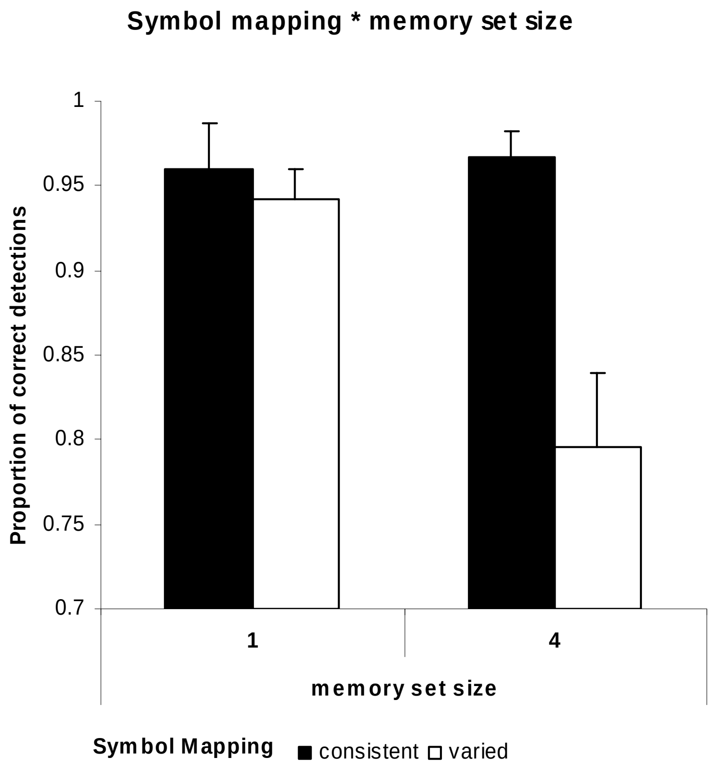
Panel B



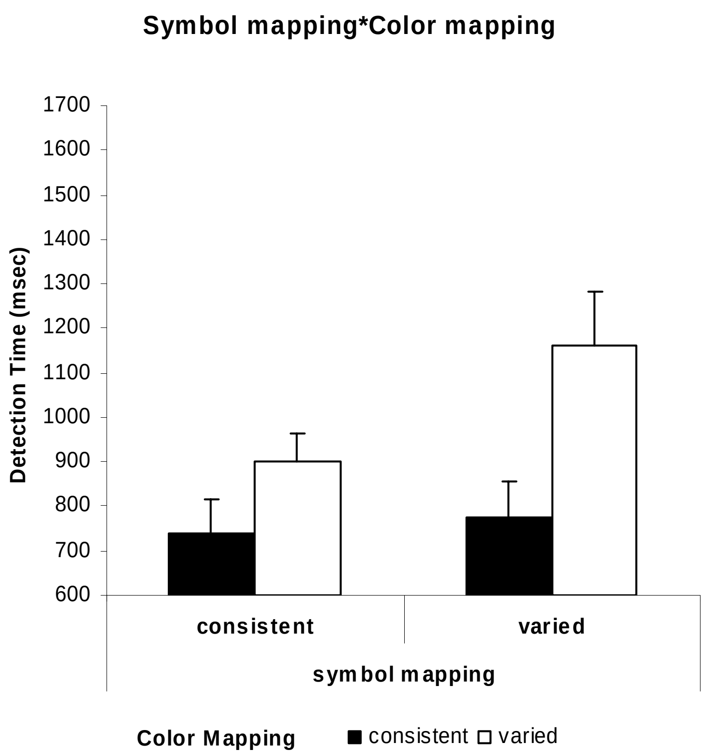
(Figure 4: two pages)

