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## Attentional Limitations and the Visual Pathways

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Attentional Limitations and the Visual Pathways

A dissertation submitted in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy

By

SATOMI MAEDA

M. S., Wright State University, Dayton, 2003

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## ABSTRACT

Satomi Maeda, Ph.D., Department of Psychology, Human Factors and Industrial/Organizational Psychology Program, 2009. Attentional Limitations and the Visual Pathways.

The present study tested the hypothesis that three visual pathways (i.e. parvocellular, magnocellular, and koniocellular pathways) may influence the degree of dual-task interference using dual-task methodology. The magnocellular pathway consists of feature-coding mechanisms that are sensitive to transients and motion, and is thought to process information about the locations and movements of objects. The parvocellular pathway consists of feature-coding mechanisms that are sensitive to red-green and brightness information, while the koniocellular pathway consists of feature-coding mechanisms that are sensitive to blue-yellow chromatic information. Both the parvocellular and the koniocellular pathway are thought to process information useful for identifying objects. The hypothesis predicted that engaging in two search tasks that were mediated by feature-coding mechanisms in two different pathways would result in less dual-task interference in performance than two tasks that were mediated by feature-coding mechanisms in the same pathway. Magnocellular stimuli were defined by brief luminance transients and motion, and parvocellular and koniocellular stimuli were defined by color. The most interference was observed for task pairs that were different in nature and mediated in one pathway. Two tasks mediated by the two different pathways

resulted in a small interference, while two identical task pairs mediated by one pathway resulted in no dual-task interference. No significant negative contingency was observed in any task pair. Dual-task interference consistent with a sampling model (e.g. Bonnel et al., 1992) and an independence model (e.g. Morrone et al., 2002 & 2004) were observed. No task pairs produced dual-task interference consistent with the prediction of a switching model (e.g. Duncan, 1996).

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## INTRODUCTION

On one morning, Zack is driving on a highway maneuvering his vehicle and gazing at the radio display to tune it to NPR. On one afternoon, Mary is searching for a pen and a paper on her desk between piles of books, journal articles and files. On one evening, Tony is scanning through the shelves in the refrigerator to grab a couple of ingredients for his dinner. Our momentary goals and intentions, often more than one, guide our interaction with the environment in those ubiquitous everyday situations. Psychologists consider that the brain mechanisms collectively called “attention” are the agents behind such purposeful interactions with our environment. Much research effort has been poured into understanding the mechanisms of attention. The current study examined the attentional mechanism in visual perception by exploring its capacity and limits.

### *Two research questions*

Accumulating research evidence suggests that visual attention has several chief characteristics. Attention allows us to preferentially process relevant information and filter out irrelevant information on the basis of location, a feature, or object identity (e.g. Huang & Pashler, 2007; Nagy, Young, & Neriani, 2004; Maeda & Nagy, 2008; Palmer, Ames, & Lindsey, 1993; Posner, 1980; Pylyshyn & Storm, 1988; Yantis & Jonides, 1990). Evidence also suggests that, when searching for one target in a visual search task, attention can be selectively directed to monitor multiple locations or multiple feature

mechanisms to guide attention to the target without any cost due to limited-capacity attention (Palmer et al., 1993; Monnier & Nagy 2001). However, simultaneously searching for two targets (i.e. dual task) sometimes results in a dual-task decrement in performance (e.g. Alvarez, Horowitz, Arsenio, DiMase, & Wolfe, 2006). The aim of the present study was to shed more light on this domain of research in visual dual-task situations.

Two questions were addressed in the present study. First, why do some dual-task pairs result in no dual-task interference and others result in dual-task interference? The present study tested the hypothesis that modularity in the visual system may influence the performance limits in dividing attention between two visual search tasks. Specifically, by modularity, I suggest that the three visual pathways that consist of functionally independent feature-coding mechanisms (Livingstone & Hubel, 1988) may influence the degree of interference. This suggestion is based on several previous studies that have examined whether two tasks involve the same or different pathways may influence the degree of dual-task interference (Alvares, et al., 2006; Alvarez & Cavanagh, 2005; Allport, 1971; Bonnel et al., 1992; Duncan, 1993; Duncan & Nimmo-Smith, 1998; Lee, Kochi, & Braun, 1999; Morrone et al., 2002 & 2003; Pastukhov, Fischer, & Braun, 2008; Treisman, 1969; Wing & Allport, 1972; Weinstein & Wickens, 1992).

Second, why are there differences in the degrees of dual-task interference when two tasks interfere with each other? The present study compared three different models of dual-task performance. The three models are a sampling model (e.g. Bonnel et al., 1992), a switching model (e.g. Duncan, 1996), and an independence model (e.g. Morrone, et al., 2002 & 2004). These three models make quantitative behavioral

predictions of dual-task performance. The degrees of dual-task interference observed in previous studies seem to range from none to very large, suggesting independence on one hand and mutual exclusivity on the other hand. The three models applied in dual-task performance were considered to evaluate the data from the present experiments as well as to summarize the findings from the literature. Two questions will be addressed in turn next: Why do some dual-task pairs result in no dual-task interference while others result in dual-task interference? Why are there differences in the degrees of dual-task interference when two tasks interfere with each other?

### *Modularity in the visual system*

Anatomical, physiological and neurophysiological evidence suggests that specialized sets of feature-coding mechanisms are organized into three largely independent visual pathways, i.e. the parvocellular, the magnocellular and the koniocellular pathways in early stages of visual system (i.e. the LGN, V1 and V2). The magnocellular pathway is considered to be specialized in processing features that are useful for judgments about the location and movements of objects. The parvocellular pathway processes features such as form or red-green colors that are useful for recognizing and identifying objects. The koniocellular pathway processes largely variations in blue-yellow colors. The segregation of these pathways begins at the sub-cortical retinal level and continues to the LGN, which further relays the information to the primary visual cortex and to the extrastriate cortex. Most importantly, evidence suggests that those pathways function entirely independent of each other at an early level of visual processing (Livingstone & Hubel, 1988).

The origin of the three pathways is seen in the three types of retinal ganglion cells, i.e., the midget, the parasol and the bistratified ganglion cells (Dacey, 2004). The parasol cells (or M cells) receive inputs from L and M cones through bipolar cells, and are sensitive to achromatic variations. Similarly, cells in the magnocellular layers of the LGN, which receive information from the parasol cells, are not sensitive to color variations, and show fast transient response patterns. The midget cells (or P cells) are found to have the highest density and have one-to-one connections to a bipolar cell, which connects to a single cone photoreceptor (Calkins, Schein, Tsukamoto, & Sterling, 1994). In addition, the midget cells are concerned with signals from long wavelength cones (L cones) and medium wavelength cones (M cones), and are sensitive to long-medium wavelength variations. Cells in the parvocellular layers of the LGN share similar characteristics: they are red-green color opponent, have smaller receptive fields, and show a sustained response pattern. The small bistratified cells are sensitive to signals related to short-wavelength cones (S cones). The small bistratified cells (or K cells) project to the inner plexiform koniocellular layers in between the magnocellular and the parvocellular layers of the LGN.

The segregation of various functions between the three pathways is perpetuated to higher levels of visual processing. For instance, the middle temporal cortex (MT), which is specialized in analyzing movement and stereoscopic depth receives input from the cells in the magnocellular layers of the LGN, while visual area 4 (V4) which processes color receives signals from the parvocellular and the kinocellular layers of the LGN (Zeki, Watson, Lueck, Friston, Kennard, & Frackowiak, 1991; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990). Further, MT primarily projects to the parietal cortex which

is involved in processing spatial information, while V4 projects to temporal cortex which is involved in processing information useful for identification and recognition.

Psychophysical studies (e.g. Livingstone & Hubel, 1988) reveal differences in spatial and temporal sensitivities of the three visual pathways. The temporal sensitivity measured with the color-contrast flicker fusion method, in which red-and-green bars alternate at various temporal frequencies, diminishes sharply as the relative luminance difference of red and green bars decreases. This is because as the luminance difference of the red-green bars decreases, the stimulus is only visible to the color-sensitive parvocellular system, which is insensitive to temporal frequencies higher than 10~15 cycles/sec (Lennie & Dzmura, 1988). On the other hand, the highest temporal variation in luminance visible to the magnocellular system is around 60 cycles/sec. Similarly, perception of speed is degraded when the movement is defined by equiluminous red-green gratings, which are only visible to the parvocellular pathway.

It is important to note that evidence also suggests that substantial lateral connections between the pathways are present especially at higher levels of visual processing (Merigan & Maunsell, 1993; Van Essen, 1995). Our perceptual experiences are generally consistent with such evidence. In our perception, different aspects of visual information such as location, colors, edges, and motions are integrated.

The present study suggests that three visual pathways, at least at an early level of the visual processing stream, may influence dual-task performance. This hypothesis is based on many previous studies that suggested whether two tasks involve the same or different pathways may influence the degree of dual-task interference (e.g. Alvares, et al., 2006; Morrone et al., 2002 & 2004). In dual-task situations, this visual pathway

hypothesis predicts that simultaneous attentive processing of feature information is most efficient when two tasks require processing features that are coded by two different pathways rather than in the same pathway. Several previous studies have examined whether independent pools of attention are reserved for processing different types of visual information (e.g. Alvarez et al., 2005; Duncan & Nimmo-Smith, 1996; Morrone et al., 2002 & 2004). However results vary. Before reviewing the literature in detail, discussion of three broad theories of attention is warranted. The three theories are the single resource theory, the multiple resource theory, and the object-based integrated competition theory.

### *Theories of attention*

The resource theory of attention (Kahneman, 1973) states that any mental activities require attention (or effort), and the total amount of attentional resources is limited. Different mental activities require different amounts of resources; more difficult tasks require more resources and easier tasks require less resources. Attention also may be divided between multiple tasks. However when the supply of attention does not meet task demand, performance will begin to break down. Single-pool resource models (e.g. Kahneman, 1973; Moray, 1967) suggest that resources of a single pool are shared for all types of mental processing. For instance, the single-pool resource theory states that cognitive and perceptual processing required to discriminate the frequencies of tones and to search a letter L among Ts in a display draw attentional resources from one generalized pool of attention, although those two tasks are very different in nature. The single-pool resource theory can be applied to three visual pathways to explain dual-task interference as follows. A dual-task decrement in performance will occur when the sum

of the resource demands of two visual tasks exceeds the available resources, regardless of whether the two tasks are mediated by the same visual pathway or two different pathways.

The object-based theory of visual attention postulates the locus of attentional limitation is in processing two objects (targets) simultaneously. Duncan (1980; 1983; 1985) postulated that early stages of perceptual processing of stimuli are not quite at a conscious level where one can make a target or non-target judgment about them. In order to make the recognition judgment about those early percepts, a limited-capacity system has to take a relevant stimulus to the postattentive stage serially. In a time-constrained dual-task experiment, observers are asked to process two targets within a brief period of time, which results in a competition. Since the time that the information is available is limited, with such a hypothesized capacity limit, one strategy observers may adopt is to process one task first on each trial. This trial-to-trial switching strategy results in negative contingency between performance on the two tasks; observers perform well on task 1 at the cost of ignoring task 2 (Sperling & Melchner, 1978).

A recent version of this theory (Duncan, 1998 & 2006) further elaborates that the two-target competition is integrated between components of the distributed states of the neural network, i.e. across different feature-coding modules, thus when one object is selected for attention or wins competition, responses to this object are supported throughout the feature-coding network. This proposition has been supported by a number of studies showing that reporting two features of two objects results in performance decrement while reporting two features of one object does not (e.g. Duncan, 1993;

O'Craven, Downing, & Kanwisher, 1999; Rodríguez, Valdés-Sosa, & Freiwald, 2002; Vandenberghe, Duncan, Dupont, Ward, Poline, & Bormans, 1997).

Note that the single-pool resource theory and the object-based theory both predict that the degrees of dual-task decrement in performance do not vary depending on whether two tasks are mediated by the same or two different pathways. However, the proposed attentional mechanisms are distinctly different. The single resource theory suggests that attentional resources can be shared between the two tasks, while the object-based theory suggests an all-or-none mechanism of processing one object at a time.

Lastly, the multiple resource theory of attention postulates that there may be independent reservoirs of attentional resources for different types of modalities, processing codes and stages of processing (Wickens, 1984 & 2002; Navon & Gopher, 1979; Just, Carpenter, & Miyake, 2003). This idea of multiple resources extends the resource theory of attention (Kahneman, 1973), and originated from accumulation of empirical studies that suggested that different combinations of tasks lead to different degrees of dual-task decrement, or sometimes no decrement. For instance, cross-modality tasks (e.g. visual & auditory) often interfere less than within-modality tasks (e.g. vision & vision or auditory & auditory; Alais, Morrone, & Burr, 2006; Alvarez et al., 2005; Duncan, Martens & Ward, 1997; Treisman & Davies, 1973, however see in Bonnel & Hafter, 1998; Lindsay et al., 1968). Within the visual perceptual processing domain, some research suggests further divisions of visual attentional resources on the basis of feature-coding mechanisms (Alvarez et al., 2005; Alvarez & Cavanagh, 2005; Allport, 1971; Bonnel, et al. 1992; Duncan & Nimmo-Smith, 1996; Morrone et al., 2002 & 2004; Treisman, 1969; Wing & Allport, 1972; Weinstein & Wickens, 1992). These

studies put forward the possibility that different types of feature-coding mechanisms in the visual system may be equipped with independent pools of attentional resources.

These three broad theories of attention provide general descriptions of attentional mechanism. In the domain of visual dual-task studies, researchers have used the three models of dual-task performance (i.e. a sampling, a switching, and an independence models) to make quantitative predictions about the degree of interference in dual-task situations (e.g. Miller & Bonnel, 1994). These three models contrast three ways to characterize dual-task performance. These three models predictions in the Attention Operating Characteristics will be described in detail below.

#### *Attention Operating Characteristics and the three model predictions*

One useful tool to visually compare the degree of dual-task interference for different tasks is to plot single-task and dual-task performance in the form of an Attention Operating Characteristic (AOC) (Kinchla, 1992; Sperling & Melchner, 1978) or a Performance Operating Characteristic (POC) (Norman & Bobrow, 1975). Figure 1 is an example of the AOC. Dual-task performance is plotted in open-squares, and the single-task performance is plotted in open-circles. Perfect dual-task performance falls at the intersection of the two dotted-lines emanating from the means of the two single-task performance. It indicates no dual-task decrement from simultaneously performing the two tasks. Dual-task performance that falls closer to the origin of the graph indicates more dual-task interference.

#### *Sampling model.*

Bonnel et al. (1992)'s sampling model within the framework of signal detection theory suggests that the limit in dividing attention may be considered as limits in making

decisions based on noisy neural signals (Luce, 1977; Bonnel & Miller, 1994; Bonnel, Possamaï, & Schmitt, 1987; Palmer et al., 1993). The sampling model was shown to account for performance trade-offs in two concurrent line discrimination tasks (Bonnel & Miller, 1994; Bonnel et al., 1987; Miller & Bonnel, 1994) and concurrent luminance identification and tone identification tasks (Bonnel et al., 1992; Bonnel & Hafter, 1998). In the present study, the sampling model was applied to two simultaneous visual search tasks.

The model distinguishes two stages of processing. In the first stage, perceptual processes collect samples of sensory representation to form an internal psychological representation of the stimuli. In the second stage, observers compare the obtained perceptual representations and make a decision about the presence of a target based on a decision rule. Sensory representations are considered imperfect and noisy, thus increasing the sample size on which the decisions were made becomes important. In other words, the variance of the perceptual representation of the stimulus is inversely proportional to the number of samples allocated to it.

In a typical psychophysical experiment in which stimuli are presented briefly, there is a limit to the number of samples for each stimulus that can be collected per unit of time. The quality of the perceptual representation of stimulus is related to the number of perceptual samples (i.e. data) that are allotted to the stimuli. This means when samples are divided between two tasks, fewer samples are collected per task resulting in degraded perception compared to when all the samples are dedicated to one task. This model posits that people *share* attention between two tasks, and the amount of attention paid to a task is proportional to the number of samples to be collected. Thus more attention paid to

a type of signals (i.e. features), more perceptual samples from sensory signals activating the attended group of neural mechanisms are taken (Luce, 1977).

The sampling model offers quantitative predictions of the effect of dual-task interference in performance (Bonnell & Miller, 1994; Bonnell et al., 1987). Assume that observers can voluntarily take  $p$   $N$  samples from one task and  $(1 - p)$   $N$  samples from the other task. For instance, when observers were instructed to split attention equally in two tasks, sensitivity ( $d'$ ) is predicted as following:

$$d' (p) = d' (1) \times p^{1/2}$$

This is equivalent to:

$$d'^2(p) = d'^2 (1) \times p$$

Performance on each of the two tasks is determined by the number of samples allocated to each of the two tasks and the sum of the samples is fixed. Assuming that the variances of the two distributions are the same for the two tasks, and attention is shared between the two,

$$d'^2_{(task 1)} + d'^2_{(task 2)} = constant.$$

Thus the sampling model predicts smooth performance trade-offs between two tasks when attention is divided between the two tasks as shown by the dashed curve (Bonnell & Miller, 1994) in the AOC plot in Figure 2. The two axes of Figure 2 are in accuracy units. When using  $N$  alternative forced-choice procedures, the table in Hacker and Ratcliff (1979) can be used to convert the quantitative predictions of the sampling model into accuracy measures. The curve shown in this figure represents how the performance on two tasks varies as a function of attention allocation policy instructions, such as “Give 70% of your attention (i.e. samples) to task 1 and 30 % of your attention (i.e. samples) to

task 2.” Also shown are predictions of an independence model and a switching model, which are discussed in turn next.

