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Do Reentrant Processes Facilitate Feature Binding?

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Do Reentrant Processes Facilitate Feature Binding?

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by

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Abstract

This series of five experiments examined whether reentrant pathways in the visual system aid in the binding of visual features. The experiments studied the involvement of reentrant processes in the binding of color, orientation, shape, and motion. Experiments #1 and #2 examined color and orientation. Experiment #1 (N = 24) demonstrated that reentrant processes were necessary only when binding was required, while Experiment #2 (N = 26) showed that reentrant processes were necessary for binding but were also necessary when binding was not required. Experiment #3 (N = 20) and Experiment #4 (N = 21) demonstrated that reentrant processes were used when participants were required to respond to shapes. These data may indicate that binding is always needed when seeing shapes. Experiment #5 (N = 23) examined color and motion, but the results were inconclusive because participants did not perceive motion in the displays used. Together, the findings of these five experiments indicate that reentrant processes always enhanced performance when binding was required but also facilitated performance in some instances when binding of features was not required. Implications of this research and future directions are discussed.

Do Reentrant Processes Facilitate Feature Binding?

Human vision has evolved to facilitate the survival of the human species. Light from the environment is reflected off objects and enters the eye, which in turn causes a cascade of neural activity. This activity ultimately works to dampen, or discard, a large amount of incoming information while simultaneously enhancing some portions of the visual signal with the goal of extracting useful information about objects in the environment. It is now becoming clear that vision is accomplished in the brain via both feed-forward and feedback processes that extract information and form a mental representation. This thesis examines the feed-forward processes and the reentrant processes that aid in the extraction and binding of visual features.

An overview of the relevant literature will be presented first. Features will be defined, and evidence from different experimental designs will be reviewed. The binding of features and possible mechanisms that contribute to binding will be discussed. The experimental paradigm of masking will be examined as a possible way to study feature binding. Then, five experiments will be reported which advance the field's understanding of how feed-forward and reentrant processes work together to achieve visual perception. Finally, implications of this research and future directions will be discussed.

Features

The human visual system is exceptional at working with enormous amounts of information and making sense of them extremely quickly. It manages to process visual input in order to construct a visual representation of the world, recognize objects, and facilitate adaptive behavior. Vision scientists have been working for many decades now on explaining how the visual system processes information, and it seems plausible that it breaks down the input into functional features (Treisman & Gormican, 1988). Features are simple properties reliant on the way information is processed by early, automatic processes (Rensink & Enns, 1995). Some examples of features are orientation, color, texture, luminance, and motion (Rensink & Enns, 1995).

Physiological Studies

Physiological studies support the existence of such basic features. In the brain, visual information is processed in the occipital cortex, and features are formed in the initial stages after the input arrives in the occipital cortex. In V1, the primary receiving area for visual information, lines and edges are extracted (Hubel & Wiesel, 1962). Hubel and Wiesel (1962) showed this in their classic paper on the cat striate cortex. They recorded activity from single cells in a cat's primary visual cortex (V1) while showing the cat stationary or moving objects. The researchers identified individual cells that responded to particular orientations of lines that were shown in particular locations in the visual field.

Color is also a basic feature, and it is processed in multiple areas: retinal ganglion cells (Calkins et al., 1998), the lateral geniculate nucleus in the thalamus (Wiesel & Hubel, 1966), V1 (Motokawa, Taira, & Okuda, 1962), V4 (Zeki, 1980), and V8 (Hadjikhani et al., 1998). Analysis of color input happens at the earliest in retinal ganglion cells (Calkins et al., 1998). Calkins et al. (1998) demonstrate that a particular ganglion cell in the macaque monkey responds to blue and yellow hues, and it is remarkable that color processing happens as early as the retina. The lateral geniculate nucleus of the thalamus also registers color in the rhesus monkey (Wiesel & Hubel, 1966) and so does primary visual cortex V1 (Motokawa et al., 1962). In the macaque monkey, cells in V4 are also sensitive to color (Zeki, 1980), and different cells in V4 have preferences for light in particular wavelength ranges. Interestingly, their peak sensitivities are approximately at the wavelength equivalents of blue, green, or orange-red. A curious finding (Hadjikhani et al., 1998) implicates area V8 for color processing in humans. Hadjikhani et al. (1998) investigate whether the area V4 in humans, the location of which matches the location of V4 in macaques, is sensitive to color. They find that it is not; rather, area V8 responds to color in humans.

Motion is another example of a feature, and it is extracted in V1 (Hubel & Wiesel, 1962) and in the medial temporal (MT) area (Schiller, 1986). Hubel and Wiesel (1962) show that particular cells in V1 are sensitive to continuously moving lines that are shown at a specific angle. The researchers utilize single-cell recordings from the cat’s visual cortex to examine the particular angle and speed of motion to which each cell responds. In addition, motion is processed in MT (Schiller, 1986), also known as V5. Cells in this area are sensitive to specific properties of motion such as directionality, speed, and movement in depth (Maunsell & Van Essen, 1983).

The pioneering physiological research discussed above established the existence of features. Evidence indicates that orientation is processed in V1, color is processed in ganglion cells, the lateral geniculate nucleus, V1, V4, and V8, and motion is processed in V1 and MT. These findings suggest that multiple brain regions are often involved in the extraction of a single feature.

Cognitive Experiments

Numerous experiments provide behavioral evidence for the existence of features, demonstrating their effect on cognition. Many studies incorporate visual search tasks; for example, participants can be asked to find an item with a particular characteristic out of a group of items. Such tasks can be very easy or very difficult depending on multiple factors such as what the target characteristic is, how similar it is to non-targets, and how many items there are in the display. Tasks like these can shed light on how features are involved in visual perception.

An important concept in the search rate approach is the distinction between parallel and serial search (Treisman & Gormican, 1988). In parallel search, the target item ‘pops out’ because its features are salient and easy to perceive. Parallel search does not require each item to be considered separately, so a target can be identified very quickly, almost immediately. In contrast, serial search takes longer than parallel search. Serial search refers to scanning each item individually and deciding whether it possesses the target characteristics. Once the target item is identified, the search ends. On average, serial search takes longer than parallel search because usually in serial search many items need to be scanned before one arrives at the target, while in parallel search the target pops out immediately. In serial search, the time necessary to identify the target increases linearly as the number of distractors increases, while in parallel search, this time remains similar as the number of distractors increases (Treisman & Souther, 1985).