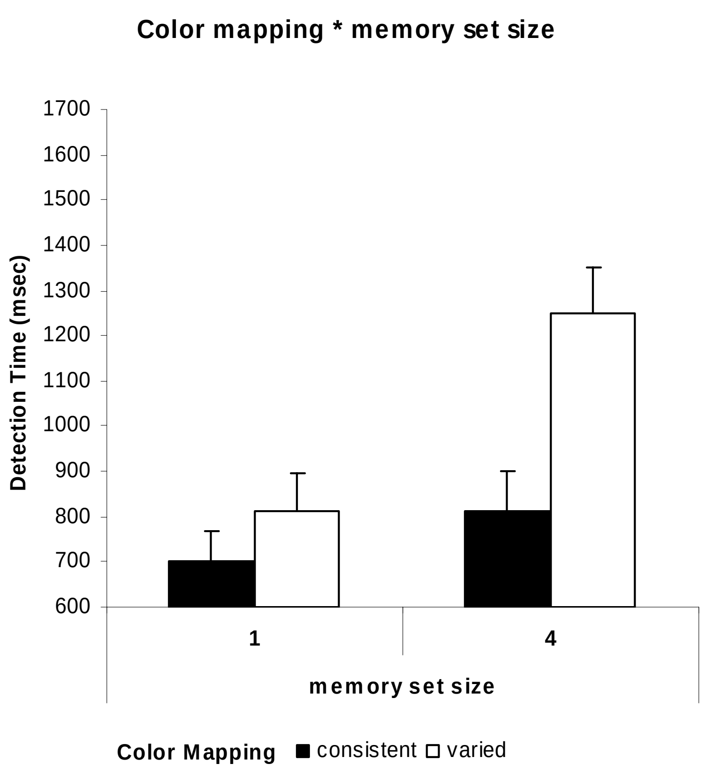


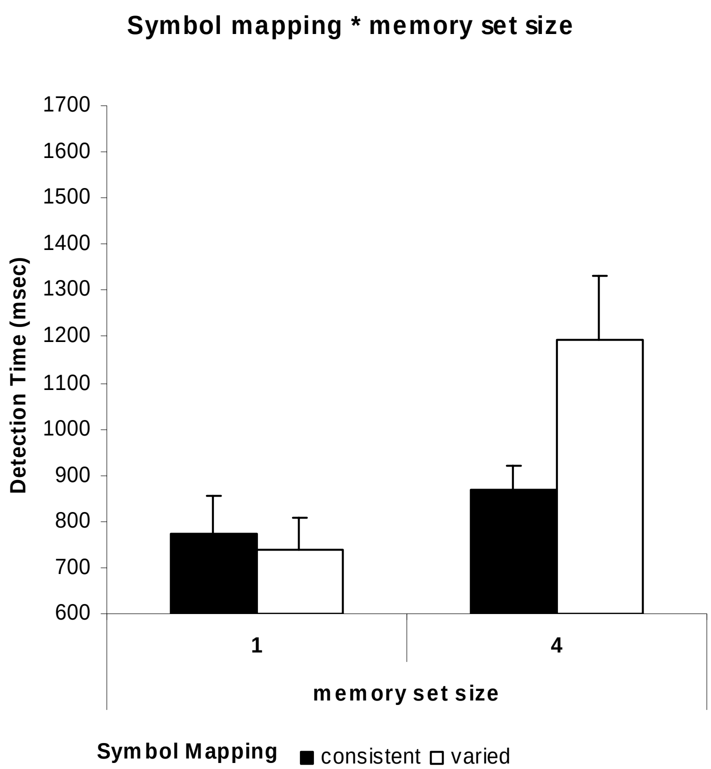


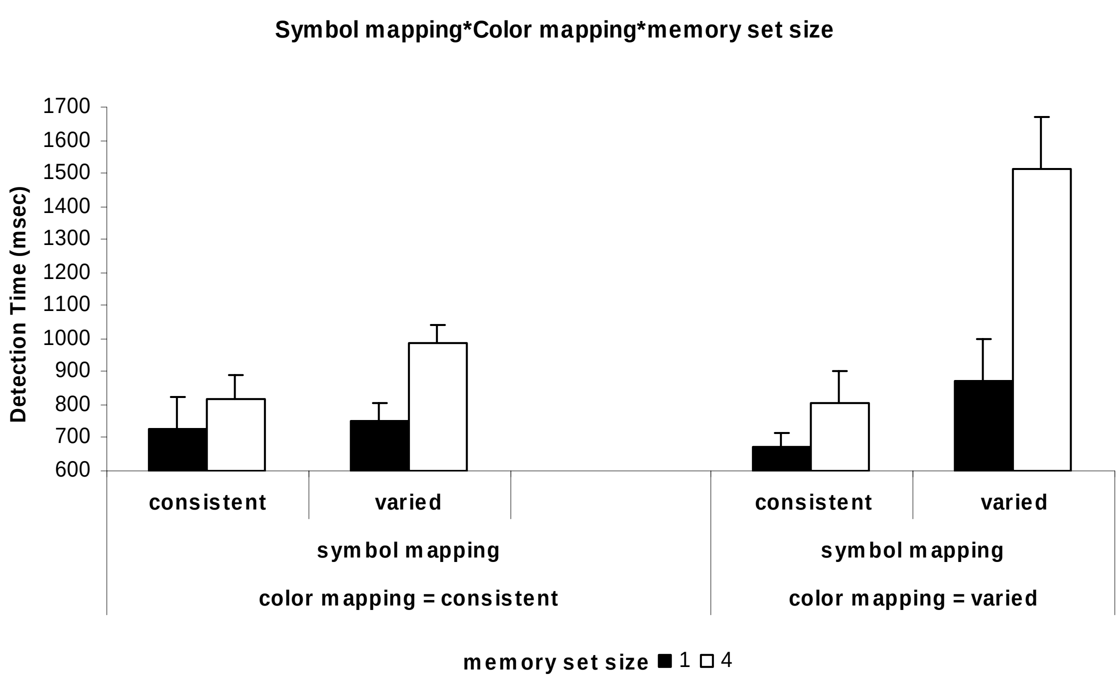

Symbol mapping * memory set size
Proportion of correct detections
1
0.95
0.9
0.85
0.8
0.75
0.7
1
4
memory set size
Symbol Mapping
consistent
varied

(Figure 5: two pages)






Symbol mapping * memory set size
Detection Time (msec)
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1
4
memory set size
Symbol Mapping
consistent
varied


Symbol mapping*Color mapping*memory set size
Detection Time (msec)
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
consistent
varied
symbol mapping
color mapping = consistent
consistent
varied
symbol mapping
color mapping = varied
memory set size
1
4