*Switching model.*

Another model of dual-task performance suggests that observers *switch* tasks. In a typical dual-task experiment in which stimuli appear very briefly, this model predicts dual-task interference because of the time constraint. One version of this switching model predicts that observers devote all attention to one task on each trial and perform the other task at a chance level on each trial (Bonnell & Prinzmetal, 1998; Miller & Bonnell, 1994; Sperling & Melchner, 1978). Such a switching mechanism predicts a linear performance trade-off. With this switching model, dual-task performance depends on three variables: baseline single-task performance at full attention, chance level performance, and attention priority instruction (Sperling & Melchner, 1978). Denote the probability of accurately finding a target with full attention in task 1 to be  $p_1$ , the probability of accurately finding a target with full attention in task 2 to be  $p_2$ , and the probability of finding a target by chance to be  $P_{\text{chance}}$ . When an observer is instructed to pay 75 % of attention to Task 1 and 25% of attention to Task 2, I assume that she will engage in Task 1 with full attention for 75% of trials while engaging in Task 2 with full attention for the remainder of trials. Based on this assumption, predicted performance on Task 1 is the sum of the probability of performing the full performance single-task baseline and the probability of performing at a chance level weighted by proportion of trials:

$$\text{Task 1 Performance} = .75 * p_1 + .25*(P_{\text{chance}})$$

Likewise, predicted performance on Task 2 is calculated by the following formula:

$$\text{Task 2 Performance} = .25 * p_2 + .75 * (P_{\text{chance}})$$

Note that the formula above generates different values depending on the baseline single-task performance (i.e.  $P_1$  or  $P_2$ ). As described, such a trial-to-trial switching strategy will yield strong negative contingency between the two searches and a linear trade-off in accuracy between the two tasks as indicated by the solid line in Figure 2.

*Independence model.*

Lastly, an independence model suggests no interference. There may be various reasons why two tasks result in little dual-task decrement. It may be because two tasks are easy or because two tasks demand attention from two independent pools of attentional resources reserved for different kinds of tasks. Previous studies have shown that two demanding tasks resulted in no interference (e.g. Alvarez et al., 2005; Alvarez & Cavanagh, 2005; Morrone et al., 2002 & 2004). Prediction of the independence model is indicated by the filled circle in Figure 2.

Each of the three models of dual-task performance is based on qualitatively different attentional processes that potentially underlie dual-task performance. In addition, the three models make quantitatively different prediction of the degrees of interference. The switching model predicts a strong negative contingency between performance on the two tasks and a nearly linear performance trade-off between the two tasks. The sampling model predicts that the performance on one task does not depend on the performance on the other task, because perceptual samples are shared between the two tasks on each trial. The sampling model predicts no negative contingency and smaller degree of dual-task interference. Lastly the independence model predicts no dual-task interference.

The three model predictions were compared to the observed dual-task performance in the present study to get an insight of the effect of the three visual pathways on dual-task performance. The proposed hypothesis suggests that the three visual pathways may influence the degree of dual-task interference between two tasks. This hypothesis predicts that two tasks that are mediated by one visual pathway lead to more dual-task interference than two tasks that are mediated by two different visual pathways. The idea of this hypothesis is consistent with the multiple resource idea (e.g. Navon & Gopher, 1979) because different pathways (i.e. modules) may be equipped with independent attentional resource pools (Alvarez et al., 2005; Morrone et al., 2002 & 2004). Comparing the results from the present study with the predictions of the three models, one can make valuable inferences about the nature of influence of the visual pathways on dual-task performance.

In summary, these three specific models of dual-task performance offer three distinct predictions for three different mechanisms of dividing attention between two tasks. The following section reviews empirical studies that examined attentional limitations in dual-task situations. Previous studies have explored various dual-task combinations with different response requirements (e.g. identification, detection, or localization), tasks (e.g. visual search, tracking, or discrimination) and stimuli (e.g. simple or complex stimuli). Some task pairs showed little or no dual-task decrement consistent with the independence model. Some showed decrements consistent with the sampling model. Others showed the decrements consistent with the switching model with significant negative contingency. Overall, evidence for all the three models were found in the literature. This review section is organized by the design of experiments in

order to compare their results. The observed dual-task decrement in each study was compared to the prediction of the three models whenever relevant data was available.

*Two identical or similar task pairs*

Studies that examined performance limits when observers were engaged in two identical tasks suggest that degrees of dual-task decrement may depend both on the complexity in the stimulus used and in the nature of task. Bonnel and her colleagues (Bonnel & Miller, 1994; Miller & Bonnel, 1994; Bonnel et al., 1987) showed that pairing two relatively simple 2 alternative-forced-choice (AFC) discrimination tasks is subjected to limited-capacity in divided attention. For example, observers in Miller and Bonnel (1994) (also in Bonnel & Miller, 1994; Bonnel et al., 1987) were briefly presented with two pairs of vertical lines on each side of a fixation point simultaneously and asked to judge whether the two lines in each pair were the same or different length. The performance in the single task condition in which observers devoted 100% of attention to one side and zero for the other side was compared to dual-task conditions with various priority instructions. Results plotted in the AOC space gave a smooth performance curve consistent with the prediction of the Sampling model. In addition, no negative contingency was observed, suggesting that observers engaged in the two tasks simultaneously rather than serially.

Simultaneously carrying out two simple visual search tasks has been found to result in some dual-task interference. Observers in Duncan (1985) searched for two 45-degree tilted line targets among vertical line distractors. The search display consisted of four stimuli arranged in the form of a plus. Each of the horizontal and the vertical stimulus pairs potentially included one target, thus in a given trial the maximum of two

targets could be simultaneously present (although targets were not always identical when there were two). Results showed that sensitivity in the simultaneous condition was poorer than in the successive condition in which the participants searched one pair of stimuli at a time successively. The observed dual-task decrement in accuracy was similar to the prediction of the sampling model, and no negative contingency was reported.

While these studies resulted in moderate degrees of dual-task interference consistent with the sampling model prediction, Bonnel et al. (1992) suggested that the extent of the information processing required in two tasks may determine whether the two identical tasks results in any interference. In their studies, the authors examined whether the degree of dual task interference differed for two simultaneous detection tasks and two simultaneous identification tasks. In Experiment 1, observers were asked to detect an incremental change in luminance of two LED diodes placed in the right and the left visual fields. In Experiment 2, the task was changed into an identification task, in which observers had to indicate the direction of luminance change (increment or decrement) in each diode. No dual-task interference was observed in Experiment 1 (consistent with the independence model) while the change in task demand in Experiment 2 led to interference in the dual-task condition consistent with the sampling model. The authors suggested that different characteristics of two different “attention modes”, which correspond to the magnocellular and the parvocellular pathways, might be responsible for this difference. They further suggested that the magnocellular pathway mediated detection of the brief transient by globally allocating attention in the visual field, while the parvocellular pathway mediated identification of the direction of luminance changes by focusing attention on each stimulus. This explanation posits that two attention

focusing parvocellular tasks led to more dual-task interference. These results were later replicated in Bonnel and Hafter (1998).

While most simultaneous discrimination tasks seem to result in moderate degrees of dual-task interference consistent with the sampling model, simultaneous visual search tasks using complex stimuli such as letters or numerals seem to result in more dual-task decrement consistent with the switching model. That is, demanding task pairs result in more dual-task decrement than the sampling model predicts, accompanied by across-trials negative contingency. For instance, Sperling and Melchner (1978) showed that two visual searches for a numeral among letters in two concentric stimulus arrays interfered with each other. Notably, task difficulty was also varied in this study by adding random noise in one condition, and by reversing the distractor–target relationship. Results plotted in an AOC space showed varying degrees of dual-task interference depending on the task difficulty. In particular, the largest dual-task decrement was observed when the roles of the target and the distractors were reversed in the inner array. In this reverse condition, observers searched for a letter among numerals in the inner array while they simultaneously searched for a numeral among letters in the outer array.

Using a slightly different methodology but with a task requirement and stimulus similar to Sperling and Melchner, Duncan (1980) showed that simultaneously searching for digits among letters in the horizontal and vertical arrays resulted in a large dual-task decrement. In this study, a maximum of two targets, one in each limb could appear in a trial, while in some trials only one target appeared. Notably, dual-task interference while simultaneously identifying two digits was found only when observers made two separate responses for the two targets. When observers made one combined response indicating

whether there was zero, one or two targets, negligible degrees of dual-task decrement were observed. This difference in dual-task decrement in performance depending on the response demand was later replicated in Duncan (1985). This suggests that having multiple targets by itself did not necessarily lead to a dual-task decrement, but searching for two targets and responding to the two targets separately lead to a decrement.

In summary, studies that paired two simple discrimination tasks provide support for the sampling model or the independence model, while studies that paired two complex visual search / identification tasks provide support for the switching model sometimes with negative contingency. Note that in all the studies above, participants engaged in two identical tasks that required fine feature discrimination that is mediated by the parvocellular pathway. It follows that these results do not necessarily rule out the idea that different pathways are equipped with independent pools of resources.

Information useful for making an identification judgment of orientations, shapes or letters is coded by feature-coding mechanisms exclusive to the parvocellular pathway. If each of the magnocellular, koniocellular and parvocellular visual pathways are associated with an independent pool of attentional resources, two attention-demanding tasks which draw resources from one pool (i.e. one pathway) are more likely to suffer from a greater dual-task performance decrement than two tasks which draw resources from two different pools. In other words, the observed dual-task decrements in the studies reviewed so far may be due to depletion of the attentional resources exclusively reserved for the parvocellular pathway. The next set of studies addresses the prediction of the multiple resource idea by comparing the degree of dual-task decrement when two dissimilar tasks are paired.

### *Two different tasks involving different feature mechanisms*

The idea of multiple resources of attention originated from cross-modality dual-task studies (e.g. Treisman & Davies, 1973; Wickens, 1980). Cross-modality dual-task studies ask whether two tasks in two different modalities are subjected to less dual-task interference, directly addressing the possibility that different modalities are equipped with different pools of attentional resources. Many studies have shown that simultaneous within-modality tasks result in more interference than the simultaneous cross-modality tasks supporting the notion of independent resources for different modalities (Alvarez et al., 2005; Duncan, Martens & Ward, 1997).

Interestingly, however, several studies have also shown that cross-modality tasks can sometimes interfere with each other though the degree of the interference may be smaller than for simultaneous within-modality tasks (Alais, Morrone & Burr, 2006; Bonnel & Hafter, 1998; Linsay, Taylor & Forbes, 1967; Tellinghuisen & Nowak, 2003). For example, Linsay et al. (1967) and Bonnel and Hafter (1998) showed that 2AFC tone discrimination task paired with a 2AFC visual discrimination resulted in a dual-task decrement consistent with the predictions of the sampling model with no negative contingency. These studies are suggestive that certain operations involving one visual task and one auditory task may interfere with each other as if they were drawing perceptual samples from one pool of resources. For pairs of visual tasks, the hypothesis that independent attentional resources are allocated to different modules (i.e. feature-coding mechanisms) was previously noted in the literature (Allport, 1971; Treisman, 1969; Wing & Allport, 1972), and continues to be evaluated to this day (e.g. Pastukhov, Fischer & Braun, 2008).

The initial investigation to test the multiple resource idea within visual attention was by Allport and his colleagues (Allport, 1971; Wings & Allport; 1972). In these studies, observers were presented with a set of three stimuli that consisted of different feature dimensions, and were instructed to report as many values as they could in one feature dimension or in two feature dimensions. In both studies, two discriminations made on one dimension (i.e. form or color) resulted in dual-task interference while no interference was found when observers made discriminations about two different dimensions. Using a visual search task, Wolfe, Yu, Stewart, Shorter, Friedman-Hill, and Cave (1990) similarly showed that “within” feature dimension conjunction searches (color & color, orientation & orientation) were very inefficient compared to “across” feature dimension conjunction searches (color & orientation).

More recently, Morrone et al. (2002 & 2004) asked observers to search for a target among distractors in the central visual field and concurrently make a discrimination judgment about the contrast of two peripheral gratings. Results showed the search task and the contrast discrimination task interfered only when the central visual search and the peripheral contrast discrimination were both based on the same feature, either luminance or color. Based on these results, the authors suggested that “attentional resources” for processing chromatic and luminance features draw on two independent resource pools.

Likewise, Alvarez, et al. (2005) found severe dual-task interference when participants engaged in two conjunction searches that involved achromatic form discriminations or two tracking tasks among stimuli that were randomly placed (or moving) in a display. No negative contingency was reported. However the degree of dual task interference was similar to the prediction of the switching model, and the

authors noted that the two tasks were “mutually exclusive.” Notably, the authors also showed that the dual-task decrement nearly disappeared when observers simultaneously engaged in visual search and tracking. Severe interference was found when observers engaged in two tracking tasks on one side of the visual field, although one visual tracking task in the left and the other in the right visual field did not show any dual-task interference (Alvarez & Cavanagh, 2005). These studies overall found a large dual-task decrement when two tasks involved the same set of feature-coding mechanisms in the parvocellular or the magnocellular pathway and less dual-task decrement when two tasks involved two different sets of feature-coding mechanisms consistent with the predictions of the independence model.

Other studies do not support the independence model within the visual modality. Duncan (1993) paired two discrimination tasks that were mainly mediated by two posited independent parallel visual pathways, the “where” pathway (i.e. magnocellular pathway) and the “what” pathway (i.e. parvocellular pathway). Two hypotheses were considered. The first hypothesis postulated that the two pathways function independent of each other and draw on different resource pools. Accordingly, this hypothesis predicted little dual-task interference when one of the two tasks is mediated by one pathway and the other is mediated by the other pathway. The second hypothesis postulated that different features processed by the two pathways are coordinated when a target (i.e. object) is selected for attention, and only one target can be selected at one time. It follows that all features that the selected target possesses will be processed without interference. Based on these assumptions, the object-based hypothesis predicted dual-task interference to occur whenever two judgments are made about two different objects regardless of types of

feature processing involved. The accuracies were higher when two discrimination judgments involved one object rather than two different objects. The results supported the object-based hypothesis.

Subsequently, Duncan and Nimmo-Smith (1996) paired two discrimination tasks that were mediated by feature-coding mechanisms that process surface and boundary properties of objects in dual-task interference paradigm. Surface properties are a set of features that fill in a region (e.g. color, texture and brightness) while the boundary properties indicate divisions between regions (e.g. shape, size, orientation or object location). Distinctions between these two feature-coding systems have a physiological basis; differences were noted between the interblob (boundary) and blob (surface) regions in the striate cortex which parallel the functional differences in the two systems (Livingston & Hubel, 1988). Performance in “two-systems” conditions, in which one surface and one boundary feature discrimination were made, was compared to the performance in “one-system” conditions in which two surface or two boundary judgments were made. Results showed that the dual-task decrement in performance from two discrimination judgments about two surface or two boundary features were similar to the decrements when making discrimination judgments about one surface and one boundary feature, with the exception of color. Color discrimination performance was unaffected by a concurrent boundary discrimination, while it was affected by a concurrent color or other surface-feature (luminance and brightness) discrimination. Interestingly, however, the observed degree of dual-task decrement in performance was similar to the sampling model, and no negative contingency was reported. This study

also indicated that the color-coding system may work differently from form, luminance or motion systems.

Lee et al. (1999) examined whether different attentional resources are allocated for processing of different features, using letter, color and motion stimuli. Observers were asked to report whether the cluster of central stimuli were all the same or different, while identifying a single peripheral target. All dual-task conditions yielded linear performance trade-offs consistent with the switching model. In addition, two visual tasks based on the same feature resulted in a similar degree of dual-task interference compared to two tasks based on different features. The negative contingency calculated for individual task pairs failed to reach significance, however the pooled data showed that the performance on one task was significantly better when observers responded incorrectly on the other task. These results support the idea that processing different feature information draws attentional resources from a common pool of resources, rather than from independent specialized pools of resources. Some evidence of negative contingency provided some evidence for the all-or-none switching mechanisms predicted by the switching model.

A recent study by Pastukhov, Fischer, and Braun (2008) similarly supported the idea that attentional resources are not differentiated for different features. In Pastukhov et al., the central task was to make 2AFC judgements about the predominant orientation of rotation (clockwise or counter-clockwise) of dumbbell stimuli. Different tasks that varied in feature dimension and complexity were paired with the central task. Their analysis of the performance resource function suggested that the central task was affected

by the different peripheral tasks to a similar degree. No negative contingency was observed even for the tasks that interfered with each other the most.

In summary, the literature suggests that two tasks that involve two different modalities seem to result in little dual-task interference, while two visual tasks often result in dual-task interference. When two tasks require dividing attention between different types of features, some studies found no or a small decrement, while others showed similar degrees of dual-task decrements irrespective of the features involved. Among studies that showed relatively larger degrees of dual-task decrement, some studies found negative contingency between the two tasks while others did not. Overall, evidence from the literature is not straight forward with regard to whether different pools of attentional resources are reserved for different feature-coding mechanisms. It appears that not only the types of feature information the two tasks share, but the complexity of tasks and the decisions made may influence the degree of dual-task interference.