A particular finding about search rates offers strong support for the differences between parallel and serial search (Treisman & Gelade, 1980). The task that yields this finding asks participants whether the target is present among the items in the display, and participants respond ‘yes’ or ‘no’. When participants are asked to indicate whether the target is present among the distractors or not, the time necessary to respond remains similar for a parallel search task as the number of distractors increases. For a serial search task, when the target is present and participants respond ‘yes,’ the time necessary to complete the task increases as the number of distractors increases, and it does so at a particular rate. This rate seems to reflect the time one needs to scan half the items in a display because this is how long, on average, it takes participants to find the target. When the target is not present among the distractors and participants respond ‘no,’ the time necessary to complete the task increases at approximately twice the ‘yes’ rate as the number of distractors increases. This happens because participants need to scan all of the items in a display before they can conclude that the target is not present in comparison with needing to scan half the items on average to find the target when it is present. The fact that the ‘no’ rate is approximately twice the ‘yes’ rate supports the claim that the search took place in a serial self-terminating manner.

Serial and parallel search are directly connected to the idea of a feature map. In order to explain visual perception, Treisman and Gormican (1988) propose that detection of features happens when attention scans a master map of locations in the visual field. The master map encodes the locations of stimuli, and attention can be deployed to determine what characteristics are present at what locations. If the detection of a feature requires serial search, then attention scans each location in the feature map separately until it finds the target characteristics. If a feature’s detection requires parallel search, then the stimulus’s location in the feature map pops out and immediately attracts attention.

To study serial and parallel search, Treisman and Souther (1985) conducted experiments that employed the presence or absence of a characteristic in an object. In some cases, the target possessed a characteristic that the distractors did not possess; for instance, the distractors were all circles, and the target was a circle with a line intersecting it. This makes the target ‘pop out’, so it is very easy to identify, and the time necessary to find it remains similar even as the number of distractors increases. These facts suggest that parallel search is employed when the target possesses a unique characteristic. On the contrary, when the target lacks a characteristic the distractors have, it takes much longer for the target to be identified. An example of this type of task would be if all the distractors are circles with a line intersecting them, while the target is only a circle. Here results indicate that serial search is employed, as the target does not ‘pop out’ and each item needs to be considered individually. Moreover, the time necessary to identify the target increases linearly as the number of distractors increases, which directly points to a serial search. The fact that the presence of a unique feature allows for parallel search, while the absence of a feature requires serial search indicates that there is a difference between these two types of processing. Treisman and Gelade (1980) hypothesize this happens because the presence of a unique characteristic in one item and its absence in all others causes activity in a particular feature map in only one location, which allows for the target to be found immediately. Conversely, when the characteristic is present in all items but one, this brings about a large amount of activity in that feature map, making it harder to locate the place where there is less activity corresponding to the target.

Another finding (Treisman & Gormican, 1988) supports a similar understanding of features. The researchers found that if an item was of average length, size, contrast, or number or if its color or shape were prototypical, serial search was necessary for detection and it took a relatively long time for the target to be identified. On the other hand, when an item possessed more extreme characteristics, such as larger contrast, number, length, or size or a non-standard color or shape, the item was detected more quickly, apparently allowing for parallel search. These findings suggest that regular amounts or standard values of a characteristic bring about an average amount of activity in a feature map, which does not facilitate easy recognition of the target. In contrast, larger amounts or non-standard values of a characteristic elicit more activity in a particular feature map, making it easier for that target to be discovered.

Duncan and Humphreys (1989) used search rate to study how degrees of similarity between targets and distractors affect accuracy. Their results indicate that reaction times were shorter when the target was dissimilar from the distractors, and reaction times were longer when the target was similar to the distractors. This is probably due to the fact that it was harder to differentiate the target when the target was similar to the distractors than when the target was dissimilar to the distractors. For instance, if the target is the letter T tilted at 75° and the distractors are the letter T not tilted, it is easy to identify the target. In contrast, when the target is the letter T tilted at 75° and the distractors are the letter T tilted at 80°, it can be very difficult to discover the target. This pattern of data can be explained by the functioning of features. When the target is dissimilar from the distractors (and the distractors are all the same), the target can be said to possess a unique characteristic, such as a distinctive tilt, that elicits particular activity in the corresponding feature map, making the target easy to identify. If the target is similar to the distractors, it may not elicit activity that is distinctive from the activity elicited by the distractors. This would not allow the target to be discovered quickly.

Another finding by Duncan and Humphreys (1989) was that the task also took a short time when the distractors were similar to each other, and it took more time when the distractors were dissimilar. For example, if the target is a T tilted at 75° and the distractors are Ts with tilts between 10° and 20°, the distractors will probably be similar enough to facilitate easy detection of the target. In contrast, if the target is a T tilted at 75° and the distractors are Ts with tilts that vary between 10° and 100°, the distractors will be so different that it will be very difficult to find the target. This seems logical because when the distractors vary across dimensions, it would be difficult to identify a target that also varies along that dimension; it would be much easier if all the distractors are similar because then the target can ‘pop out.’ This finding can also be explained by the existence of features. When the distractors are similar to each other, they all bring about similar activity in the corresponding feature map, allowing the dissimilar target to cause a different type of activity in the map. If the distractors are dissimilar from each other, they may elicit distinctive types of activity in the feature map, making it harder for the activity elicited by the target to stand out.

An intriguing addition to these studies is the contribution by Treisman and Gelade (1980). The experiments reviewed so far had targets identifiable by a single feature, while Treisman and Gelade (1980) examine what happens when the discovery of a target requires a conjunction of two features. When a target requires the recognition of a single feature, the task is easier than when a conjunction of two features is needed. An example of a task necessitating the recognition of a single feature is when a red X needs to be discovered among some blue X’s. In this case, the time needed to detect the target remains similar as the number of distractors increases. In contrast, when the detection of a target necessitates the conjunction of two features, the task is more difficult. This would be the case if a red X needs to be identified among red O’s and blue X’s. Here the characteristic ‘red’ and the characteristic ‘X’ need to be found together in order to satisfy the requirements for a target. In this case, the time required to detect the target would increase linearly as the number of distractors increases. When the target is present among the distractors, it will be discovered after scanning half the items on average. When the target is not present among the distractors, the time needed will increase at twice that rate because all the items need to be scanned before giving a response. The task is much more difficult when a conjunction of features needs to be detected than when a single feature is needed because activity from two separate feature maps needs to be bound together for the perception of a conjunction of features. When a target is identified by a single characteristic, the activity from one feature map is sufficient, making the task easier.

The experiments reviewed above study cognitive abilities and behavioral performance to illuminate the functioning of features. The presence of a unique feature in a target elicits specific activity in a feature map, making it easy to identify the target (Treisman & Souther, 1985). Similarly, an extreme amount or a non-standard value of a characteristic causes a particular type of activity in the corresponding feature map, which can be differentiated from the rest of the activity (Treisman & Gormican, 1988). This leads to the quick identification of the target. When a target is dissimilar from the distractors, it can be identified easily because of the unique activity it causes in the feature map. When the distractors are dissimilar from each other, they elicit distinctive types of activity in the feature map just as the target does, which makes it harder to detect the particular type of activity elicited by the target (Duncan & Humphreys, 1989). Finally, if the identification of a target requires activity from a single feature map, it is easier to detect the target than if it requires the conjunction of activity from two feature maps (Treisman & Gelade, 1980).