#### *The present study*

The present research used pairs of visual search tasks, in which observers searched for two targets, one in the inner array of distractors and the other in the outer array of distractors. In order to examine the potential effect of modularity on the degree of dual-task interference when dividing attention between two search tasks, it was imperative that each task be designed to isolate as well as possible a set of neural mechanisms in question. In other words, when making an inference about the influence of the modularity on dual-task performance, stimuli should be designed so that the effective signals for executing one task are only available from one set of feature-coding mechanisms, and the same set of feature-coding mechanisms are ineffective for signaling

types of information that the other task is based on. Colors along the cardinal directions of color space (Krauskopf, Williams, & Heeley, 1982) were used to define targets that stimulate the parvocellular and koniocellular pathways, while brief transients and motion were used for targets that stimulate the feature-coding mechanisms in the magnocellular pathway. The task and the target stimuli were designed to be as simple as possible to place a minimum demand on higher level visual processing. A critical comparison was made between the “within-pathway” conditions, in which two searches were based on signals from the feature-coding mechanisms in one pathway, and the “between-pathways” conditions, in which two searches relied on signals from two anatomically and functionally independent sets of feature-coding mechanisms in different pathways.

The two different within-pathway conditions and the between pathway condition were designed to examine the influence of the visual pathways and the potential influence of decision processes involved in simultaneous search tasks. In the “within-identical” task pairs, observers searched for two identical targets signaled by the same feature-coding mechanisms in one pathway. In the “within-different” task pairs, observers searched for two different targets signaled by feature-coding mechanisms within one pathway or they searched for two identical targets among arrays of distractors of different color. In the “between” task pairs, observers searched for two different targets signaled by two different feature-coding mechanisms in two different pathways. Observers made two different kinds of decisions based on two different criteria in the within-different and the between task pairs, while observers made two identical decisions using the same criteria in the within-identical task pairs.

The attentional priority instruction was fixed at equal attentional priority, hence observers were asked to perform both tasks as well as possible. Dual-task interference was computed by taking the difference in accuracies between the single-task performance

$$\text{Dual-task decrement} = \text{Single-task accuracy} - \text{Dual-task accuracy}$$

and the dual-task performance for each task pair as follows:

The predictions of three models that fall on the 45-degree diagonal line emanating from the origin of the AOC plot in the Figure 2 were converted into accuracy differences using the predicted dual-task performance from each model and 75% correct single-task baseline performance. A difference of zero indicates no dual-task decrement in performance, and the positive differences indicate various degrees of dual-task interference. Degrees of dual-task interference and phi coefficients predicted by the three models for the equal attentional priority condition are shown in Figure 3. These two types of dependent measures were used to distinguish between the predictions of the sampling model and the switching model. The visual pathway hypothesis predicts no dual-task interference in the “between-pathways” conditions and larger dual-task interference in the “within-pathway” conditions. This hypothesis predicts that the observed dual-task decrement in accuracy in the “between-pathway” conditions will be consistent with the prediction of the independence model as in the middle graph in Figure 3.

No a-priori prediction was made by the independence model in terms of whether the sampling model or the switching model would describe the performance in the within-identical and the within-different group. The two within-pathway conditions

differed in task characteristics in terms of decisions and criteria, thus two different attentional processes may explain the dual-task performance. The visual pathway hypothesis would be rejected if similar degrees of dual-task decrement are observed across the within-pathway and the between-pathways conditions as predicted by the sampling model or the switching model. Results consistent with the sampling model in the left graph as in Figure 3 would suggest that the visual pathways do not influence the limits in dividing attention, and the process underlying dividing attention between two simultaneous visual search tasks is sampling of perceptual information. Results consistent with the switching model as in the right graph in the figure would suggest that the visual pathways did not influence the limits in dividing attention, and the underlying attentional mechanism is switching.

## METHOD

### *Overview of the Study*

The present study was designed to investigate the degree of dual-task interference when attention was divided between two visual search tasks. The targets for the two search tasks were either both coded by the feature-coding mechanisms in one visual pathway or by the feature-coding mechanisms in two different pathways. A brief transient stimulus and a motion stimulus were used to isolate the magnocellular pathway. The transient and motion stimuli should be invisible to the parvocellular and the koniocellular pathways. Color targets that were signaled by the L and the Achromatic color mechanisms were used to isolate the parvocellular pathway, while a color target that was signaled by the S color mechanism was used to isolate the koniocellular pathway. These color targets were chosen from the cone excitation diagram (MacLeod & Boynton, 1979) which defines colors as a function of excitation levels of the three types of cones (i.e. S, M and L). The magnocellular and the koniocellular pathways should be insensitive to signals in the L cardinal color mechanism. Similarly, the magnocellular and the parvocellular pathways should be insensitive to signals in the S cardinal color mechanism. It is possible that both the parvocellular and the magnocellular pathway may contribute to processing achromatic information (Kaiser & Boynton, 1996).

To best isolate the three pathways, targets that yielded approximately 75% correct were estimated for each observer and for each condition in the preliminary work.

Searching for a target at threshold ensures that signals from only one pathway indicate the location of the target. Various targets at threshold were combined to create visual search task pairs that are processed within one visual pathway or between two different visual pathways.

The hypothesis was that two tasks that depend on information coded by feature-coding mechanisms in one visual pathway would yield more dual-task interference than two tasks that depend on information coded by feature-coding mechanisms in two different visual pathways. The nature of the distractor-target difference, i.e. feature differences, was manipulated in the between- and the within-pathway conditions. The methodology used to test the hypothesis for transient and color experiments was similar to the methodology used for the motion task pair, although the motion experiment was done with a different display in a different laboratory. In color and transient experiments, observers searched for two targets in two briefly presented arrays of eight stimuli (see Fig 4). The inner and outer arrays each contained one target. An eight-alternative forced-choice procedure was used. Observers indicated which one of 8 locations contained the target in each array. In motion experiments, observers identified the direction of two trajectories among randomly moving dots. One of the target trajectories appeared on the left and the other appeared on the right side of the fixation mark. The target trajectories took on any of 8 possible directions including the cardinals and obliques at 45 deg intervals. Again an 8 AFC procedure was used.

In addition, two control experiments were conducted to test whether observers could ignore the presence of an irrelevant array if they were instructed to do so. The following sections describe the details of the study.

### *Experimental Conditions*

Experimental conditions were organized into three groups. Table 1 shows an overview of the conditions in each experiment. Experiments that used color and transient stimuli were conducted in one laboratory while experiments that involved motion stimuli were conducted in another laboratory.

In Experiment 1 (within-identical), observers searched for two identical targets that were coded within one pathway among identical distractors. The Transient/Transient (Tran/Tran) task pair combined the transient target with another identical transient target among uniform white distractors. The Red/Red task pair combined a reddish target with another identical reddish target, and Blue/Blue task pair combined a bluish target with another identical bluish target. In Experiment 2 (within-different), observers searched for two dissimilar targets that were coded within one pathway among identical distractors or searched for two identical targets that were coded within one pathway among dissimilar distractors (reverse conditions). In the M/M task pair, observers identified the direction of trajectories that appeared to the left and the right side of the fixation mark. In the two reverse conditions, the Red/Red Reverse (Red/RedRev) & the Blue/Blue Reverse (Blue/BlueRev), the roles of the target feature and the distractor feature were reversed in the inner and the outer arrays (Sperling & Melchner, 1978) to determine whether the roles of the target and the distractor features in two visual search tasks moderated the degree of dual-task interference. The Red/Bright task pair combined a reddish target in the inner array and a bright target in the outer array. Experiment 3 (Between) consisted of task pairs that required attention to be divided between features that were coded by two different visual pathways. The Tran/Red task pair combined the transient target

with the reddish target and the Tran/Blue task pair combined the transient target with the bluish target. The Red/Blue task pair combined the reddish target in the inner array with the bluish target in the outer array. The Blue/Red task pair combined the bluish target in the outer array with the reddish target in the inner array. Previous research showed that sensitivity to short-wavelength light increases with eccentricity to a maximum at 1 degree and slightly declines at greater eccentricity (Castano & Sperling, 1982), and the proportion of short-wavelength cones increases with eccentricities (Curcio, et al., 1991). The stimulus arrangement was reversed in those two task pairs to examine whether searching for the bluish target is more difficult for the outer ring than in the inner array due to eccentricity.

#### *Control Conditions*

Two conditions were conducted to examine whether the two visual search tasks, one search among the inner array of stimuli and the other search among the outer array, were independent of each other. In other words, these control experiments examined whether observers could restrict their search to the relevant array while ignoring the irrelevant array. Studies have shown that selective space-based attention enables us to preferentially process stimuli that fall within an attended area and filter out stimuli in the unattended areas (e.g. Palmer et al. 1993). On the other hand, other studies suggest that feature-based attention is spatially global unlike space-based attention. When selective attention is directed to a particular feature value, neural processing of the attended feature is facilitated throughout the visual field (Martinez-Trujillo & Treue, 2004; Sàenz, Buraças & Boynton, 2002 & 2003). It was important to determine whether observers could selectively attend to a target feature in one array and make a response to it while

ignoring stimuli in the irrelevant array. Particularly, it was of interest for dual-task conditions in which two identical sets of targets and distractors were paired and in the reverse conditions in which targets were identical but the distractors differed (i.e. Red Reverse and Blue Reverse).

In the two reverse conditions, observers searched for two identical targets in both arrays, yet the target-distractor relationship reversed in the two arrays. For example, in the Red / Red Reverse task pair, observers searched for the same reddish target in both arrays. Yet the reddish target was among more saturated red distractors in one array and the other target was among white distractors in the other array. When observers were searching for a reddish target among white distractors in the outer array in this Red/Red Reverse task pair, observers might have difficulty in filtering out the saturated red distractors in the inner array that were also red. In other words, observers might be unable to restrict their search for a reddish target to the outer 8 stimuli. If observers were unable to filter out the irrelevant array, signals from those irrelevant saturated red stimuli would add additional noise to the decision process, which would lower the accuracy producing the familiar set-size effect (Palmer et al., 1993). The two control conditions were compared to test whether the mere presence of irrelevant stimuli affected performance when observers attended to one array (Figure 4).

In the single-array control condition, observers searched for a target in the absence of the irrelevant array of stimuli. In the double-array control condition, observers searched for a target in one array in the presence of the irrelevant array of distractors and the target. The observers did not respond to the irrelevant array. In the motion single-side control condition, observers identified the direction of a trajectory on the relevant side of

the screen while ignoring the noise on the irrelevant side of the screen. In the motion double-side control condition, observers identified the direction of a trajectory on the relevant side of the screen while ignoring an irrelevant trajectory in noise on the other side of the screen. If observers could filter out the irrelevant array and attend only to the relevant array, the accuracy in the double-array control condition should be similar to that in the single-array control condition. The single-array and the double-array control conditions were conducted for all the task pairs in the main dual-task experiment.

### *Participants*

Two undergraduate university students and the author took part in the study. The two undergraduate students were paid, and were naïve to the purpose of the study. The author (SM) was highly trained in similar psychophysical experiments, while the two undergraduate students (BW & CW) were not as experienced as the author. All observers self-reported that they have normal or corrected-to-normal visual acuity, and were tested for normal color-vision using the Ishihara color vision test. All of experiments with transient and color targets were conducted first. The same three observers participated in all experiments.

## Chromatic and Transient Targets

### *Apparatus and Stimuli*

A Power Macintosh 8500 with a 19-inch Sony GDM-F520 cathode ray tube color monitor driven at a frame rate of 75Hz by a Radius Thundercard was used to collect data for chromatic and transient targets data. The monitor was calibrated with a Minolta CS-100 Chroma Meter. The stimuli were small disks (0.16 deg in diameter) displayed

against a white background. The luminance of the white background field was fixed at 5 cd/m<sup>2</sup>. The disks were randomly jittered around imaginary inner and outer circles. The radiuses of the imaginary circles were 2.03 deg and 4.06 deg respectively. The luminance of the stimulus disks was fixed at 7.5 cd/m<sup>2</sup> except for the targets in the transient and the bright target task conditions. The stimuli were presented for a duration of 100 msec to prevent eye movements. Each of the two arrays of stimuli included one disk that contained a target increment and seven distractors. The cone excitation coordinates (MacLeod & Boynton, 1979) of the white distractors were  $L = .666$ ,  $S = .999$ . A viewing distance of 1.33m was held constant with a use of a mounted chin rest.

Parvocellular and koniocellular targets were defined by an additional small chromatic or luminance increment. The degree of increment was determined separately for each array and for each observer in the preliminary work. Studies have shown that the cells in the magnocellular pathways, at least at an early level of visual processing, are insensitive to chromatic variations (Daisey, 2004; Livingstone & Hubel, 1987; Merigan & Maunsell, 1993; Schiller & Logothetis, 1990). In particular, the parvocellular targets were designed to produce excitation in the L cardinal color mechanism or the Achromatic color mechanism (i.e. red and bright targets) that differed from the distractors.

Koniocellular targets were designed to result in excitation in the S cardinal color mechanism (i.e. blue target). The luminance of chromatic targets matched the luminance of the distractors. The chromaticity coordinates of the bright target matched the chromaticity coordinates of the distractors. In the parvocellular reverse condition (Red Reverse), observers searched for the same slightly reddish target among white distractors

in one array while they search for a target that was slightly less reddish (i.e. desaturated red) among saturated red distractors in the other array.

Transients and motion were used to define the magnocellular type targets (motion stimulus will be described in the next section). The transient target was a brief dynamic temporal change in luminance. The parvocellular and the koniocellular pathways are thought to be very insensitive to temporal frequencies higher than 15 cycles/sec (Lennie & Dzmura, 1988). For a short period of about 50 msec after onset of the stimuli, the luminance of the transient target first increased and then decreased before returning to baseline. The degree of the incremental change in luminance was determined separately for each array and for each observer in the preliminary work. The transient consisted of two frames of the 75 cycle/second refresh rate of the monitor for a duration of 26.6 msec, yielding a temporal frequency of 37.5 cycles/second. Meanwhile, the distractors remained at the baseline luminance throughout the duration of a trial (see Figure 5). This created a perception of flicker while keeping the target's average luminance equivalent to the luminance of the distractors.

### *Procedure*

For chromatic and transient targets, observers viewed the monitor from a distance of 1.33 m in a dark room with flat black walls and floor so that little was visible other than the stimuli displayed on the monitor. At the beginning of each block of trials, the observers were cued to the appearance of the target for that block. An eight-alternative forced choice (8AFC) accuracy search task was used. Observers indicated the location of the target in each array of 8 stimuli. For a short interval after the display of the target and the distractors, response circles appeared in the places of the target and the distractors.

Observers indicated their response for each stimulus array by placing a mouse cursor inside of the circle indicating the location of the target, and clicking the mouse. Observers were free to indicate their two responses in any order. One block of trials consisted of a cuing display illustrating the target and distractors, five practice trials, and fifty experimental trials. See Figure 6 for a schematic illustration of the displays which were used for chromatic and transient targets.

Prior to collecting the dual-task data, targets that yielded approximately 75% correct were estimated for each observer and target feature in the single-task preliminary work. Observers were presented with a single array of eight stimuli as in single-array control condition, and searched for a target. Several levels of differences between the target and the distractors were used to estimate psychometric functions. A Weibull function was fit to the accuracy data to estimate the 75% correct threshold for each target type. The estimated target increments were then used to collect data for both the single-task control conditions and each dual-task experimental conditions. The observers repeated four blocks of trials in the dual-task condition and in each of the two single-task control conditions (i.e. inner and outer array) for a total of 200 trials per condition.

## Motion Targets

### *Apparatus and Stimuli*

An x-y cathode ray tube display (Tectronix 604) with a P4 phosphor running a frame rate of 50 Hz was used to display the motion stimuli. Stimuli generated on the screen were viewed through a 10-degree diameter square mask divided in half by a 7-millimeter wide cardboard strip. A mounted chin rest was used to keep a constant

viewing distance of 57 cm. Each trial lasted for 100 msec to control for eye movements. Stimuli were presented to the observers while the overhead lights were turned on, yielding veiling luminance of approximately  $23.3 \text{ cd/m}^2$ . A beeping sound was emitted from the computer to indicate the beginning of every trial. Immediately after the display onset, one or two of the dots moved in one of the eight possible directions (0, 45, 90, 135, 180, 225, 270, 305 degree directions) for the entire duration of the display at the speed of 6 deg/sec. Remaining distractor dots moved in random directions changing their direction of movement each frame (see Figure 7). Eight number keys on a keyboard were used to record observers' response. The luminance of each dot was about  $57 \text{ cd/m}^2$ .

### *Procedure*

For motion targets, observers identified the direction of one or two trajectories embedded in random motion noise. An eight-alternative forced choice procedure was used. A target trajectory appeared moving in one of 8 directions, and observers indicated their response by a bottom press. A single beep prompted the beginning of a trial and observers initiated a trial by pressing a space bar on the key board. The locations of eight number keys (1, 2, 3, 4, 6, 7, 8, and 9) corresponded to the 8 alternative directions (225, 270, 305, 180, 0, 135, 90, and 45 deg respectively). For instance, when observers indicated a 90-degree trajectory, the observer pressed the 8 key (Figure 8). No feedback indicating correct or incorrect response was provided to observers. Two consecutive beeps indicated an inappropriate key press. The experiment program remained open until observers made an appropriate key press. When there were two trajectories in the dual-task condition, the observers were instructed to make a response to the target in the left field first and then to the target in the right field.