Conclusion on Features

To summarize, features are basic characteristics that are extracted from visual input early in the information processing stream, as illustrated by multiple sources of neurophysiological evidence. Some examples of features are orientation, color, and motion. Behavioral studies demonstrate that the difficulty in detecting stimuli can vary depending on both the target’s and the distractors’ features. Neurophysiological and behavioral research concur that features are essential building blocks of visual perception. Features are some of the first pieces of information to be processed, and they affect visual perception at early stages. The main question that follows the identification of these features is how they are combined to form the representation of an entire object. An object can be characterized by all of these features, so any complete account of visual perception must explain how features are integrated, or bound.

Binding

Binding refers to a perceptual phenomenon when two or more features are combined together to characterize an object. As discussed in the previous section, the visual system detects individual features such as color, orientation, and motion. However, when a person perceives an object, she usually binds the features that are characteristic of it and experiences a unified object (Treisman, 1996). For instance, if one observes an arrow, she perceives its color (e.g., yellow), orientation (e.g., pointing to the left), texture (e.g., smooth), motion (e.g., stationary), and luminance (e.g., bright). These characteristics are bound together to form a unified representation of the object. If the person is asked to identify an object which is yellow and is oriented to the left, she can correctly select the arrow as an example. A conjunction of a specific color and orientation characterizes the object, so that conjunction can be used to correctly identify the object.

Feature-Integration Theory (FIT)

One of the prominent theories of binding, feature-integration theory (FIT), was proposed by Treisman and Gelade (1980). They suggested that when one engages in a visual search task, if the target is specified by a single feature, the person can identify it through parallel search. In contrast, if the target is characterized by a conjunction of features, she needs to engage in serial search to find it. This means that focused attention needs to be allocated to each item separately for the identification of the target. A more thorough explanation of the proposed process (Treisman, 1996) explains that focused attention scans a map of locations where items are present. In this way, one notes that specific features are active at particular locations in the feature map. She binds the features that are active at the same location because they are likely to belong to the same object. FIT maintains that identifying a target by a conjunction of features necessitates focused attention and a serial search.

Treisman and Gelade (1980) discuss an intriguing question about binding: why does a conjunction of features need to be detected by serial search? Cannot it be detected by two parallel searches? This question is particularly fascinating because it ponders what it truly means for two features to be bound together in perception. An example may help illustrate this issue. A person is asked to look for a red X among blue X's and red O's. FIT predicts that a serial search will be necessary to identify the target. Why is it not possible, however, to run a parallel search for all red items, to run another parallel search for all X's, and then find the one item that is both red and an X? Treisman and Gelade (1980) suggest that this cannot be the case because it would require attention to be focused at multiple locations at the same time, which is impossible. If one engages in a parallel search for red and identifies several items, attention is needed to keep active the locations of all the identified items. In addition, one would need to engage in another parallel search for X's, which requires focused attention to keep active the locations of the discovered X's. Paying attention to all the red items and all the X's in order to identify an item which is both red and an X surpasses the limitations of attention. Therefore, it seems unlikely that a conjunction of features can be identified through two parallel searches. Rather, as FIT suggests, a serial search is required.

Psychological Evidence for FIT

Numerous pieces of psychological evidence support the idea that attention is necessary for binding (Treisman, 1996). An experiment by Treisman (1988) specifically showed that attention to a particular location aids with detecting conjunctions of features. A cue directed participants' attention to a particular location before the stimuli were presented. When the cue's location correctly indicated the target's location, accuracy improved remarkably for the detection of conjunctions of features and only slightly for the detection of a single feature. This demonstrates how much more important focused attention is for identifying conjunctions of features than single features. FIT predicts this because it proposes that search for a single feature is already parallel and thus should not benefit greatly from localized attention to the target. On the other hand, search for a conjunction of features is serial, so attention focuses on one item at a time. If attention is directed to the location of the target at the beginning of the search, then the target would be found immediately, making the task substantially easier than it is without a cue.

A study with similar findings was described by Prinzmetal, Presti, and Posner (1986). They presented a cue before the array of items appeared, but it did not predict specifically where the target would be presented. Rather, it predicted the location of a group of four items, one of which would be the target. This intervention also helped the detection of conjunctions more than it helped the detection of single features; however, it did not make the task as dramatically easier as the cue in the previous study did. Treisman (1988) explains that this is due to the fact that the cue in Prinzmetal, Presti, and Posner's (1986) study only predicted the general area in which the target would appear. Serial search was still required among the four items presented in that area, making the task relatively difficult.

Experiments with illusory conjunctions also demonstrate that correct feature binding depends on attention. Treisman and Schmidt (1982) showed that when too little attention is allotted to a stimulus, erroneous binding may occur. For instance, in an array of green T's and orange F's, one may perceive an orange T or a green F if her attention is diverted or overloaded. In this case, the person detects the separate characteristics (green, orange, T, and F) but does not have enough executive resources to bind them to the correct objects (a green T and an orange F). Thus, she cannot correctly report which two characteristics were manifested together, so she makes erroneous conjunctions between features (an orange T or a green F). This evidence suggests that attention is integral to the correct binding of features because without the necessary attention binding errors occur.

According to the psychological evidence presented here, it seems that feature binding depends on attention and is essential to object perception. Studies incorporating cues to a target's location and studies eliciting illusory conjunctions demonstrate that binding relies on attention. These types of experiments also suggest how important feature binding is to the perception of objects: if binding is unsuccessful due to attentional limitations or other factors, objects are not perceived correctly.

Binding and Reentrant Processes

A plausible hypothesis is that feedback processes, also called reentrant processes, are necessary for binding. Tononi, Sporns, and Edelman (1992) explain why reentrant processes may be the solution to the binding problem. The visual cortex is divided into functionally separate areas that somehow yield a unified representation of the world. After visual information is registered by the eye and travels to the brain, low-level areas such as V1 in the occipital cortex perform the first sets of computations to process the data. Afterwards the information travels to middle-level areas such as V4 and MT for further processing, and then it reaches high-level areas such as inferior temporal cortex (IT) where object recognition takes place (Treisman, 1996). These multiple areas of the visual cortex are functionally separate from each other, but they all contribute to visual perception. There does not seem to be a central executive brain area which receives and puts together information from all of them (Tononi, Sporns, & Edelman, 1992); nevertheless, most humans experience unified objects with integrated features. It is unclear how separate brain areas achieve such unification of information, but it is possible that this happens through communication via feedback connections among areas.

Feed-forward and feedback processes seem to be essential for visual perception and may allow for binding. Via feed-forward processes, visual input travels from low-level areas such as V1 to high-level areas such as IT (Tononi, Sporns, & Edelman, 1992). Once high-level areas have achieved some object recognition and have identified some important aspects of that object, feedback processes direct perception to more specific characteristics of the object. To do this, information travels from high-level areas to low-level areas, so specific properties of interest can be perceived in more detail (Tononi, Sporns, & Edelman, 1992). These forward and backward sweeps may underlie binding (Treisman, 1996). Via feed-forward processes, features such as color, orientation, and motion can be detected in low-level areas; then, high-level areas note which features belong to the same object. Afterwards, information from high-level areas flows back to low-level areas to dictate which features need to be bound together in an object. Thus, feedback processes, or reentrant processes, may be the mechanism for binding.

An important objection to the neuroscientific basis of this view is raised by Di Lollo (2012a). He maintains that binding of information among separate brain regions is actually not necessary because the same brain regions extract multiple features. For instance, area V1 codes for orientation (Hubel & Wiesel, 1962), color (Motokawa et al., 1962), and motion (Hubel &

Wiesel, 1962). Specifically, many of the neurons sensitive to color in V1 are also sensitive to orientation (Friedman, Zhou, & von der Heydt, 2003). Similarly, neurons in V2 sensitive to color are also sensitive to directionality of motion and size (Gegenfurtner, Kiper, & Fenstemaker, 1996). In area V4 there are neurons that respond to both color and shape (Mandelli & Kiper, 2005). The fact that regions in the brain considered to be modular actually code for multiple features suggests that multiple features are bound together as they are being extracted.

Di Lollo (2012a) concludes that the binding problem is ill-posed because features are bound as they are being perceived and are integrated into object representations via feedback processes. Wolfe (2012) disagrees and points out that the binding problem is well-posed because selective attention is required to bind features. Di Lollo (2012b), however, disagrees with this proposed mechanism for feature integration. Whereas Wolfe (2012) proposes that attention binds features, Di Lollo (2012a) suggests that features are bound as they are being perceived, and feedback processes integrate these features into object representations. Wolfe (2012) and Di Lollo (2012a; 2012b) agree that features are bound in visual perception, but they disagree about the mechanism that achieves binding.

Conclusion on Binding

In conclusion, the visual system detects separate features such as color, orientation, motion, texture, and luminance, but people tend to experience the world as a unified blend of all these features. This means that features are probably bound at some point in visual processing. FIT (Treisman & Gelade, 1980) proposes that the binding of features together to represent an object requires attention, and numerous sources of evidence support this idea (Treisman, 1996). A fascinating question is how the brain accomplishes binding, and Tononi, Sporns, and Edelman

(1992) suggest reentrant processes are responsible for that. They hypothesize that feed-forward processes allow for the perception of separate features, while feedback processes bind different features that belong to a single object. Di Lollo (2012a) disagrees and maintains that features are bound while they are being processed in low-level brain areas. Then, he suggests, feedback processes integrate these features into object representations. How binding works and what the function of feedback processes is are questions open to debate that require further inquiry.

Masking

Reentrant processes can be studied experimentally with a task that implements object substitution masking. In order to explain how this can be done, a brief overview of masking paradigms and specifically the object substitution paradigm will be presented here.

A masking paradigm refers to an experimental design in which an object (the target) is presented and then disrupted by a subsequently presented object (the mask) (Enns & Di Lollo, 2000). The mask interferes with the perception of the target because the two are presented in spatial and/or temporal proximity. Experiments can vary how close to the target's location a mask is presented and how long after the target's disappearance the mask is presented. Such alterations affect participants' accuracy in recognizing the target, and the results shed light on how visual perception works (Enns & Di Lollo, 2000).

In the masking literature, two types of masks are often distinguished: the pattern mask and the metacontrast mask (Enns & Di Lollo, 2000). A pattern mask is a visual display that is presented in the same location where the target was presented. For example, if the target is a circle and the mask consists of three X's next to each other, the circle is presented first and is followed by the three X's in the same location where the circle was just shown. Therefore, the contours of the pattern mask are spatially superimposed on the contours of the target. On the other hand, a metacontrast mask surrounds the location of the target. If the target is a small circle and the mask is a larger circle (the shape is not filled but is just an outline), the small circle is presented first and is followed by the large circle. The large one does not overlap with the small one but rather surrounds it, so the contours of the metacontrast mask do not overlap with the contours of the target.

The standard views about how these masks function assume the processes that encode the target are interrupted by the mask. For pattern masking, it is important that the target and the mask overlap. Two types of methods are believed to interfere with the correct perception of the target (Scheerer, 1973). If the mask is presented less than 100 ms after the target, it is proposed that the contours of the target and the mask are integrated into a single object. If the mask is presented more than 100 ms after the target, then the mask interrupts the processing of the target, which results in the incomplete perception of the target.

For metacontrast masking, the contours of the target and the mask do not overlap, so the proposed explanations of pattern masking cannot be applied. Rather, researchers maintain (Weisstein, Ozog, & Szoc, 1975) that first when an object appears, a fast signal in the brain notes it and then ongoing activity processes the stimulus. When the target is presented, a fast signal occurs and then sustained activity begins to encode the target’s features. When the metacontrast mask is presented, the fast signal noting its appearance interrupts the processing of the target, which leads to the target’s incorrect perception. For metacontrast masking to be effective, the mask must follow the target, and the timing is critical (Enns & Di Lollo, 2000). When the interval between the presentation of the target and the presentation of the mask is either very short or very long, almost no masking occurs. When the interval is of intermediate length, perception of the target is impaired. In addition, the visual angle between the mask contours and the target contours is critical: if the distance between the target and the mask increases by less than one degree, masking effects are reduced remarkably (Enns & Di Lollo, 2000).

Object Substitution Masking

Another mask, the object substitution mask, reveals different mechanisms in visual perception. Enns and Di Lollo (1997) describe this mask as consisting of four dots surrounding the target. When the target appears in a display, it is surrounded by the four dots, and the four dots remain on the screen after the target disappears. This mask has the capacity to interfere with the target perception. The four-dot mask is similar to a metacontrast mask as the contours of the dots do not overlap with the target. The four-dot mask is different, however, in the respect that the four dots do not constitute a continuous contour surrounding the target as a metacontrast mask does. In addition, the visual angle between the mask contours and the target contours is critical for the metacontrast mask but not for the four-dot mask (Enns & Di Lollo, 2000). The longer the object substitution mask remains on the screen after the target, the more the mask interferes with target processing.