In preliminary work, the density of random dot distractors was varied to estimate the density level for 75 % correct threshold for each individual observer using one side of the screen. Two observers used the left screen to estimate their threshold dot density while the other observer used the right screen to estimate his threshold. Identification performance was similar for the left and for the right field for the three observers, thus the dot density using either the left or the right visual field was generalized to the other side in the experimental data collection. Each block of trials consisted of 10 practice trials plus 128 experimental trials, in which all possible pairs of 8 directions in the left and the right field appeared twice ( $8 \times 8 \times 2$ ). Observers completed four blocks of trials for the single-trajectory control, the double-trajectory control, and the dual-task conditions for a total of 512 trials per condition.

## RESULTS

### *Single-task and dual-task conditions ~ test of the visual pathway hypothesis*

The visual pathway hypothesis states that searching for two target features that are coded by feature mechanisms within one pathway should result in more dual-task interference than searching for two targets that are coded by feature mechanisms in two different pathways. To test the visual pathway hypothesis, confidence intervals (CIs) were used to make inferences about mean differences across conditions by following recommendations for a repeated measure paired-data design by Cumming and Finch (2005). Accuracy from the double-array dual-task condition was first subtracted from the accuracy from the double-array single-task condition to obtain the difference in the two accuracy measures (i.e. dual-task decrement in performance). Four accuracy differences were obtained for each task. An average of eight accuracy differences (i.e. four estimates per task) was calculated per observer for each task pair. Those eight estimates of the accuracy difference were pooled across observers to obtain group mean differences. A positive mean difference between the single-task and the dual-task conditions suggests the presence of dual-task interference, while a mean difference of zero suggests the absence of dual-task interference. CIs were calculated by multiplying the Standard Error of the Mean (SEM) by the critical  $t$  for a  $p$ -value of .05 (2-tail). When the CIs at 95% do not include zero (zero difference indicates the absence of dual-task interference), the

results suggest that the two tasks reliably resulted in a dual-task decrement in performance when they were conducted simultaneously.

The pooled accuracy differences and their 95% CIs ( $df=23$ ,  $t=2.069$ ) are plotted in Figure 9 (top). The two solid vertical lines in the figure separate the within-identical, within-different and the between groups data. It is important to note that the stimulus display in the double-array single-task control condition was identical to the display in the dual-task condition. The only difference was the observer's task; observers searched for two targets, one in each array in the dual-task condition, while they searched for a target in only one array and ignored the other array in the double-array single-task condition. Thus it was assumed that the observed accuracy difference between these two conditions reflects the performance cost from having to attend to two arrays of stimuli and make two responses.

The figure shows that the observed degrees of dual-task interference were fairly consistent within each group. The within-identical group consisted of within-pathway task pairs with two identical targets and distractors (Tran/Tran, Red/Red, and Blue/Blue). The within-different group consisted of within-pathway task pairs with two different targets among identical distractors or two identical targets among different distractors (Red/RedRev, Blue/BlueRev, Red/Bright, and M/M). The between group consisted of between pathway task pairs with different targets but identical distractors (Tran/Red, Tran/Blue, Blue/Red, and Red/Blue). Comparing these three groups of task pairs suggests that the degree of interference differed depending on: 1) whether one or two different visual pathways were involved and 2) whether those sets of targets and

distractors were the same or different in appearance. The two factors are now discussed in turn.

The within-identical group overall showed very little dual-task decrement, while the within-different group resulted in a large dual-task decrement. This result suggests that simultaneously searching for two identical targets was as efficient as searching for one target, although they were both coded by the feature-coding mechanisms in one visual pathway. On the other hand, searching for two different targets among identical distractors or two identical targets among different distractors resulted in dual-task interference. The absence of any dual-task interference in the within-identical group is not consistent with the visual pathway hypothesis, and was surprising given that the single-task condition itself was challenging yielding on average 70% correct accuracy. Possible reasons why the within-identical task pairs resulted in little dual-task interference will be discussed in the Discussion section.

The within-different group resulted in much larger dual-task interference than the between group. The within-different and the between task pairs both required observers to make two different decisions based on two different criteria. The difference in the dual-task decrement in performance in these two groups suggests that dual-task performance was influenced by the visual pathways coding the two targets. Consistent with the visual pathway hypothesis, the results showed that the dual-task decrement was smaller when two targets were coded in the two different pathways rather than in the same pathway.

The M/M condition, in which observers identified the directions of two trajectories, was slightly different from the other task pairs. The datum plotted in Figure

9 combines both “identical” and “different” trials. In a block of trials in the M/M condition, 12.5 % of trials (16 trials) were the “identical-direction” trials in which two trajectories that were in the same direction appeared while the rest of the trials (112 trials) were the “different-direction” trials in which trajectories in two different directions appeared. The dual-task decrements separately calculated for each type of trial are plotted in Figure 10. The figure shows that observers performed slightly better in the identical-direction trials than in the different-direction trials, yet the difference was not significant.

Lastly, the mean accuracy differences in the between group appear to lie in between the within-identical and the within-different groups. This suggests that attending to two different targets coded by two different visual pathways resulted in some dual-task interference but interfered less than attending to two targets that are coded in one visual pathway.

To examine which model of attention best describes the observed dual-task interference, in addition to the use of CIs, a series of paired t-tests was conducted on the differences between the observed data and each model prediction for the within-identical, the within-different and the between groups (Figure 9, bottom). Pooled double-array single-task accuracy across all task pairs was 0.7. Thus quantitative predictions of the degree of dual-task decrement in performance were calculated for the three models( the independence, sampling, and switching) using the accuracy of 0.7 as the single-task baseline performance (see Appendix for how the predictions were derived). The independence model predicts no dual-task decrement in the between task pairs and a decrement of either .19 or .29 for all within-pathway task pairs. The sampling model

predicts the dual-task decrement in performance of .19 for all task pairs. The switching model predicts the decrement of .29 for all task pairs.

The following steps were taken to compare the fit between the observed and the predicted values for the three models. First, differences between the observed dual-task decrements and the predicted dual-task decrements were calculated for the three models. The pooled differences were squared to eliminate negative signs. The squared differences were summed to obtain total sum of squared difference between the observed and the predicted for the three models. To illustrate, a set of hypothetical data and predictions of the independence model and the sampling model are shown in Figure 11. Schematically, the differences between the observed and the independence model (M1) prediction are shown by the arrows on the right side of the figure, and the differences between the observed and the sampling model (M2) prediction are shown by the arrows on the left side of the figure. The summed squared differences for M1 and M2 were subtracted from each other and the  $t$ -value of the differences was computed. The null hypothesis was that the sum of the differences between the observed and the predicted for M1 and M2 are similar, so the numerator equals zero. The alternative hypothesis was that the sum of the differences for M1 and M2 are significantly different from zero to yield a large numerator, resulting in a large  $t$  value, suggesting that one of the models (M1 or M2, depending upon the sign of  $t_{\text{obs}}$ ) was a better fit to the data.

Table 2 lists the summary of this analysis. Model comparison between the independence model and the sampling model suggests that the independence model fits the observed degree of dual-task interference in the within-identical task pair significantly better than the sampling model ( $p < .001$ ). On the other hand, the sampling

model fits the observed dual-task interference in the within-different task pairs significantly better than either the independence model ( $p < .001$ ) or the switching model ( $p < .001$ ). The observed dual-task decrement from the between task pairs in general fits the independence model prediction better than the sampling model (at  $p < .05$ ). The  $t$ -tests for comparing model fit between the sampling model and the switching model for the within-identical and the between groups were not conducted. This was because Figure 9 (bottom) indicated clearly that only the within-different group resulted in a degree of dual-task interference that was comparable to the prediction of the switching model.

The mean accuracy differences for each of the observers are plotted in Figure 12. As seen in the figure, the patterns of the dual-task decrement for individual observers conform to the general trend. Consistent with the visual pathway hypothesis, the within-different task pairs resulted in more dual-task interference than the between task pairs for observer BW and CW. The between task pairs were more similar to the within-identical task pairs for observer CW. For observer SM, the two reverse task pairs resulted in slightly larger dual-task decrement than the rest of the within-pathway task pairs, while all four between-pathway task pairs were similar to each other. Unlike observers BW and CW, for observer SM, mean difference for the M/M task pair was very small and more similar to the within-identical task pairs.

#### *Equal attention instruction and prioritizing strategy*

Observers were instructed to divide attention equally between both arrays in the dual-task condition. To determine whether observers followed the instruction, dual-task decrements were calculated separately for the inner and the outer task. The mean

accuracy differences between the double-array single-task and the dual-task conditions for each task and their CIs ( $df = 3$ ,  $t = 3.182$ ) for each task were plotted in Figure 13. This analysis shown in the figure can unveil whether the observers followed the equal attention instruction or consistently favored one task over the other despite the instruction. These graphs indicate that generally observers followed the equal priority instruction. It appears that, in only a few task pairs, observer BW consistently favored one task over the other as seen by the significant difference in the means. This prioritizing strategy seemed to enlarge CIs in Figure 12. For instance, the outer mean difference was significantly larger than the inner mean difference for Red/Bright and Red/RedRev task pairs for observer BW in Figure 13, which contributed to the large CIs for those two task pairs in Figure 12. This indicates that observer BW consistently favored the inner array over the outer array in those task pairs.

It is interesting to note that those task pairs that showed evidence of a prioritizing strategy were the ones with an overall large degree of dual-task decrement. One probable explanation for this association is the following: When observers perceived that it was difficult to simultaneously search for two targets, they tended to devote more of their attention to one array to search for at least one target. This analysis overall suggests that the observers followed the equal priority instruction.

#### *Negative contingency and within-trial switching strategy*

The switching model postulates an attentional limitation in processing two objects (targets) simultaneously. It follows that the switching model predicts that observers can only do one task at a time because the duration of a trial is very short (100 msec.). An instruction to divide attention equally between the two tasks was given to the

observers in the present study. To follow the instruction, the switching model predicts that observers will switch tasks from trial to trial so half of trials in a block are devoted to one task and the other half are devoted to the other task. Phi coefficients based on the contingency table (Hays, 1988, Sec. 18.4) were used to examine whether observers used this switching strategy. The coefficient indicates the strength of association between the two task performances. It indicates whether, across trials, the likelihood of correctly responding to one task is related to the likelihood of correctly responding to the other task.

The coefficients also provide insights to whether or not observers were able to engage in two search tasks simultaneously. Large negative phi coefficients indicate that better performance on one task is consistently associated with poorer performance on the other task. The switching model predicts large negative coefficients. In contrast, the sampling model predicts that the phi coefficients should be indistinguishable from zero. The sampling model suggests that observers share perceptual samples between the two tasks on each trial. This sampling strategy would predict statistical independence between the two tasks.

Phi coefficients of all task pairs for the three observers are plotted in Figure 14 for each repetition of each condition. There were only a handful of coefficients that were significantly negative at  $p = .05$  level ( $df = 1, \chi^2 = 3.84$ ) as indicated by the double asterisks in the figures. However those significant negative coefficients did not appear consistently across observers for any task pair. It is interesting to note that those six coefficients that were significantly negative were all from the first two repetitions of data collection. This perhaps indicates that the negative contingency was only a product of an

earlier data collection phase when observers were fairly new to the attentional demand of the dual task. After a couple of repetitions, the two task performances did not negatively correlate with each other. Thus phi coefficients in general scattered around zero, yielding non-significant averages for all task pairs across the three observers, suggesting that observers were not switching between tasks across trials.

Lastly, dual-task performance was broken down into the three types of trials: both correct, both incorrect, and one correct/one incorrect to examine changes in the proportions of the three types of trials as attentional demand increased. The profile of the three types of trials together with the individual phi coefficients for each observer was shown in Figure 15. The figure shows, for observers BW and CW, the proportions of trials in which observers responded incorrectly for both tasks were larger in the more attentionally demanding within-different task pairs than in the other task pairs. In addition, the proportions of trials in which they responded correctly for both tasks were smaller in the within-different task pairs than other pairs. On the other hand, the proportions of trials in which observers responded incorrectly for one task and correctly for the other task were similar across all the task pairs. For observer SM, this trend was not as apparent. The results suggest, at least for two of the three observers, the large dual-task decrements observed in the within-different group were due to an increase in the number of trials in which they were unable to find any target, rather than an increase in the number of trials in which observers could find only one target.

Figure 14 and 15 together suggest that, in general, across trials there was no relationship between how well one performed on one task and how well one performed on the other task. Thus observers did not use the switching strategy as predicted by the

switching model, but instead engaged in two tasks simultaneously as predicted by the sampling model.

*Single-array and double-array single-task conditions ~ the sensory interference to dual-task*

Two types of single-task control conditions were conducted to examine whether the presence of an irrelevant array of stimuli has any influence on single-task performance. In the double-array condition, observers searched for a target in the relevant array and were instructed to ignore the irrelevant array. In the single-array condition, observers searched for the same target in the absence of the irrelevant array. It is important to assess whether having the other array present interfered with a single visual search, since such sensory interference may contribute to the difficulty in the dual-task conditions. Mean accuracy difference was calculated by subtracting the accuracy in the double-array condition from the accuracy in the single-array condition. The pooled mean accuracy differences across the three observers and their CIs ( $df = 23$ ,  $t = 2.069$ ) are plotted in Figure 16. A mean difference of zero indicates that performance in the double-array condition was similar to performance in the single-array condition. The zero difference suggests that the observers could ignore the presence of the irrelevant array of stimuli in the double-array condition. Positive values indicate that the performance in the double-array condition was poorer than the performance in the single-array condition. The positive difference suggests that the presence of the irrelevant array of stimuli interfered with the search in the double-array condition. The decision model of Palmer et al. (1993) predicts a .11 decrease in accuracy due to a set-size increase from 8 in the single-array condition to 16 in the double-array condition. If observers could not restrict

their attention to the relevant array but instead attended to all 16 stimuli in the double-array condition and selected a stimulus that elicited the largest signal in the target feature dimension, the mean difference would be similar to the prediction of the decision model.

The mean accuracy differences were in general not as large as predicted by the decision model for most task pairs. Only the Tran/Tran task pair included the decision model prediction within its CI and excluded zero. The mean difference for the Red/Tran task pair was significantly higher than zero, but was not as large as the decision model prediction. This result suggests that the observers were successful in filtering out irrelevant stimuli for the Red/Tran task pair, but the search was slightly less efficient than it was in the single-array condition. CIs of the mean differences for the rest of the task pairs included zero, indicating that observers were able to filter out any sensory interference from the irrelevant array of stimuli in the double-array conditions. Similarly, no significant mean differences between the single-side and the double-side conditions for M/M task pair were observed, suggesting that irrelevant trajectory in the ignored field had no effect on attending to a target trajectory in the attended field. The idea that feature-based attention is spatially global (Sàenz, Buraças, & Boynton, 2002 & 2003) suggests that observers would have a difficult time filtering out irrelevant distractors in the double-array condition for the reverse task pairs. The results suggest, in contrast, that the mean differences of the reverse task pairs were no larger than the mean differences of the other task pairs, even though the color of the target in the relevant array was similar to the color of the distractors in the irrelevant array in the reverse task pairs.

The mean accuracy differences for each observer and their CIs ( $df = 7$ ,  $t = 2.365$ ) were plotted in Figure 17. At the individual observer level, the irrelevant array of stimuli

appears to have a small effect on performance for a few task pairs and no effect for other task pairs. For instance, mean accuracy difference of the Tran/Tran task pair for observer BW, the Red/RedRev, Blue/BlueRev task pairs for observer SM were significantly larger than zero. Overall, accuracy differences for each observer appear to conform to the trend of the pooled group mean accuracy differences.

Another way to examine the effect of sensory interference is to compare the degree of dual-task interference when the double-array condition was used as the baseline single-task performance to when the single-array condition was used as the baseline performance. This analysis indicates whether sensory interference from the presence of two arrays of stimuli itself contributed to overall dual-task interference, and if it did, to what degree. The presence of such sensory interference will lower the degree of dual-task interference estimated using the double-array condition compared to the degree of dual-task interference estimated using the single-array condition. The two sets of the accuracy differences pooled across observers and their CIs ( $df= 23, t = 2.069$ ) were plotted in Figure 18. The figure shows that the two ways to estimate a degree of dual-task decrement resulted in a similar pattern. This suggests that the additional sensory noise that was present in the dual-task condition, which was absent in the single-array single-task condition, was not a contributing factor to the degree of dual-task interference.

The last analysis was aimed at examining whether single-task performance in the double-array conditions was similar across the inner and the outer tasks. The classical view of attention suggests that attention is unitary as in the spotlight theory or in the zoom lens theory of attention (LaBurge, 1983; Eriksen & St. James, 1986), although more recent studies (e.g. McMains & Somers, 2004) suggest that attention can be split

into discrete regions in space. Such a view of attention might suggest that attending to the outer array while ignoring the inner array was more difficult than the reverse because the scope of attention unavoidably included information from the irrelevant inner array when the scope was widened to process information in the outer array. On the other hand, it might also be expected that performance would have been better when observers only responded to the inner array and ignored the outer array, because the scope of attention could be narrowed so that it only included the inner array. In order to evaluate this possibility, the accuracy differences and their CIs ( $df = 3, t = 3.182$ ) were calculated separately for the inner and the outer array in the two single-task conditions and are plotted in Figure 19. This analysis was not applied to the M/M task pair, since the display was split into right and left visual fields in the M/M single-side and double-side single-task conditions. Figure 19 shows that the performance for the outer tasks was not different from the performance for the inner tasks across the three observers. In summary, the analyses of single-task control conditions showed that observers were able to ignore the presence of the irrelevant stimulus array. The data for the M/M condition also showed that the presence of the irrelevant trajectory had no effect on performance.