Another notable difference between these two masks is that the effectiveness of the four-dot mask is highly dependent on attention, while the effectiveness of the metacontrast mask is not (Enns & Di Lollo, 1997). In one of the first experiments investigating object substitution masking, participants were presented with displays of stimuli and were asked to correctly recognize the stimulus surrounded by four dots. The target was always centrally displayed on the screen. Sometimes the target was the only stimulus in the display, and sometimes there were three stimuli in total. When the target was the only stimulus, the four-dot mask had a small effect. Interestingly, when there were three stimuli, accuracy was drastically reduced even though the target was centrally located. In comparison, when the same task employed a metacontrast mask, accuracy was equally reduced for one as well as three stimuli. When a display only contains one object, attention is automatically drawn to that stimulus, but when a display contains three objects, attention cannot be allocated simultaneously to all of them (Enns & Di Lollo, 1997). These findings indicate that attention is not important with the metacontrast mask, but attention is critical with the four-dot mask.

Since the object substitution mask was discovered, it has been believed to only impair performance when sufficient attention could not be devoted to a stimulus (Enns & Di Lollo, 1997). A study by Argyropoulos, Gellatly, Pilling, and Carter (2013) demonstrated, however, that this might not be the case. In previous experiments, it had been inferred that the effect of the object substitution mask was marked by an interaction between the mask duration and the number of stimuli in a display. However, Argyropoulos et al. (2013) argue that this interaction is due to a ceiling effect. Thus, they call into question whether the object substitution mask’s effect on perception actually relies on attention.

Reentrant Processes and Object Substitution Masking

As discussed earlier, theories about the functioning of pattern and metacontrast masks maintain that the process of encoding a target’s features is interrupted in some way by the mask, and this results in decreased accuracy in recognizing the target. Notably, these explanations rely on feed-forward processes in the brain: the mask interferes with the feed-forward processes which encode the target’s characteristics. The theory behind object substitution masking proposes different underlying mechanisms. Di Lollo & Enns (2000) maintain that both feed-forward and feedback processes contribute to visual perception, and this is exemplified by the behavioral results of tasks with the four-dot mask.

Di Lollo and Enns (2000) describe visual perception as a phenomenon reliant on feed-forward processes as well as reentrant, or feedback, exchanges among multiple brain regions. When visual input enters the system, it first enters low-level areas where features are extracted and then travels to high-level areas for more complex analysis and object recognition. Once object representations have been activated by high-level areas, these representations need to be confirmed by information from low-level areas. These cycles of comparison and confirmation necessitate feedback processing. Di Lollo and Enns (2000) maintain that such a cycle of feed-forward and feedback processing compares and updates the object representation in high-level areas based on the information available in low-level areas. If the information in low-level areas has not changed and matches the representation in high-level areas, then the object representation is retained. If the information has changed, however, then the representation is updated with the newly available input.

Di Lollo and Enns (2000) hypothesize that this mechanism allows a four-dot mask to interfere with the perception of a target. First, the four-dot mask and the target appear together, and a feed-forward process encodes them. The simultaneous onset of the target and the four dots is critical. An object representation is formed in high-level areas, and feedback processes compare that representation to the input available at low levels. However, when the target disappears, only the four-dot mask remains, so the feedback processes supplant the target information with information about the mask. Since the newly available information only contains the four-dot mask, the object representation is updated, and the target is not processed fully. Thus, the target cannot be correctly recognized.

In accordance with the proposed mechanism underlying the four-dot mask, Lleras and Moore (2003) presented evidence that the four-dot mask and the target are perceived as one object. When the target and the mask were related and thus perceived as the same object, performance was impaired; when the two were perceived as separate, performance was not impaired. In order for the target and the mask to be perceived as related, Lleras and Moore (2003) presented them in such a way that motion was perceived: when the time interval between the target presentation and the mask presentation was short, motion between the two was perceived. This apparent motion caused the target and the mask to be perceived as one object. According to Lleras and Moore (2003), the fact that the target and the mask were perceived as one object was crucial to the impairment of target perception observed in object substitution masking.

Conclusion on Masking

To conclude, masking paradigms can be quite useful in helping researchers better understand the processes involved in visual perception. Pattern masks and metacontrast masks are understood to interfere with object recognition by interrupting feed-forward processes in the visual system. On the other hand, object substitution masking is considered to interfere with object recognition via feedback processes, which happens when the target and the mask have simultaneous onset. Di Lollo and Enns (2000) propose that the four-dot mask leads to incorrect visual perception by updating the object representation before the target has been fully processed. This theory states that feedback processes compare the object representation in high-level areas with the altered input available in low-level areas. Then, feedback processes update the representation, making the target inaccessible for further processing. Di Lollo and Enns (2000) demonstrate that the four-dot mask relies on reentrant processes. Because feature binding may also rely on reentrant processes, a paradigm employing the four-dot mask can be used to study feature binding.

Studying Feature Binding and Reentrant Processes

Bouvier and Treisman (2010)

Bouvier and Treisman (2010) offer an insightful experimental design to study how reentrant processes are involved in feature binding. They used a four-dot mask in their behavioral task in order to determine if reentrant processes are involved in feature binding. Bouvier and Treisman (2010) hypothesized that when binding is needed, reentrant processes will facilitate performance. It is important to note that they did not make predictions about the involvement of reentrant processes when binding is not needed.

In their task, Bouvier and Treisman (2010) showed participants different variations of two crossed bars (see Figure 1). Bouvier and Treisman (2010) used a 3x2x2 design that manipulated the type of judgment (color or orientation), the number of bars (one or two), and the type of mask (simultaneous offset mask, delayed offset mask, or pattern mask). Six stimuli were presented in the display for each trial, and each stimulus was composed of bars of different colors and orientations. The target stimulus was always surrounded by four dots.

Participants were asked to make color judgments and orientation judgments. Stimuli contained a non-white bar (red, blue, or green) and a white bar. When two bars were shown, they always crossed, so one bar was horizontal and the other was vertical. When participants were asked to identify the color of the non-white bar (red, blue, or green), they did not need to employ feature binding. They could determine what the color was through a scan of active features in the color feature map, which only required the detection of a single feature, color. Since the color judgment did not require binding, it was not expected to require reentrant processes. When participants were asked, however, to identify the orientation of the non-white bar (vertical or horizontal), they needed to employ binding when two bars were crossed. They had to first find the non-white bar by scanning the color feature map, and then they had to match that with the appropriate orientation for that bar from the orientation feature map. This required the detection of two features, color and orientation, and the integration of those two features in one object. Thus, when two bars were crossed, the orientation judgment required binding, and as such it was predicted that reentrant processes would be needed to help achieve feature binding.