## DISCUSSION

The current study was founded on the idea that modularity of the visual system may affect our ability to divide attention between two visual search tasks. Specifically, the study tested the visual pathway hypothesis that postulates the parvocellular, the koniocellular and the magnocellular pathways may be equipped with independent pools of attentional resources. The hypothesis predicted that dividing attention between searching for two targets that were coded by feature-coding mechanisms in one pathway would lead to more dual-task interference compared to searching for two targets that were coded by feature-coding mechanisms in two different pathways. Seven within-pathway and four between-pathways conditions were grouped into three experiments in terms of 1) pathway conditions (within or between) and 2) whether tasks (i.e. target feature or distractor features) were identical or different (within-identical or within-different) in the within-pathway condition. The dual-task performance decrements for these three groups, the within-identical, the within-different and the between, were compared. The present study also examined whether a sensory effect was a contributing factor to dual-task interference by comparing the degree of dual-task interference using both the single-array and the double-array control conditions.

In addition, the study investigated which of the three models of attention (the sampling model, the independence model, and the switching model) best described the mechanisms of dividing attention between the two visual search tasks. The sampling

model postulates that perceptual processes collect samples of a percept to establish a perceptual representation of a stimulus. When samples are divided between two tasks, fewer samples are simultaneously collected per task, resulting in degraded perception compared to when all the samples are dedicated to one task. The independence model suggests that samples can be shared without any interference, possibly because the two tasks draw samples from two different pools of attentional resources. The switching model postulates that two targets would compete for attention in an all-or-none fashion, forcing observers to switch between tasks.

Based on these postulates, each of the three models predicted different degrees of a dual-task decrement in performance for the dual-task pairs. The sampling model predicts that the accuracy should decrease approximately 0.19 in proportion correct when samples are simultaneously shared between two tasks, and predicts no contingency in performance across trials. The switching model predicts a decrease of approximately 0.29 in proportion correct if observers switched between tasks and predicts a significant negative contingency across trials. The independence model predicts no dual-task interference when tasks involve two independent visual pathways. Dual-task decrements consistent with either the sampling model or the switching model in all three groups of conditions would suggest that the visual pathways do not influence performance in divided attention. No dual-task decrement in performance in the between-pathway condition would be consistent with the independence model, and would support the visual pathway hypothesis that each pathway may be equipped with an independent pool of resources.

The study found that the within-different task pairs resulted in the largest dual-task decrement in performance compared to the within-identical and the between task pairs. The four between task pairs produced a small degree of dual-task interference that lies between the within-identical and the within-different group. Consistent with the visual pathway hypothesis, the four within-different task pairs showed more interference than the between task pairs. The observed decrement in the within-different task pairs was consistent with the prediction of the sampling model. The within-identical task pairs showed little or no dual-task interference. The lack of any interference in the within-identical group was not in accordance with the visual pathway hypothesis. None of the observed dual-task decrements was as severe as the switching model predicted. The dual-task decrements estimated using the two types of single-task control conditions were similar to each other.

In summary, these results suggest that whether attention was divided within one or between two independent visual pathways influenced performance, and the nature of the two tasks also influenced the degree of dual-task interference. No single model of divided attention was consistent with the observed dual-task decrements in performance in all of the conditions. Together, the findings of the present study put forward a complex picture that various factors potentially affect the efficiency in dividing attention between two visual search tasks.

#### *Influence of visual pathway, and nature of task on dual-task performance*

The degrees of dual-task decrements observed in the literature range widely, yet those all roughly seem to group into three categories. Some task pairs showed little or no dual-task decrement, some showed decrements that are consistent with the sampling

model within the framework of the signal detection theory, and others showed decrements that are consistent with the switching model which suggests all-or-none processing of the two tasks with significant across-trials negative contingency. The results from the current study suggest that multiple factors influence variations in interference between two simultaneous perceptual tasks. First, results from the present study suggest that whether the two search tasks involve information from one visual pathway or two independent visual pathways influences the amount of interference between the two tasks. Second, the decision process and criteria involved influence the degree of dual-task interference. These two factors are now discussed in turn.

*The within-identical and the within-different groups*

One surprising finding from the present study was that two within-pathway groups, the within-identical and the within-different, resulted in two different degrees of dual-task decrement in performance. The visual pathway hypothesis predicted more dual-task decrement in the within-pathway task pairs compared to the between-pathways groups. Inconsistent with the hypothesis, the within-identical task pairs did not result in any dual-task interference. The lack of any interference suggests that those two concurrent search tasks were processed as efficiently as a single search task. This finding was unexpected because it was believed that the search tasks used in the current study required substantial attentional resources for the following two reasons. First, each single task itself was challenging because the performance was adjusted to approximately 70 % correct, which was far below the ceiling level of performance. Second, attention is critical even for detecting an odd feature in an easy visual search task that was far above threshold (Joseph et al., 1997). The task in the current study was to localize a target at

threshold, which was considered to be more attentionally demanding than merely detecting the presence of a suprathreshold target.

One potential reason why the within-identical task pairs did not produce any decrement in performance is that observers conducted one search for two targets among fourteen identical distractors. It has been shown that “similarity grouping” (Kahneman, 1973) can facilitate simultaneous perceptual processing of similar features. For example, Santhi and Reeves (2004) showed that multiple disks can be grouped together to be treated as one disk when they were in the same color. However, results from the within-identical group do not fit the idea that observers conducted only one search for two most likely targets among 16 stimuli. If observers were to search for two targets among 16 stimuli (two arrays of 8 stimuli), the decision model of Palmer (Palmer et al., 1993) predicts a .12 decline in proportion correct due to the set-size increase from 8 to 16. But the pooled accuracy differences for the within-identical group clearly indicate that the observed dual-task decrement in performance was indistinguishable from zero and their 95 % CIs did not include .12 in accuracy difference as predicted by the decision model. Altogether these observations imply that two concurrent searches in the within-identical group were done separately, and were not treated as one search.

The within-identical task pairs may be special because these two search tasks were identical. The two targets in the within-identical group were coded by the same feature-coding mechanisms, and those identical targets were embedded in identical sets of 7 distractors. The type of search task was simple feature search (Treisman & Gelade, 1980) in which signals in a single set of feature-coding mechanisms indicated the presence of the target among the distractors. Within the signal detection framework, the

observers made two identical decisions using two identical criteria. For instance in the Red/Red within-identical task pair, observers picked the stimulus that elicited the maximum signal in the red-green feature-coding mechanism for both of the two tasks.

In contrast, the two searches involved different kinds of decisions and criteria in the within-different group. For instance in the Red/Red Reverse within-different task pair, for one search task observers must pick the stimulus that elicited the maximum signal in the red-green feature-coding mechanism. For the other search task observers must pick the stimulus that elicited the minimum signal in the red-green feature-coding mechanism. Results showed that the within-different group led to dual-task interference similar in magnitude to that predicted by the sampling model. The lack of negative contingency is also consistent with the sampling model prediction. This suggests that samples are collected simultaneously for two tasks rather than switching between tasks across trials, despite the task requirement of making two dissimilar decisions in the within-different group. Thus the present study suggests that the difference in the decision and criteria in the within-identical and the within-different group led to the difference in the observed dual-task decrement in performance.

#### *The between and the within-different groups*

The present study also suggests that visual pathway influences dual-task performance. In the between group, observers made two different kinds of decision based on different criteria similar to the within-different group. But the two decisions in the between group were based on signals from two feature-coding mechanisms in two different pathways. For instance, in the Red/Blue task pair, observers had to attend to signals in the red-green feature-coding mechanism in the parvocellular pathway to find

the reddish target for one search task. Simultaneously, they had to also attend to signals in the blue-yellow feature-coding mechanisms in the koniocellular pathway to find the bluish target for the other search task. Results showed that the degree of dual-task decrement was significantly reduced in this task pair and similarly for the other three task pairs in the between group compared to the within-different group. This finding is consistent with the visual pathway hypothesis. It suggests that when observers must attend to two different visual pathways, the cost of simultaneously making different kinds of decisions is minimized. This finding is also consistent with studies that suggested independent pools of attentional resources for processing different types of features coded by different pathways (Alvarez et al., 2006; Morrone et al., 2002 & 2004; Bonnel & Hafter, 1998; Bonnel et al., 1992). Thus the comparisons between the within-identical, the within-different and the between groups suggest that both the decision and criteria and the visual pathway influenced dual-task performance. These proposed factors for dual-task interference are compared to other explanations discussed in the literature next.

#### *Relations to the literature*

One school of thought in the literature considers that some tasks require more attentional resources than others, and the differences in the resource requirement leads to variations in the degrees of dual-task decrement (Ben-Av, Sagi, & Braun, 1992; Braun, 1994; Bonnel, et al. 1992; Braun & Juresz, 1998; Kahneman, 1973; Lee et al., 1999; Pastukhov et al., 2008). This account suggests that if the two tasks require more resources than the total available, dual-task performance begins to break down. If the two tasks require less than the total available resources, the two tasks will not result in any dual-task interference. For example, Braun and Juresz (1998) paired a letter

discrimination task (i.e. detect the presence of odd letter among a cluster of letters) with various peripheral tasks that varied in complexity. The peripheral tasks were letter discrimination, localizing an odd-ball orientation target, identifying the orientation of an odd-ball target, discriminating hues of two color odd-ball targets, and discriminating hues and orientations of two odd-ball targets. The main finding of the study was that different task combinations led to different degrees of dual-task interference. A large dual-task decrement and negative contingency was found when the central letter task was paired with the peripheral letter task, while almost no dual-task decrement was found when the central task was paired with a peripheral odd-ball orientation localization task. The authors explained that this was because some peripheral tasks require more attentional resources than others, and thus produced different degrees of interference with the central task.

Consistent with this resource demand idea, many of the studies that observed a large dual-task decrement used complex tasks involving a variant of form discrimination, pattern discrimination or identification that involved multiple dissimilar distractors (Alvarez et al., 2006; Bonnel et al. 1987; Broadbent & Broadbent, 1987; Duncan, 1993; Duncan et al., 1994; Duncan et al., 1997; Lee et al., 1999; Sperling & Melchener, 1978; Pastukhov et al., 2008). These complex tasks are expected to require large amount of resources, thus leading to severe dual-task interference.

Similarly Bonnel and colleagues (Bonnel et al, 1992; Bonnel & Hafter 1998) showed that more attention demanding identification tasks led to dual-task interference consistent with the sampling model, while less attention demanding detection tasks led to no dual-task interference. In their study, observers were required to monitor an

increment or decrement from the baseline luminance in two diodes. In the detection condition, the observers reported whether they detected any change in luminance for each of the two diodes. In the identification condition, the observers had to report the type of luminance change. The authors discussed that identification tasks require higher level processing of the stimulus than the mere detection tasks, and therefore demand more attentional resources.

Bonnel's studies may also be reinterpreted by considering the underlying decision processes. Suppose that Bonnel's detection condition only required observers to make two decisions about the presence of transients. This means observers made two identical decisions for the two tasks. Alternatively, suppose that Bonnel's identification condition required observers to monitor both the achromatic mechanisms that signal luminance increment and the achromatic mechanisms that signal luminance decrement. In this identification condition, observers were required to make two different kinds of decisions with two different criteria to do the two tasks.

In this light, Bonnel's luminance detection condition has task characteristics similar to the Tran/Tran task pair in the present study. Both the Tran/Tran task pair and Bonnel's detection condition resulted in no dual-task interference. Bonnel's identification condition has task characteristics similar to the within-different task pairs in the present study, and both resulted in dual-task decrement that is consistent to the sampling model. Interestingly, Bonnel also found that when the luminance of the two diodes changed in the same direction (i.e. increment & increment or decrement & decrement) the dual-task interference was reduced. Dual-task interference was also reduced in the M/M task pair in the present study when the two trajectories were in the

same direction compared to when they were in two different directions. Thus the results from the present study are consistent with the results from the Bonnel's study when taking the underlying decision requirements into consideration.

Considering decision requirements may be also important for the sampling versus switching debate in the dual-task literature (e.g. Miller & Bonnel, 1992). The literature has shown that some task pairs result in moderate degree of interference without any significant negative contingency, and others result in severe interference that is suggestive of switching. Within-different task pairs that required two different decisions and criteria resulted in dual-task decrement predicted by the sampling model. Similarly, task pairs that required simple feature discrimination on one feature dimension, such as luminance identification or line-length discrimination, seemed to produce the degree of dual-task interference that is also consistent with the sampling model (Bonnel & Hafter, 1992; Bonnel et al., 1992; Bonnel & Miller, 1992; Bonnel et al., 1987; Miller & Bonnel, 1992)

In contrast, when two tasks involve multiple feature-coding mechanisms, such as in the case of conjunction search (Treisman & Gelade, 1980), additional attentional interference above and beyond that predicted by the sampling model seems to emerge. The Feature Integration Theory of visual search suggests that the focal attention directed to one location at a time is necessary to combine information from multiple feature-coding mechanisms (Treisman & Gelade, 1980). Consistent with this idea, studies that involve conjunctive operations like visual search among letters or numerals led to a dual-task decrement that is suggestive of switching processing (Alvarez et al., 2006; Bonnel et al. 1987; Broadbent & Broadbent, 1987; Braun & Jurez, 1998; Duncan, 1993; Duncan et

al., 1994; Duncan et al., 1997; Lee et al., 1999; Sperling & Melchener, 1978). Hence considering the underlying decision process may explain why there are differences in the degrees of dual-task decrements for many other studies. It also complements the resource demand idea (Braun & Juresz, 1998) by providing one underlying principle of why some tasks require more or less attentional resources, and why some tasks produce severe dual-task interference that accompanies switching.

*Separate resources or integrated resources?*

The current study also suggests that the cost of simultaneously making two different kinds of decisions is reduced when those two decisions are based on signals in the two feature-coding mechanisms in two different visual pathways. This finding is consistent with the previous studies that suggested independent pools of attentional resources for processing features coded by different pathways (Alvarez, et al., 2006; Morrone, et al., 2002 & 2004; Bonnel & Hafter, 1998; Bonnel, et al., 1992). However, several studies also came to the opposite conclusion that attentional capacity is undifferentiated for features coded by different pathways (Duncan, 1993; Duncan & Nimmo-Smith, 1996; Lee, et al., 1999; Pastukhov et al., 2008).

Duncan (1993) previously examined whether the “what” pathway (i.e. the parvocellular pathway) and the “where” pathway (i.e. the magnocellular pathway) were equipped with independent pools of resources. Observers in Duncan’s study made 2AFC identification judgments about spatial frequency, orientation, length (the parvocellular features) and location (the magnocellular feature) on a display of two patches of bright lines against a dark background. Duncan found that the dual-task decrement in two discrimination tasks involving one pathway was similar to the dual-task decrement

involving two different visual pathways, and concluded that the visual pathways do not influence our ability to divide attention between two simultaneous discrimination tasks. One potential methodological issue in Duncan (1993) is that the stimuli were bright white against dimmer white background. It has been suggested that both the parvocellular and the magnocellular pathway may contribute to processing achromatic information (Kaiser & Boynton, 1996). Thus Duncan might have not effectively isolated the pathways, hence both pathways might have taken a part in all of the discrimination task pairs. In contrast, the display in the present study was carefully designed so that the three visual pathways were isolated.

Duncan and Nimmo-Smith (1996) compared the degree of dual-task decrement in performance when observers made 2AFC judgments about motion or color of two objects. In the “same-attribute” condition, observers made two identification judgments about either color or motion for both objects. In the “different-attributes” condition, observers made judgments about color for one stimulus and motion for the other stimulus. In this experiment, the display was carefully designed to address the influence of the visual pathway. The visual pathway hypothesis would predict no dual-task decrement in the different-attribute (i.e. between-pathway) condition and larger dual-task decrement in the same-attribute (i.e. within-pathway) condition. The results were different for motion and color. The dual-task decrement in the different-attribute and the same-attribute conditions was similar for the motion task. For the color task, the dual-task decrement was absent when the color task was paired with the motion task while two color tasks interfered with each other.

These results are mixed in terms of the influence of the visual pathways on dual-task performance. The result for the color task is consistent with the visual pathway hypothesis, and is consistent with the results from the Tran/Red and the Tran/Blue task pairs in the present study. The result for the motion task, however, is not consistent with the visual pathway hypothesis. The color task produced dual-task interference on the concurrent motion task, however the color task was unaffected by the concurrent motion task. Comparing the results of the motion and color tasks from Duncan and Nimmo-Smith to the results from the Tran/Red and the Tran/Blue task pairs suggests that the motion discrimination task and transient localization task, although both are processed within the magnocellular pathway, may have been affected differently by the concurrent color task. Duncan and Nimmo-Smith (1996) suggested that color is special and was not affected by the concurrent motion discrimination task, but was affected if it was paired with another color discrimination task. Lee et al. (1999) did not support this suggestion, and speculated that the color discrimination task in Duncan and Nimmo-Smith did not require any attentional resources. Further work is necessary to address this asymmetry.

Lastly, Lee et al. (1999) and Pastukhov et al. (2008) found evidence against differentiated attentional resources for different features. Both studies showed that the degree of dual-task interference between two tasks does not vary depending on the features involved. One reason why they did not find any effect of the visual pathways may be due to their methodology. Both studies paired a complex central task with various peripheral tasks that were very attentionally demanding. The central task in Lee et al. was a conjunctive feature discrimination task and the central task in Pastukhov et al. was a “rotating dumbbell” task in which observers reported the direction of rotation

prominent in the set of multiple rotating dumbbells. These complex central tasks were paired with peripheral tasks that varied in complexity. It is possible that these complex tasks interacted with the effect of visual pathway on dual-task performance. Conjunctive operations in these complex tasks might have resulted in high demand for central attentional resources (Bonnell et al., 1992; Bonnell & Hafter, 1998). Thus the demand of central attentional resources might have influenced the allocation of peripheral resources for processing different features. Further investigation is warranted to examine the influence of the visual pathways and the interaction with the type of tasks and decision processes.

## SUMMARY, IMPLICATION AND CONCLUSION

In summary, the present study found that the nature of the task and the visual pathways involved may influence efficiency in dual-task performance. Searching for two targets that are identical among identical distractors was as efficient as searching for one target at a time. Searching for two targets that differed in appearance or two identical targets among dissimilar distractors produced dual-task interference when the same pathway was involved in both tasks. In other words, both target and the distractors have to be identical to achieve the most efficient dual-task performance. This difference in the observed degree of dual-task decrements may be explained by the different decision processes that underlie different task pairs. In addition, more interference was observed when the two targets were coded by the same visual pathway rather than by two different pathways. Control conditions indicated that sensory effects did not contribute to the dual-task performance decrement. These results indicate that, at a very early level of visual processing, the neurophysiological modularity of the visual system influences the efficiency in dividing attention between two tasks. Together, the findings of the present study put forward a complex picture that various factors potentially affect the efficiency in dividing attention between two perceptual tasks.

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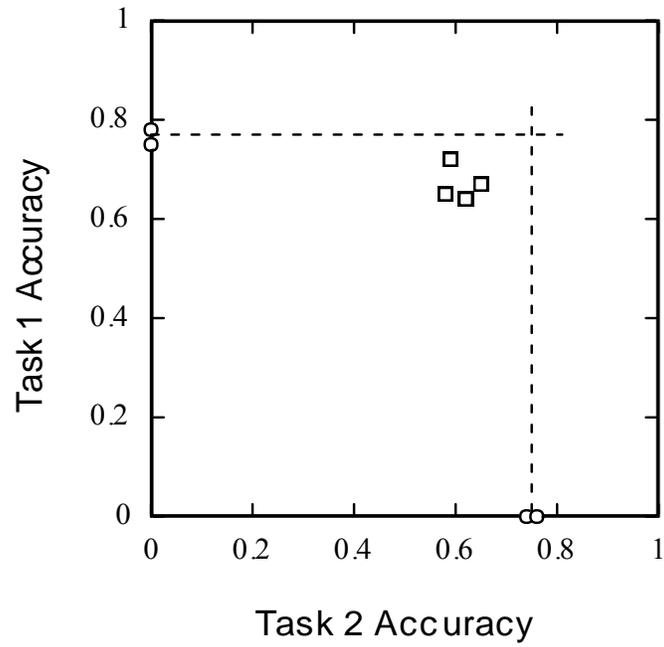


Figure 1.  
An example of AOC.

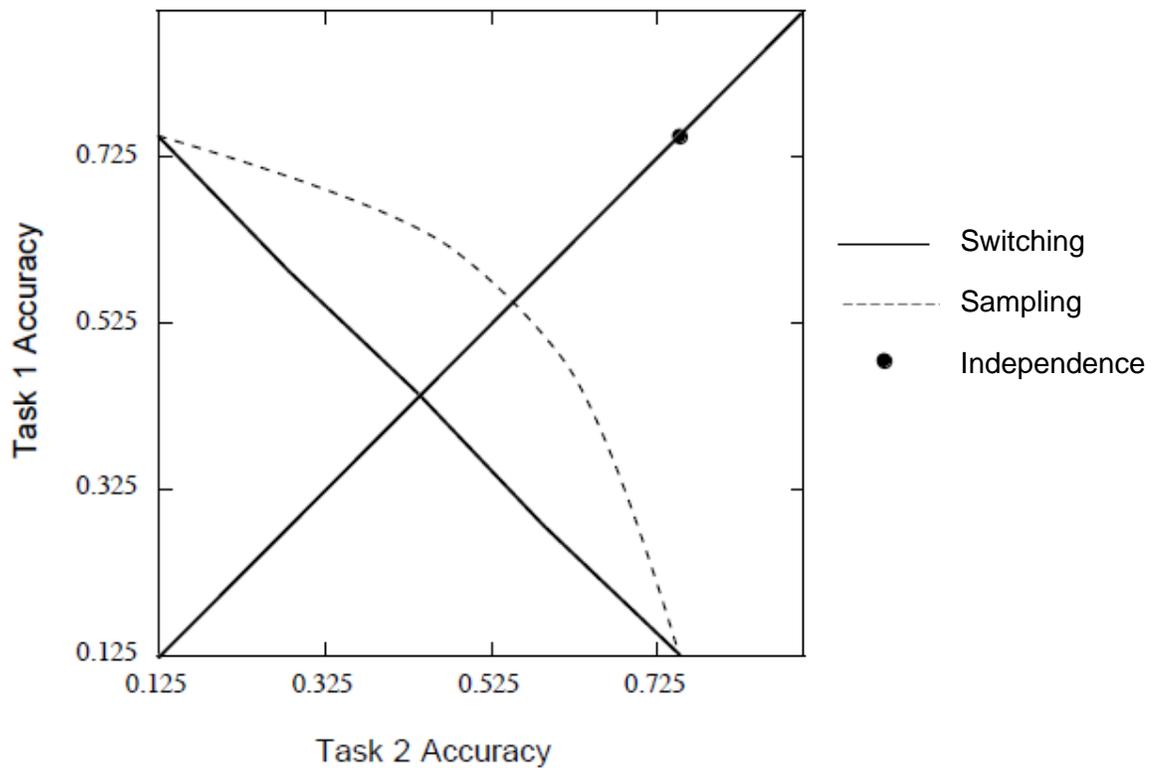


Figure 2.  
 Predictions of the sampling model, the switching model and the independence model.



Table 1. List of experiments and task pairs.

	PATHWAYS	INNER	OUTER
Experiment 1 <b>Within-Identical</b>	M–M	Transient	Transient
	P–P	Red	Red
	K–K	Blue	Blue
Experiment 2 <b>Within-Different</b>	M–M	Motion	Motion
	P–P	Red	Bright
	P–P	Red	Red Reverse
	K–K	Blue	Blue Reverse
Experiment 3 <b>Between</b>	M–P	Transient	Red
	M–K	Transient	Blue
	P–K	Red	Blue
	K–P	Blue	Red

M: Magnocellular pathway, P: Parvocellular pathway, K: Koniocellular pathway

**Instruction "Attend to the inner ring"**

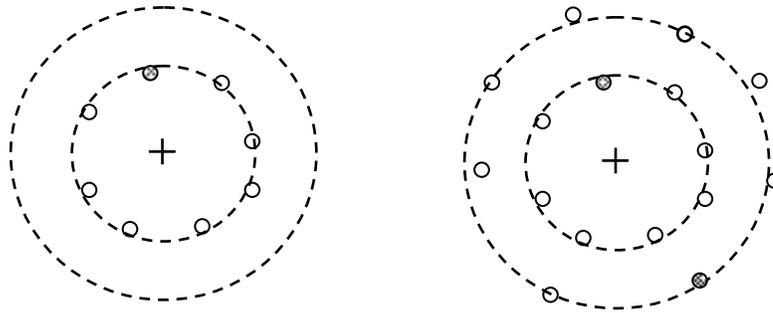


Figure 4. Schematic illustration of single-array & double-array color and transient control conditions.

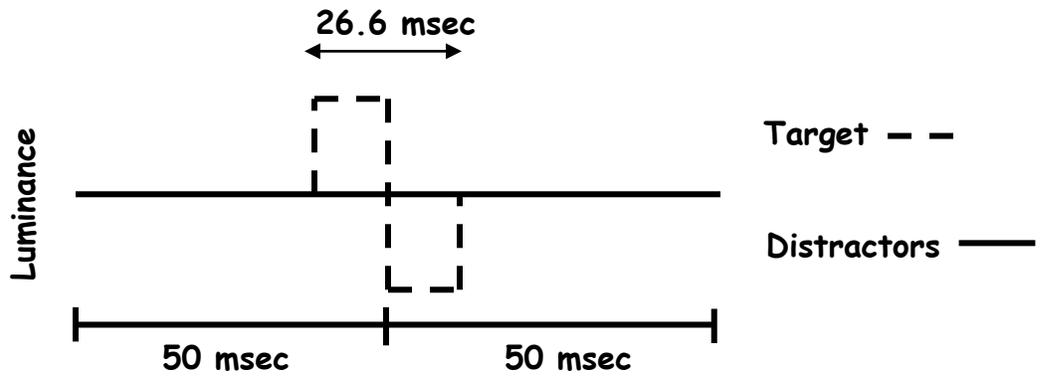


Figure 5. Schematic illustration of a transient target and distractors

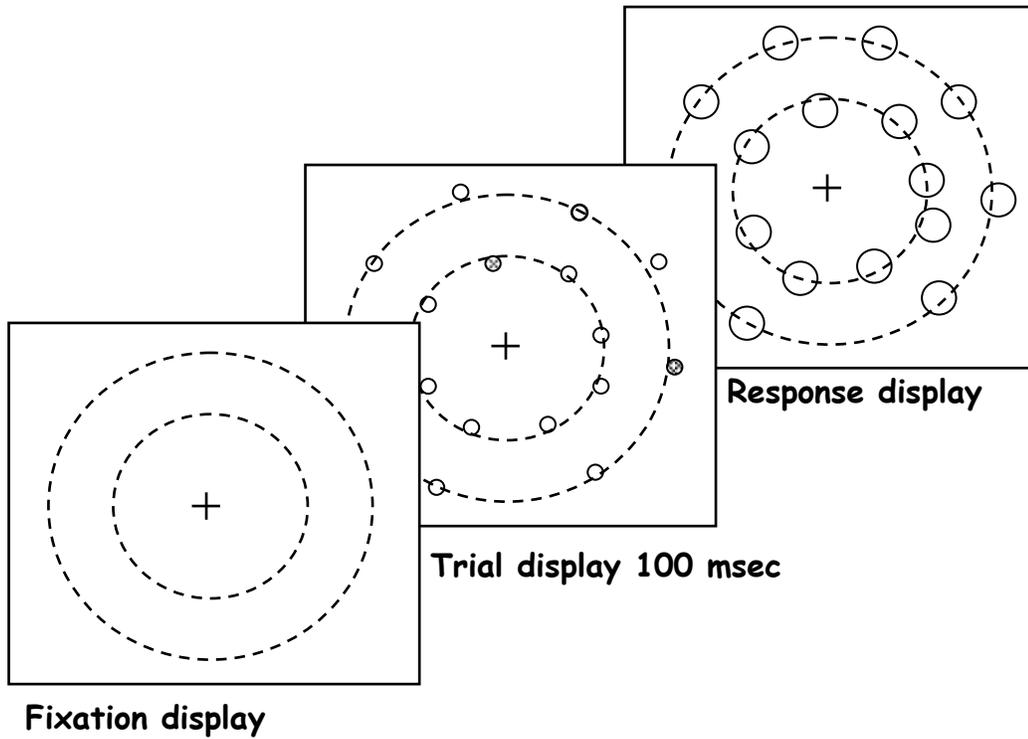


Figure 6. Schematic illustration of the sequence of a color and transient trial.

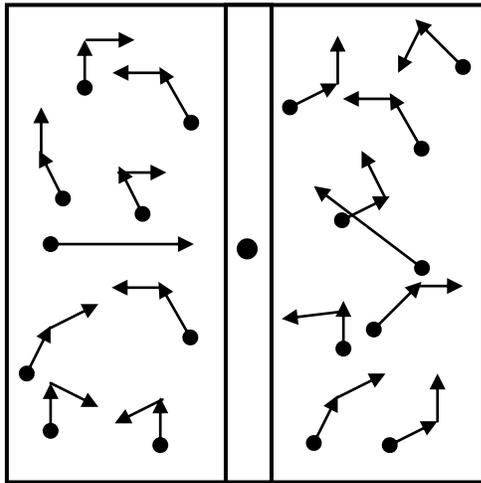


Figure 7. Schematic illustration of stimuli used in the motion experiment (Exp. 3).

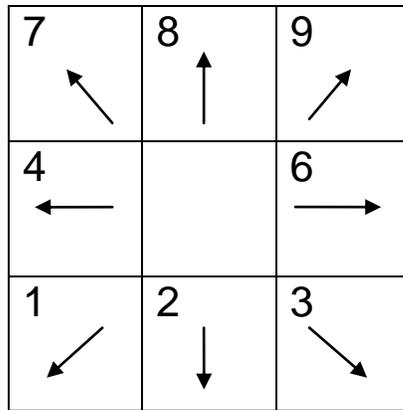


Figure 8. Illustration of the response key layout for the motion experiment (Exp. 3).

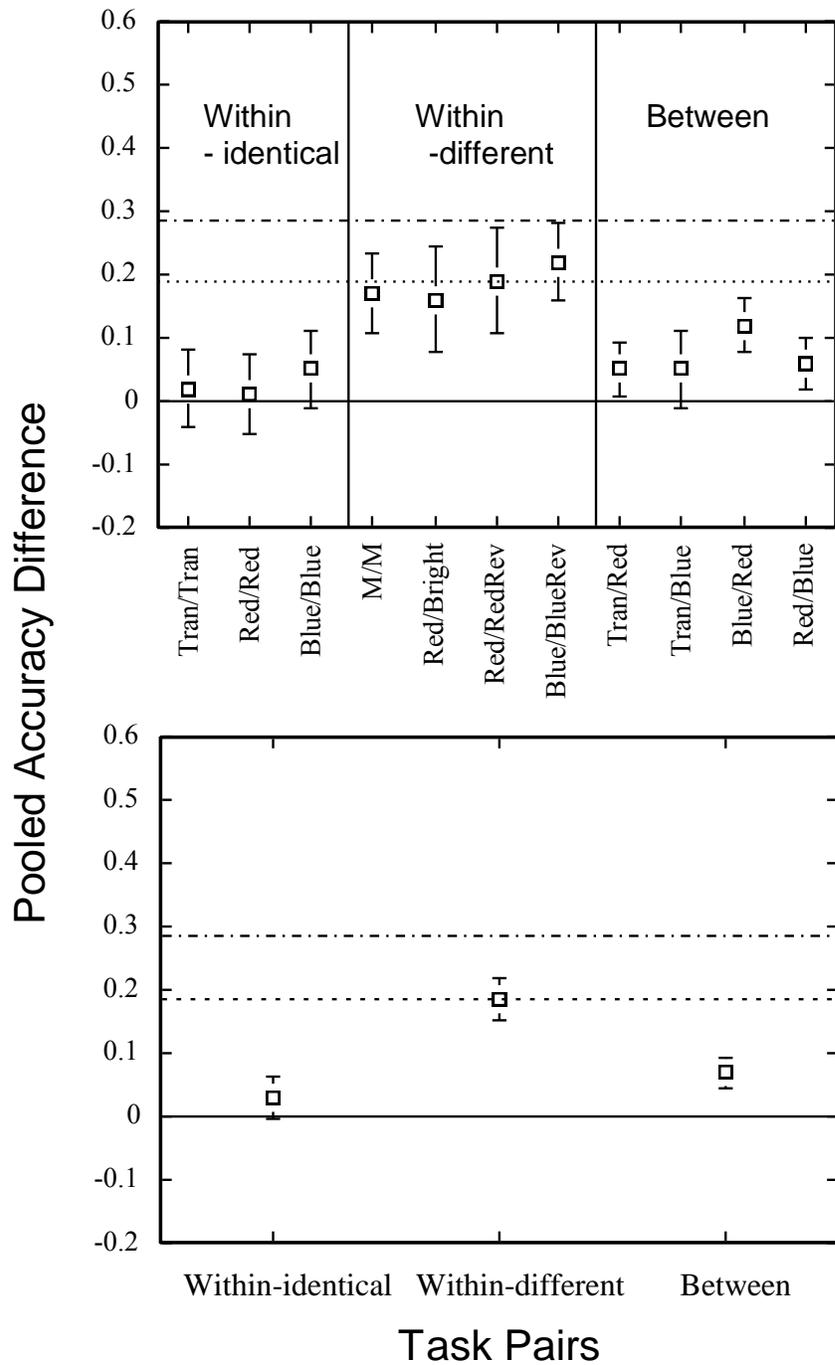


Figure 9. (Top) Dual-task decrement in accuracy between the double-array single-task performance and dual-task performance. Two vertical lines separate the within-identical, the within-different and the between task pairs. Predictions made by the sampling, independence, and switching models are indicated by the three horizontal lines. Error bars represent 95% CI. (Bottom) Dual-task decrement in accuracy pooled across task pairs in the within-identical, the within-different, and the between groups with 95% CI.