Stimuli could be composed of either one or two bars. A colored bar was always present, and it could be presented by itself or with a white bar. When only one bar was presented it was always the non-white bar. Since only one orientation and one color were perceived, feature binding was never required. In contrast, when a stimulus consisted of two bars, binding was necessary when participants were required to make orientation judgments. When a white bar was crossed with a colored bar, participants perceived two orientations along with the color information. In order to determine which orientation belonged to the non-white bar, participants needed to bind color and orientation.

Bouvier and Treisman (2010) also manipulated the type of mask such that the four dots could disappear at the same time as the stimulus (simultaneous offset mask), the four dots could remain on the screen after the stimulus had disappeared (delayed offset mask), or a colored grid could appear on the screen after the stimulus (pattern mask). The three types of masks affected participants' performance in different ways.

For the simultaneous offset condition, accuracy was high regardless of whether the task required binding. This was the case because the four dots disappeared at the same time as the stimulus, so no masking occurred. Thus, it was assumed that reentrant processes functioned normally to achieve feature binding. This condition was used as the baseline for comparison with delayed offset.

For the delayed offset condition, accuracy was decreased when binding was required. Bouvier and Treisman (2010) explained why such performance might have resulted. The delayed offset mask allowed the first pass of feed-forward processes to correctly encode the target's features. However, because the target object disappeared and the mask remained on the screen, reentrant processes supplanted the target information with information about the masking dots. This impaired performance when reentrant processes were necessary for visual processing of the target. Bouvier and Treisman's (2010) results showed that the delayed offset condition impaired performance when binding was necessary, which suggested that reentrant processes were used in the binding of features.

For the pattern mask, accuracy was decreased for all tasks, regardless of whether reentrant processes were required or not. The pattern mask interfered with perception more profoundly than the delayed offset mask because the pattern mask was presented in the same location where the stimulus was presented, while the delayed offset mask surrounded the stimulus. The pattern mask did not allow feed-forward processes to correctly encode features. This was why participants could not carry out tasks that required the perception of a single feature, and they also could not carry out tasks that required the binding of features.

To summarize, Bouvier and Treisman (2010) conducted an experiment which tested whether reentrant processes are required for feature binding. They manipulated three variables: type of judgment (color or orientation), number of bars (one or two), and type of mask (simultaneous offset, delayed offset, or pattern mask). These distinct conditions presented unique opportunities to interfere with perception at different points in the visual processing stream in order to determine whether reentrant processes are necessary for feature binding. This experimental design allows for a well-controlled study of feature binding; therefore, it would be helpful to use this methodology in other experiments in order to study feature binding more fully.

Overview of Experiments Conducted for This Thesis

Bouvier and Treisman’s (2010) study demonstrated that reentrant processes facilitated feature binding when color judgments did not require binding regardless of bar number and when orientation judgments required binding in two-bar cases. Reentrant processes facilitated binding in this specific situation, but it should be examined whether this is also true for other situations and other features. Thus, this thesis adapted Bouvier and Treisman’s (2010) design to study the role of reentrant processes in multiple other situations and features. A series of five experiments was conducted. The first experiment attempted to replicate Bouvier and Treisman’s (2010) methods and findings. The second experiment used the same design, but the task was changed in a manner where orientation judgments did not require binding but color judgments did require binding. The third and the fourth experiments studied color and shape and shape and orientation, respectively. Finally, the fifth experiment examined color and motion. These five experiments studied color, orientation, shape, and motion and switched around which features required binding and which ones did not.

Experiment #1

The goal of the first experiment was to determine whether Bouvier and Treisman’s (2010) findings were replicable. The experiment used the same design as in Bouvier and Treisman (2010). Thus, it was hypothesized that the delayed offset condition would significantly decrease performance for the orientation judgment in two-bar cases. In the color judgment task, binding was not required. Binding was required, however, when an orientation judgment was needed and two bars were crossed. Participants were asked to report the color and orientation of a non-white bar. Three masking types were used, namely simultaneous offset mask, delayed offset mask, and pattern mask. These allowed for different amounts of visual processing of the target stimulus, which could elucidate the related function of reentrant processes. The presence and absence of a white bar were used to differentiate between trials when binding was needed and trials when binding was not needed. It was hypothesized that reentrant processes would not be necessary for color judgments but would be necessary for orientation judgments when two bars crossed; thus, the delayed offset mask would more dramatically affect performance in the latter situation than in the former one.

Method

Participants. Twenty-four participants completed the study. All were college students attending Bates College. All had normal or corrected-to-normal vision.

Materials. The program E-Prime (Version 2.0) was used to present stimuli and record responses (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The monitors that ran the experiment had a resolution of 1024 x 768 pixels.

Participants viewed objects composed of one or two bars. The stimuli are presented in the Appendix. When two bars were presented, one bar was horizontal, and the other was vertical. When only one bar was presented, it could be either horizontal or vertical. A bar could be white, red, blue, or green. When two bars were presented, one was always white, and the other was red, blue, or green. The target appeared in one of six locations on the screen, and all of the other locations contained distracting stimuli. In order to indicate which one the target was, four dots surrounded the target stimulus.

Responses were provided by pressing keys on a standard keyboard. Participants pressed ‘r’ for red, ‘g’ for green, and ‘b’ for blue, and they pressed ‘1’ for horizontal and ‘2’ for vertical.

Procedure. First, participants received instructions about the task and completed 20 practice trials. Then, participants completed 600 trials (there were 620 trials in total). Participants took a brief, self-paced break every 100 trials.

Stimuli were presented against a black background. Each trial began with a fixation: a white circle was presented in the center of the screen for 1000 ms, and participants were instructed to fixate on it. Then, the array of six objects was presented for 75 ms, and the target item was surrounded by four dots (see Figure 1). Stimuli were randomly selected and arranged in the display. Afterwards, a randomly selected mask was presented. In the simultaneous offset condition, a 300 ms blank display followed the stimulus array. In the delayed offset condition, the dots remained on the screen following stimulus offset for 300 ms. In the pattern mask condition, a colored grid was displayed in the location of the target and the four dots for 300 ms. Following this, participants were prompted for a color response and then for an orientation response. The color and orientation prompts remained on the screen until a response was provided. After responses were made, a blank screen was presented for 1000 ms and served as an intertrial interval. Accuracy data were recorded.

Results and Discussion

Accuracy rates are displayed in Figure 2. A 3x2x2 ANOVA was conducted to compare the effects of judgment type, number of bars, and mask type on accuracy. The critical finding was that the three-way interaction was significant, $F(2, 46) = 19.28$, $p < .001$. All of the main effects and interactions along with significance levels are presented in Table 1.

To better understand this interaction, two separate 2x2 ANOVAs were conducted on the number of bars (one or two) and mask type (simultaneous offset or delayed offset). One of these was conducted on orientation judgments (see Table 2), and the other was conducted on color judgments (see Table 3). The critical finding was that for the orientation task the two-way interaction was significant, $F(1, 23) = 6.97$, $p = .015$. However, the two-way interaction was not significant for the color task, $F(1, 23) = .28$, $p = .601$. This means that, for orientation judgments, the difference between the simultaneous offset condition and the delayed offset condition when one bar was present was significantly different from that difference when two bars were present. In contrast, for color judgments, the difference between the simultaneous offset condition and the delayed offset condition when one bar was present was not significantly different from that difference when two bars were present.

As discussed earlier, the delayed offset mask interferes with reentrant processes. As such, if participants' accuracy on a task is decreased by a delayed offset mask, then one can conclude that the task requires reentrant processes. As evidenced by the 2x2 ANOVA on color judgments, the delayed offset mask decreased accuracy similarly in both one-bar trials and two-bar trials for the color judgment. This indicates that the two-bar trials of the color judgment did not require reentrant processes because accuracy on those trials was not significantly different from that for one-bar trials. Therefore, reentrant processes did not appear to be necessary for color judgments. The pattern of results is different for orientation judgments, however. The 2x2 ANOVA on orientation judgments demonstrated that the delayed offset mask decreased accuracy significantly more for two-bar trials than for one-bar trials. This indicates that reentrant processes were necessary for the orientation task when two bars were present.

In Experiment #1, the color judgment did not require reentrant processes regardless of the number of bars. In contrast, the orientation judgment did require reentrant processes when two bars were present, which was when binding was necessary. The findings of this experiment suggest that reentrant processes are required when binding is necessary. These results replicate Bouvier and Treisman's (2010) findings.

Experiment #2

The second experiment reversed the design of the first. It tested situations where orientation did not require binding and color did require binding. In this way, it could be determined if reentrant processes are only necessary when binding is required, which here are situations when two bars cross and a color judgment is needed. Thus, it was hypothesized that the delayed offset mask would significantly decrease performance for the color judgment in two-bar cases. The experimental task once again used bars of different orientations and colors, but this time participants were asked to report the orientation and color of the non-vertical bar. Each bar was horizontal, diagonal slanted to the right, or diagonal slanted to the left. Also, each bar was red or blue. Participants needed to make orientation judgments, which did not require binding and thus should not necessitate reentrant processes. Participants also made color judgments, which required binding and thus should necessitate reentrant processes when two bars crossed. Three masking types were used: simultaneous offset mask, delayed offset mask, and pattern mask. A vertical bar was present or absent in a stimulus, and participants were instructed to disregard the vertical bar when it was present. Binding was never needed when only one bar was shown. Conversely, binding was necessary when a vertical bar was present and the task was to identify the color of the non-vertical bar. In order to report the color of the non-vertical bar, participants needed to bind the color to the bar, intentionally disregarding the vertical bar. Therefore, reentrant processes should be necessary when a vertical bar is present. If reentrant processes are necessary for color judgments but not for orientation judgments when two bars cross, this will support the hypothesis that binding requires reentrant processes.

Method

Participants. Twenty-six participants completed the study. All were college students attending Bates College. All had normal or corrected-to-normal vision.

Materials. The program E-Prime (Version 2.0) was used to present stimuli and record responses (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The monitors that ran the experiment had a resolution of 1024 x 768 pixels.

Participants viewed objects composed of one or two bars. All stimuli are shown in the Appendix. When two bars were presented, one bar was blue, and the other was red. When only one bar was presented, it was either blue or red. A bar could be vertical, horizontal, diagonal slanted to the right, or diagonal slanted to the left. When two bars were presented, one was always vertical, and the other was horizontal, diagonal slanted to the right, or diagonal slanted to the left. The target appeared in one of six locations on the screen, and all of the other locations contained distracting stimuli. In order to indicate which one the target was, four dots surrounded the target stimulus.

Responses were provided by pressing keys on a standard keyboard. Participants pressed ‘r’ for horizontal, ‘g’ for diagonal slanted to the right, and ‘b’ for diagonal slanted to the left, and they pressed ‘1’ for red and ‘2’ for blue.

Procedure. First, participants received instructions about the task and completed 20 practice trials. Then, they completed 600 trials (620 trials in total). Participants took a brief, self-paced break every 100 trials.

Stimuli were presented against a black background. Each trial began with a fixation: a white circle was presented in the center of the screen for 1000 ms, and participants were instructed to fixate on it. Then, the array of six objects was presented for 75 ms, and the target item was surrounded by four dots (see Figure 3). Stimuli were randomly selected and arranged in the display. Afterwards, a randomly selected mask was presented. In the simultaneous offset condition, a 300 ms blank display followed the stimulus array. In the delayed offset condition, the dots remained on the screen following stimulus offset for 300 ms. In the pattern mask condition, a colored grid was displayed in the location of the target and the four dots for 300 ms. Following this, participants were prompted for an orientation response and then for a color response. The orientation and color prompts remained on the screen until a response was provided. After responses were made, a blank screen was presented for 1000 ms and served as an intertrial interval. Accuracy data were recorded.

Results and Discussion

Accuracy rates are shown in Figure 4. A 3x2x2 ANOVA was conducted to compare the effects of judgment type, number of bars, and mask type on accuracy. The critical finding was that there was no significant three-way interaction, $F(1.57, 39.29) = 1.35$, $p = .268$.[1] All three two-way interactions were significant, *F*(1, 25) = 187.74, *p* <.001, *F*(2, 50) = 28.00, *p* < .001, and *F*(1.42, 35.55) = 8.13, *p* = .003. All of the main effects and interactions along with significance levels are presented in Table 4.

To understand the pattern of results better, a 2x2x2 ANOVA was conducted on judgment type (orientation or color), number of bars (one or two), and mask type (simultaneous offset or delayed offset) (see Table 5). The interaction between number of bars and mask type was significant, *F*(1, 25) = 41.65, *p* < .001. This suggests that, collapsing across judgment types, the difference in accuracy between simultaneous offset and delayed offset when one bar was present was significantly different from that difference when two bars were present. Thus, the delayed offset mask significantly decreased accuracy in two-bar trials compared to one-bar trials.

In order to understand this interaction better, a 2x2 ANOVA was conducted on judgment type (orientation or color) and mask type (simultaneous or delayed offset) in two-bar cases (see Table 6). Here, there was no significant two-way interaction, *F*(1, 25) = .87, *p* = .361. This means that when two bars were present, the difference between simultaneous offset and delayed offset for orientation judgments was not significantly different from that difference for color judgments. Therefore, the delayed offset mask decreased accuracy in two-bar trials for orientation judgments to a similar extent as it did in two-bar trials for color judgments. Orientation and color judgments were equally susceptible to the delayed offset mask.