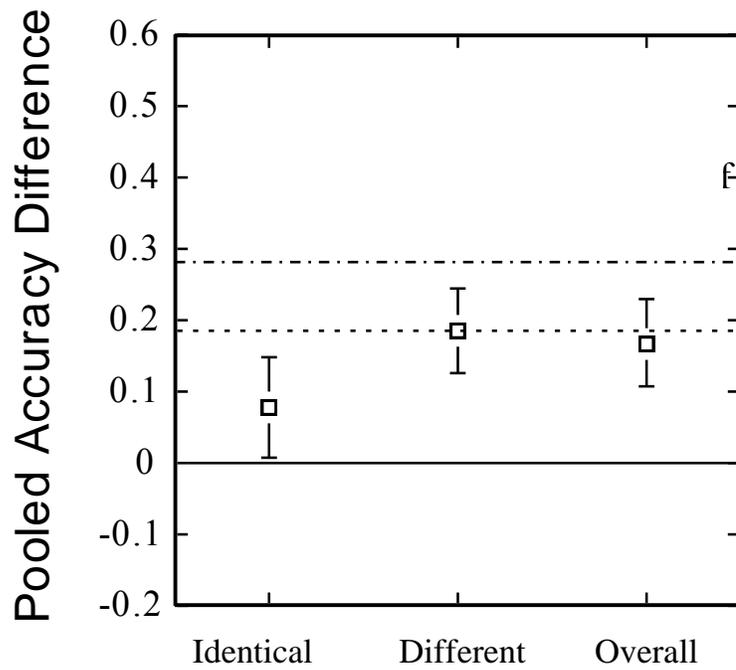
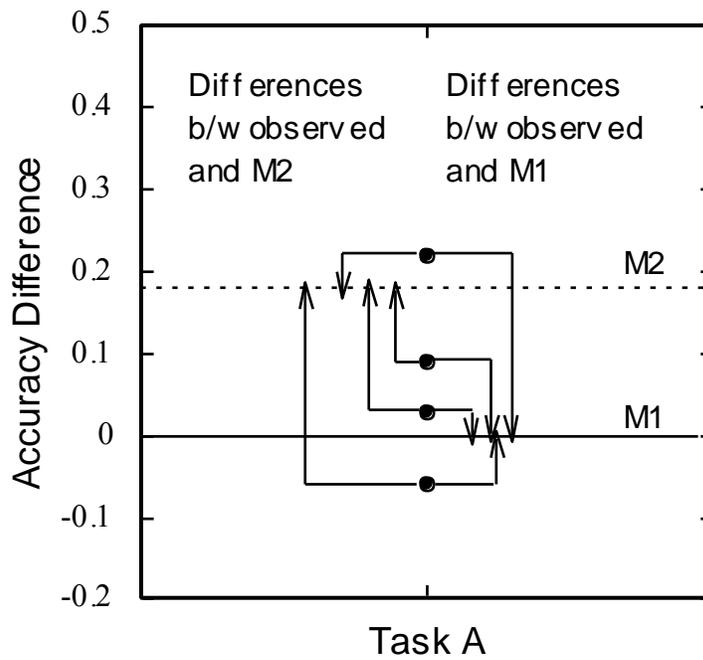


Figure 10  
 Dual-task decrement in accuracy for “identical-trials” in which two trajectories appeared in the same direction, “different-trials” in which two trajectories moved in two different directions, and the overall accuracy difference.



Observed	Predicted M1	Predicted M2	$(Diff\ M1)^2$	$(Diff\ M2)^2$
.09	0	.19	$(.09 - 0)$	$(.09 - .19)$
.03	0	.19	$(.03 - 0)$	$(.03 - .19)$
-.06	0	.19	$(-.06 - 0)$	$(-.06 - .19)$
.22	0	.19	$(.22 - 0)$	$(.22 - .19)$

$$t = \frac{\sum(Diff\ M1)^2 - \sum(Diff\ M2)^2}{SEM}$$

Figure 11.  
Paired T-tests were applied to a pair of models to compare the differences between the observed data and each pair of two models.

Table 2. Model fit comparison.

1. Independence model – Sampling model comparison			
$t = \frac{\sum(Diff\ Independence)^2 - \sum(Diff\ Sampling)^2}{SEM}$	Paired Differences		
	Mean	t	Sig. (2 tailed)
Within-identical	-.025	-3.933	.001
Within-different	.034	5.416	.001
Between	-.01	-2.169	.033
2. Sampling model – Switching model comparison			
$t = \frac{\sum(Diff\ Sampling)^2 - \sum(Diff\ Switching)^2}{SEM}$	Paired Differences		
	Mean	t	Sig. (2 tailed)
Within-different	-.01	-3.282	.001

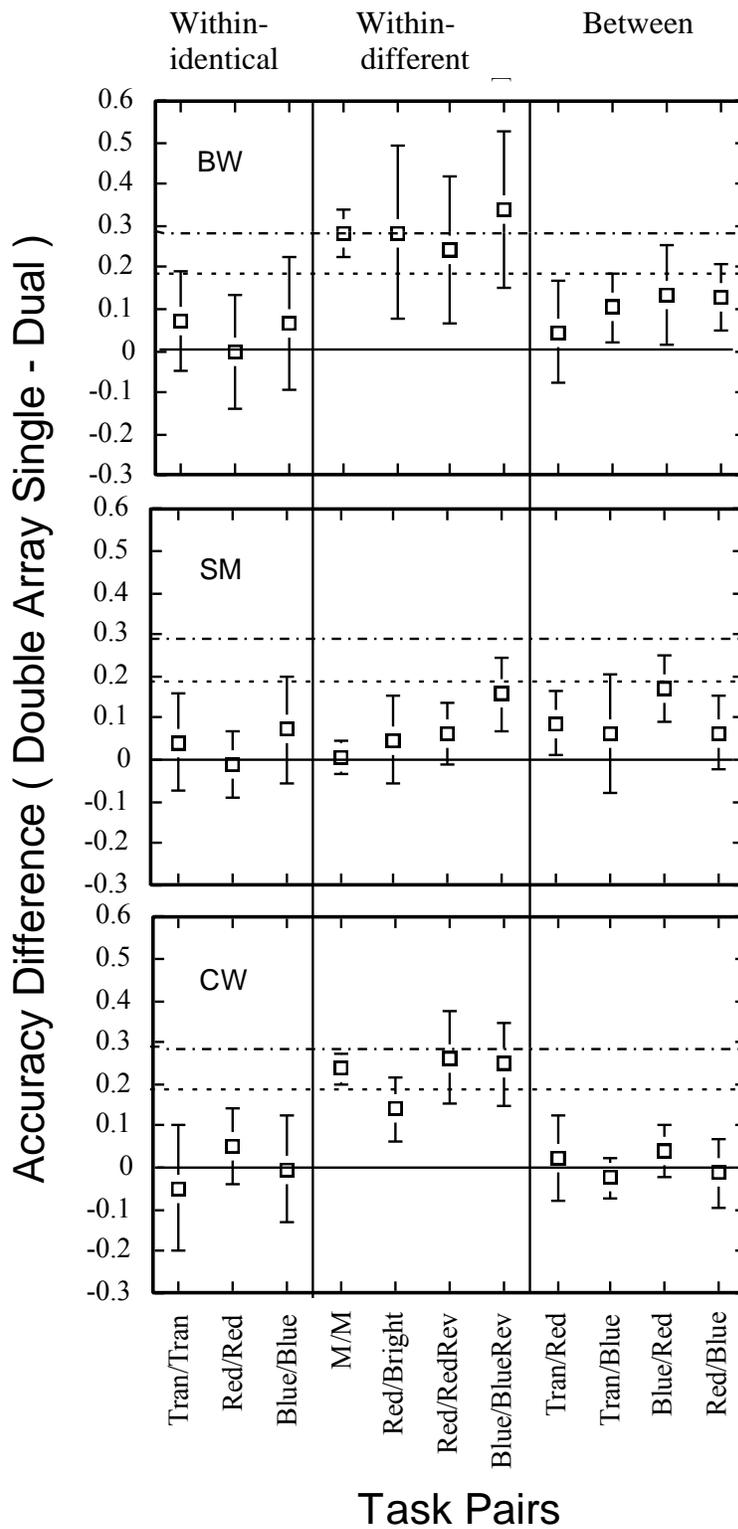


Figure 12.  
Mean accuracy difference between the double-array single-task condition and the dual-task condition for each observer. Error bars represent 95% CI.

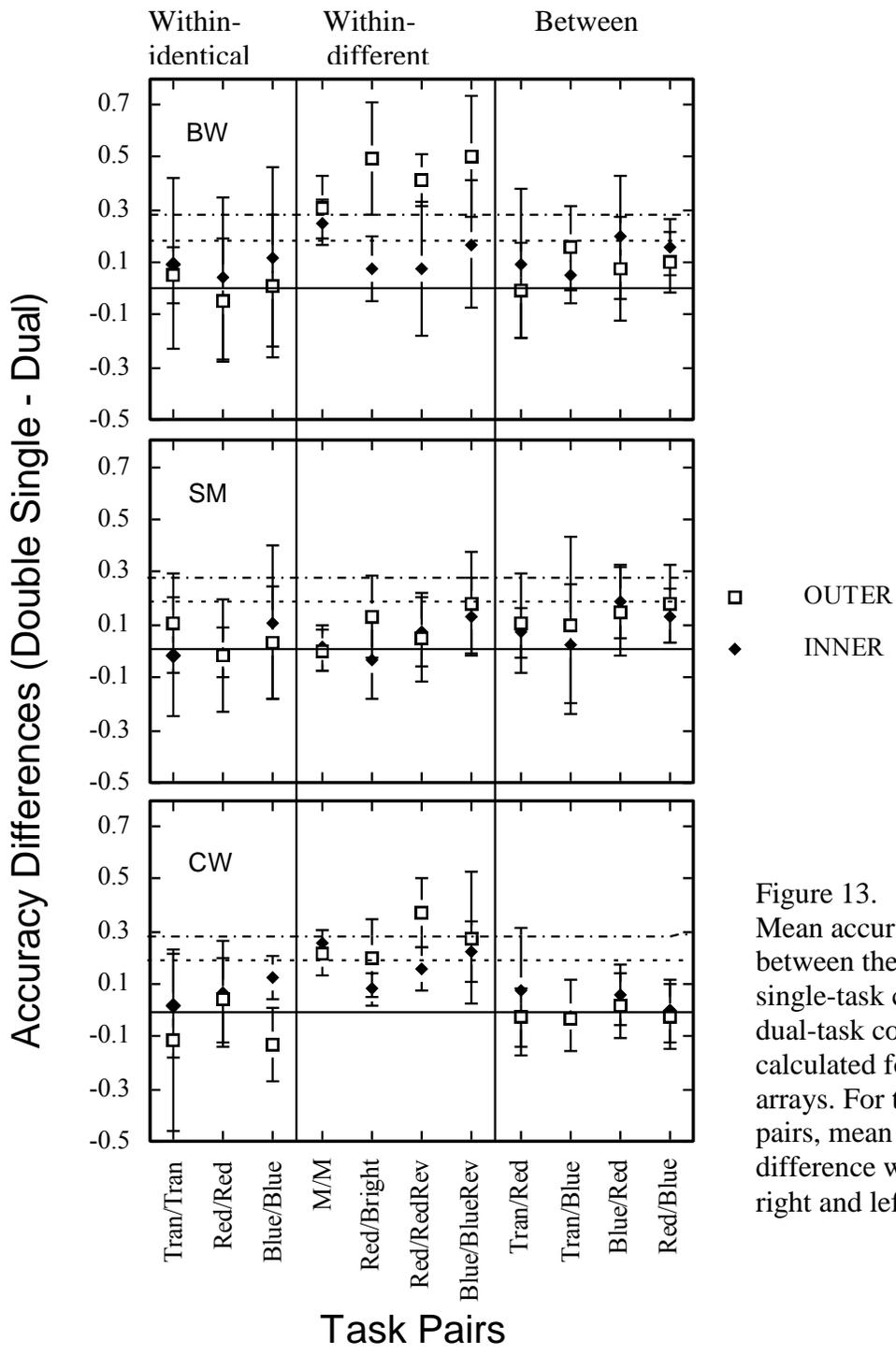


Figure 13. Mean accuracy difference between the double-array single-task conditions and dual-task condition separately calculated for outer and inner arrays. For the M/M task pairs, mean accuracy difference was computed for right and left visual fields.

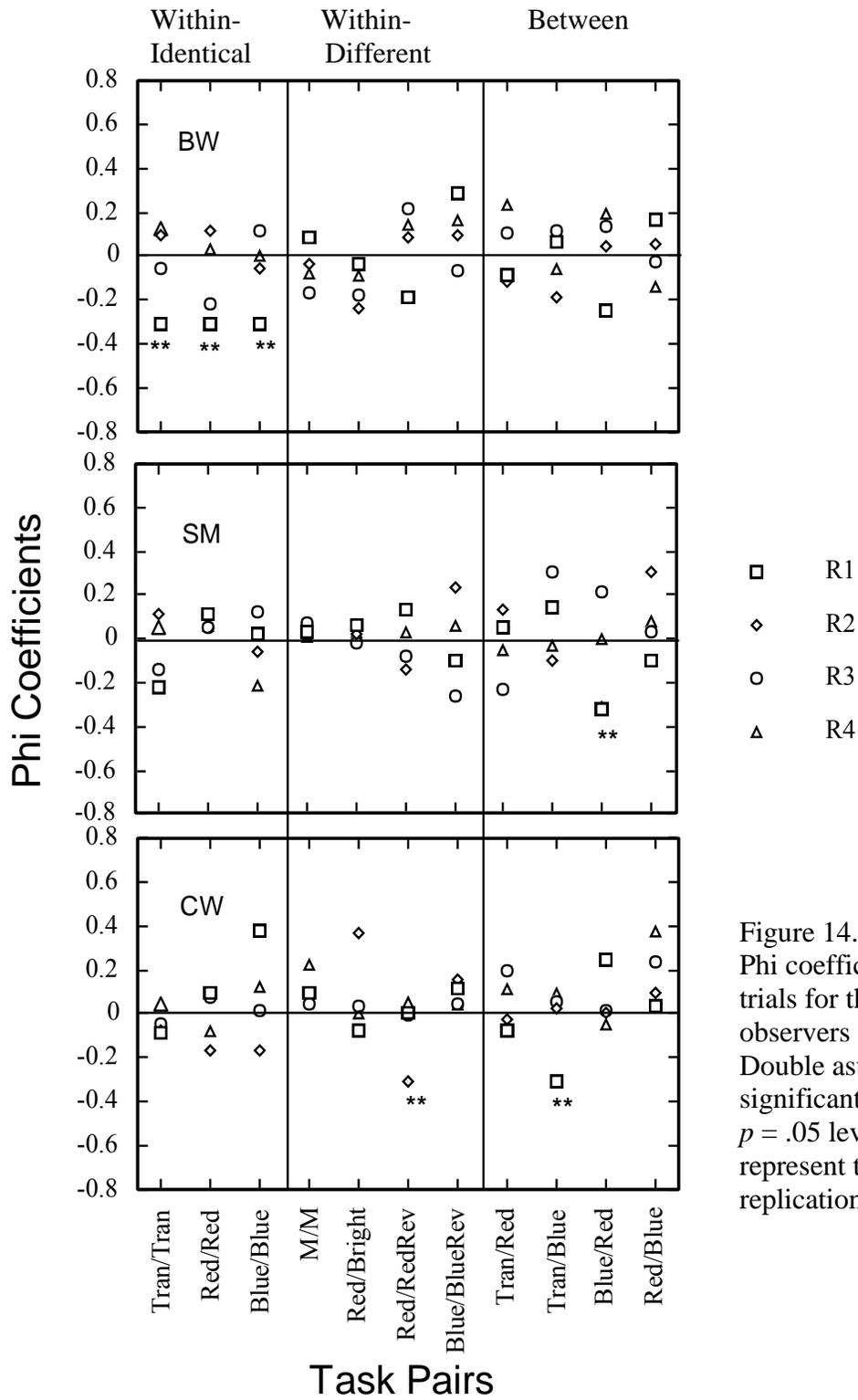


Figure 14. Phi coefficients for all trials for the three observers were plotted. Double asterisks indicate significant coefficients at  $p = .05$  level. Symbols represent the order of replication.

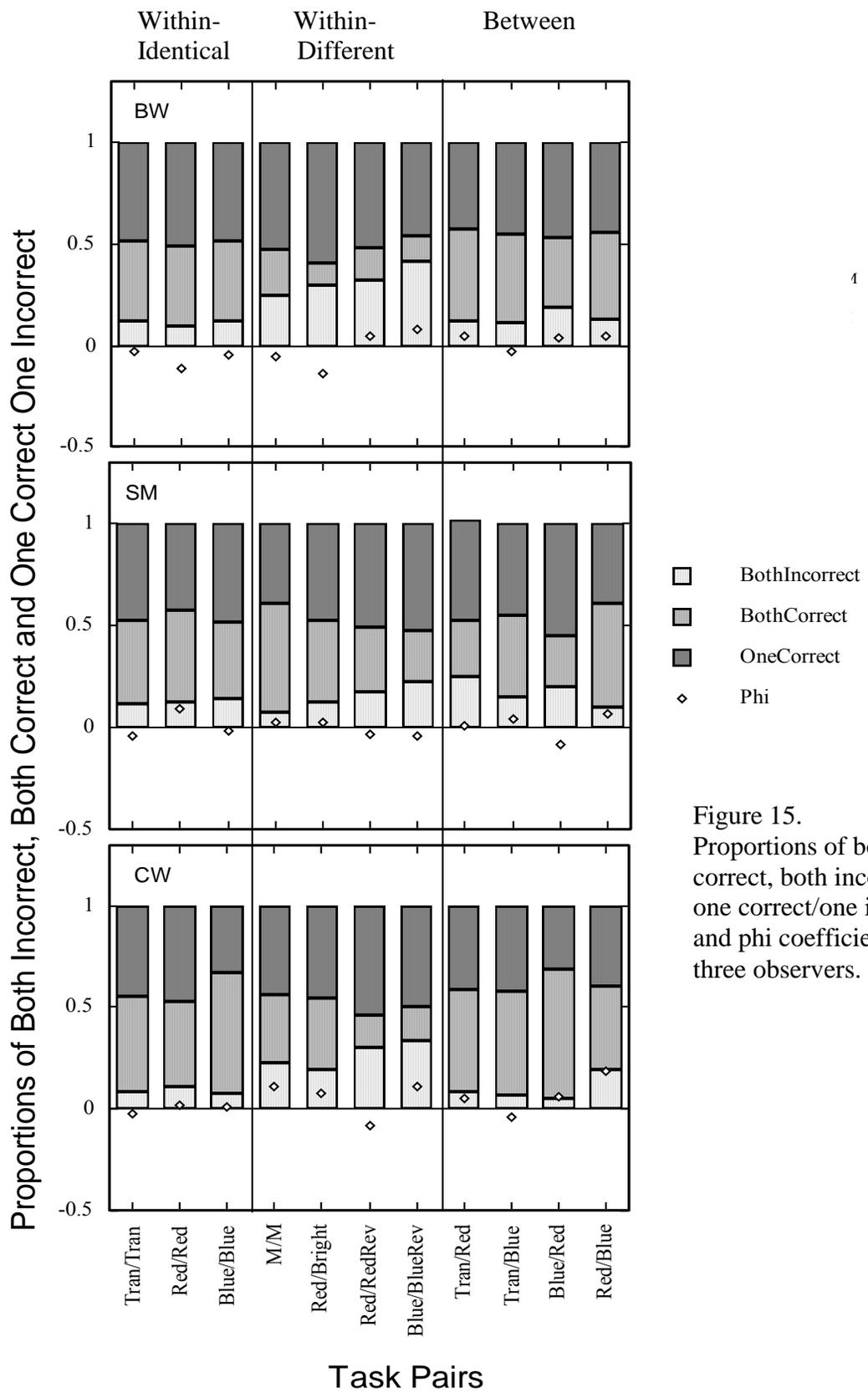


Figure 15. Proportions of both correct, both incorrect and one correct/one incorrect and phi coefficients for the three observers.

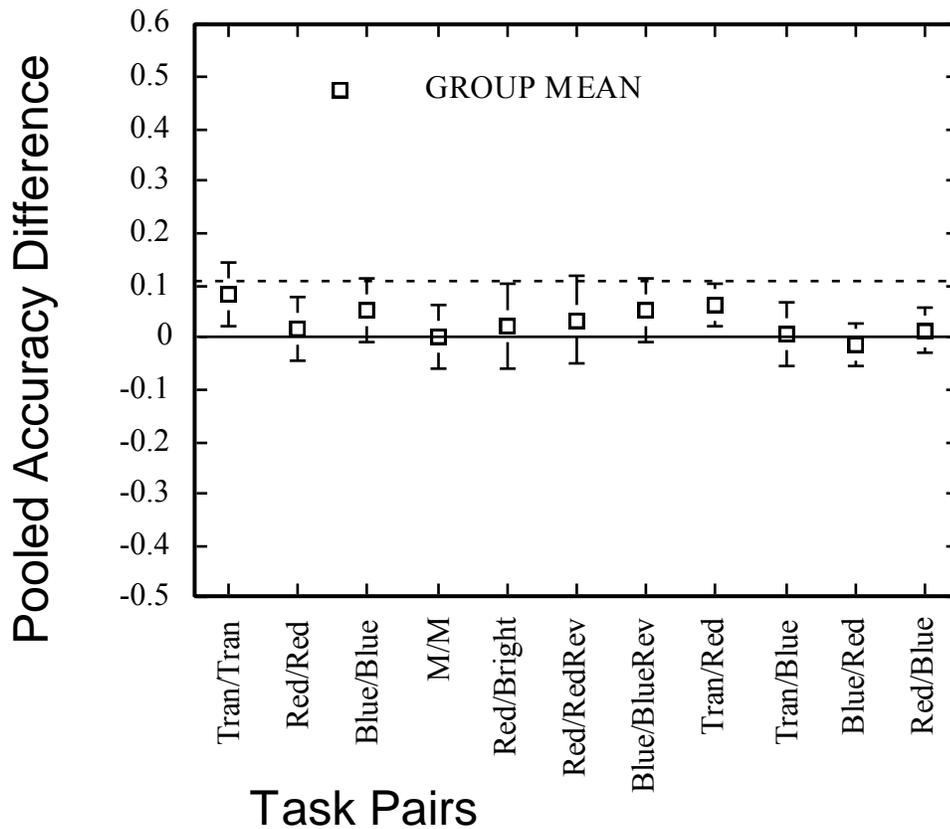


Figure 16. Pooled accuracy difference between the double-array single-task condition and the single-array single-task condition. Error bars represent 95% CI. The dotted line indicate the prediction of the decision model of Palmer et al, (1993). If observers were unable to filter out the irrelevant array of stimuli but attended to all 16 stimuli, the decision model predicts .11 in accuracy difference between the double-and the single-array conditions.

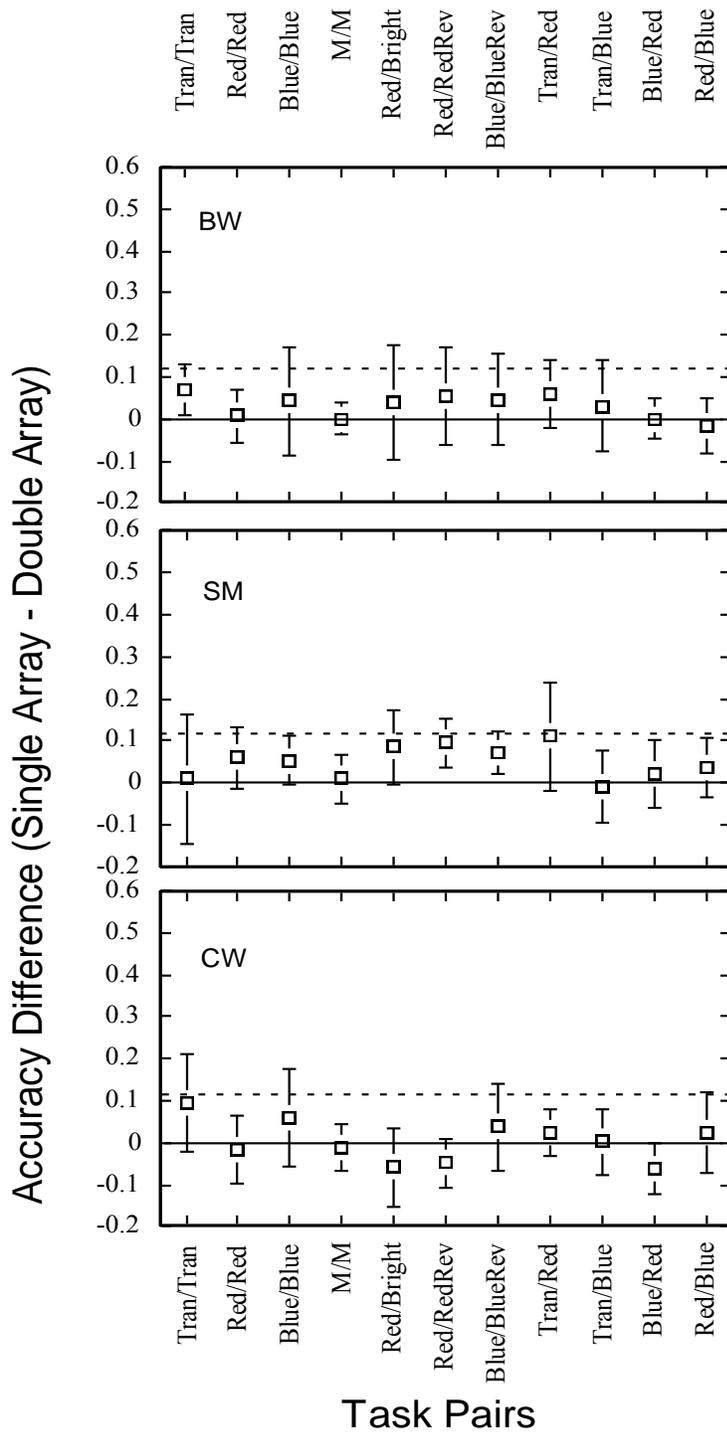


Figure 17. Mean accuracy difference between the double-array single task condition and the single-array single task conditions for each observer. Error bars represent 95% CI. The dotted horizontal line in each figure indicates the prediction of the decision model of Palmer et al. (1993).

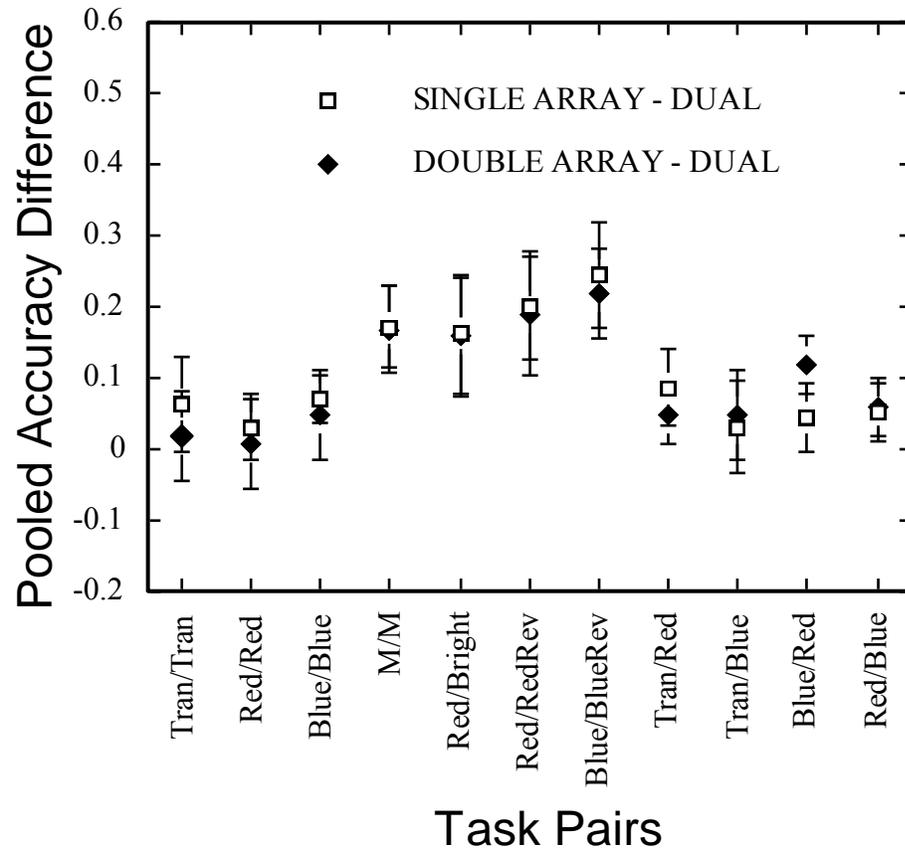


Figure 18.  
 Pooled accuracy difference between the single-array and the double-array single-task conditions and the dual-task conditions.

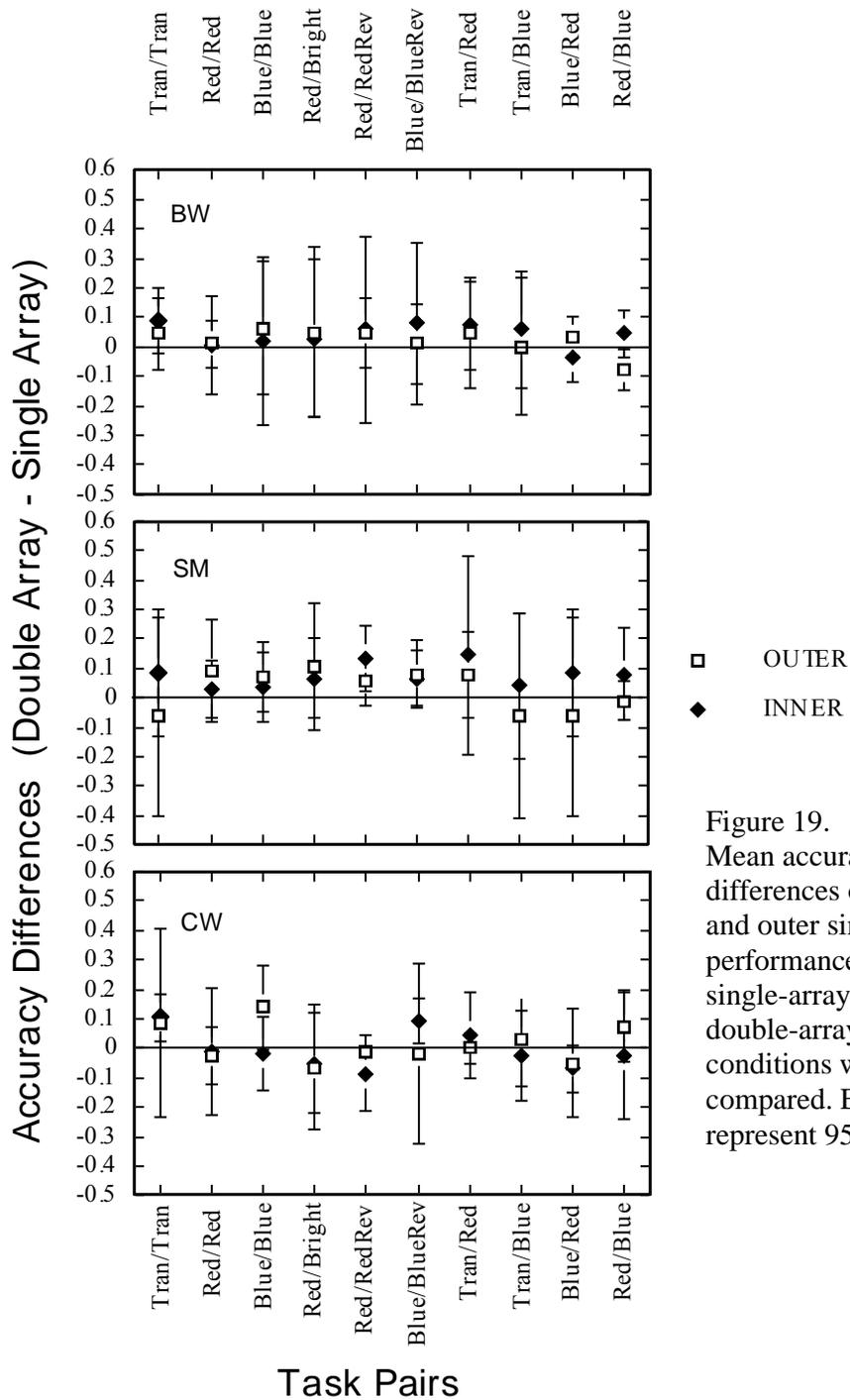


Figure 19. Mean accuracy differences of the inner and outer single-task performance when the single-array and the double-array single-task conditions were compared. Error bars represent 95% CI.

## APPENDIX

.70 in accuracy was used for the single-task performance baseline for all three models.

**The sampling model:** .7 in accuracy in 8AFC corresponds to a d-prime of 1.96 (Hacker & Ratcliff, 1979). The formula  $d'^2_{(\text{task 1})} + d'^2_{(\text{task 2})} = \text{constant}$  creates a perfect circle in the d-prime AOC space. The sin and cos of 45 degree is .7071, which corresponds to dual-task performance for the equal priority instruction.

Thus the dual-task performance is:

$$.7071 * 1.96 = 1.386$$

A d-prime of 1.386 corresponds to .515 in accuracy. Thus the predicted dual-task decrement in performance is:

$$.7 - .515 = .185 \approx .19$$

**The switching model:** A probability of performing at chance was .125 (8AFC). The IC switching model predicts that in a given trial, observers engage in one task with full attention, and perform at a chance level in the other task. The model also predicts that observers will switch tasks across trials to follow the equal priority instruction. This means observers will engage in task 1 with full attention for half of trials in a block:

$$\begin{aligned} \text{Mean task 1 performance} &= .50 * .70 + .50 * .125 \\ &= .4125 \end{aligned}$$

and engage in task 2 with full attention for the other half of trials in a block:

$$\text{Mean task 2 performance} = .50 * .125 + .50 * .70$$

$$= .4125$$

The predicted dual-task decrement in performance for the two tasks is:

$$.7 - .4125 = .2875 \approx .29$$

**The independence model:** The independence model predicts no dual-task decrement in performance in the between group. The model does not apply to the two groups of the within-pathway condition.