In this experimental task, binding was not needed in the orientation task, while binding was needed in the color task. Accuracy for color judgments in two-bar trials was significantly lower than one-bar trials when the delayed offset mask was employed, which suggests that reentrant processes did facilitate performance for color judgments when two bars were present.

Accuracy for orientation judgments in two-bar trials was also significantly lower than one-bar trials when two bars were present, indicating that reentrant processes also improved performance when orientation judgments were made and two bars were present.

The findings of Experiment #2 suggest that reentrant processes may be needed even when binding is not required. Orientation judgments did not require binding regardless of the number of bars, but reentrant processes were needed when two bars were present. Therefore, it appears that reentrant processes may be necessary even when binding is not needed. This finding differs from the finding of Experiment #1, where reentrant processes were only necessary when binding was required. This suggests that orientation and color may be perceived differently in the visual system. In Experiment #1, color did not require binding and did not require reentrant processes. In contrast, in Experiment #2, orientation did not require binding, but it did require reentrant processes in two-bar trials. Perhaps color is fully extracted after a first-wave pass of processing and thus did not necessitate reentrant processes when two bars were present. Orientation, on the other hand, may be more difficult to extract after a single pass, which is why it necessitated reentrant processes when two bars were present.

Treisman and Gormican (1988) share similar results in which color is easier to process than orientation. In an experiment they conducted, participants had to discriminate among objects of slightly different orientations. When the display consisted of a single item, reaction times were around 500 ms. Reaction times increased as the number of items in the display increased and reached 1200 ms for twelve items. This means that a particular orientation was difficult to discern when multiple distractors were presented. In another experiment, participants had to discriminate among similar shades of color. Even though the distinctions were difficult, reaction times remained fast (500-600 ms) as the number of distractors in the display increased from one to twelve. This suggests that colors were easily perceived even as the number of items in the display increased. Thus, it appears that color is processed more easily than orientation.

A similar conclusion can be justified by Erlikhman et al.'s (2013) data. Erlikhman et al. (2013) studied object grouping based on features such as color and orientation. When items were of the same color, those items were strongly grouped together. When targets were of the same color and non-targets were of a different color, all the targets were grouped together. Thus, the accuracy for recognizing the targets was high (90%). When some targets and some non-targets were of the same color, all these items were grouped together. This significantly decreased the accuracy for recognizing the targets (69%) because targets and non-targets were grouped. In contrast, orientation did not produce such robust grouping effects. When targets were of the same orientation and non-targets had a different orientation, it was easy to recognize the targets, and accuracy was high (90%). When some targets and some non-targets were of the same orientation, however, these items were not grouped together strongly. The accuracy for recognizing the targets only decreased to 87%, indicating that the items were not grouped strongly based on their shared orientation. For color, the difference between targets grouped together and targets and non-targets grouped together was 21%; for orientation, this difference was 3%. It is evident from this pattern of results that color leads to much stronger grouping than orientation. According to Erlikhman et al. (2013), this demonstrates that color is processed more readily and more automatically than orientation.

Experiment #3

The third experiment tested whether reentrant processes were necessary for the perception of color and shape. It was hypothesized that the delayed offset mask would significantly decrease performance for the shape judgment in two-object cases. The stimuli in this experiment were composed of a circle or a rectangle that could appear in four colors: white, red, blue, or green (see Appendix for stimuli). Participants made color judgments, which did not require binding, and shape judgments, which did require binding when two shapes were shown. Three mask types were used: simultaneous offset, delayed offset, and pattern mask. When two objects were shown, binding was required and reentrant processes should be needed in the shape judgment task. As was the case in Experiment #1, participants were instructed to disregard the white object and to report the color and shape of the non-white object. When only one object was shown, binding was not required for either task.

Method

Participants. Twenty participants completed the study. All were college students attending Bates College. All had normal or corrected-to-normal vision.

Materials. The program E-Prime (Version 2.0) was used to present stimuli and record responses (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The monitors that ran the experiment had a resolution of 1024 x 768 pixels.

Participants viewed objects composed of one or two shapes. The stimuli are shown in the Appendix. When two shapes were presented, one was a circle, and the other was a rectangle. When only one shape was presented, it could be either a circle or a rectangle. A shape could be white, red, blue, or green. When two shapes were presented, one was always white, and the other was red, blue, or green. The target appeared in one of six locations on the screen, and all of the other locations contained distracting stimuli. In order to indicate which one the target was, four dots surrounded the target stimulus.

Responses were provided by pressing keys on a standard keyboard. Participants pressed ‘r’ for red, ‘g’ for green, and ‘b’ for blue, and they pressed ‘1’ for circle and ‘2’ for rectangle.

Procedure. First, participants received instructions about the task and completed 20 practice trials. Then, they completed 556 trials (576 trials in total). Participants took a brief, self-paced break every 100 trials.

Stimuli were presented against a black background. Each trial began with a fixation: a white circle was presented in the center of the screen for 1000 ms, and participants were instructed to fixate on it. Then, the array of six objects was presented for 150 ms, and the target item was surrounded by four dots (see Figure 5). Stimuli were randomly selected and arranged in the display. Afterwards, a randomly selected mask was presented. In the simultaneous offset condition, a 300 ms blank display followed the stimulus array. In the delayed offset condition, the dots remained on the screen following stimulus offset for 300 ms. In the pattern mask condition, a colored grid was displayed in the location of the target and the four dots for 300 ms. Following this, participants were prompted for a color response and then for a shape response. The color and shape prompts remained on the screen until a response was provided. After a response was given, a blank screen was presented for 1000 ms and served as an intertrial interval. Accuracy data were recorded.

Results and Discussion

Accuracy rates are shown in Figure 6. A 3x2x2 ANOVA was conducted to compare the effects of judgment type, number of objects, and mask type on accuracy. The critical finding was that there was no significant three-way interaction, $F(2, 38) = .11$, $p = .898$. There was a significant interaction, however, between judgment type and number of objects, $F(1, 19) =$

123.98, $p < .001$, and a significant interaction between judgment type and mask type, $F(1.30, 24.66) = 6.91$, $p = .010$. All the main effects and interactions along with significance levels are shown in Table 7.

To understand this pattern of results better, a 2x2x2 ANOVA on judgment type (color or shape), number of objects (one or two), and mask type (simultaneous offset or delayed offset) was conducted (see Table 8). This analysis yielded a significant interaction between judgment type and mask type, $F(1,19) = 27.10$, $p < .001$. This suggests that, collapsing across number of bars, the difference in accuracy between simultaneous offset and delayed offset for color judgments was significantly different from that difference for shape judgments. Thus, the delayed offset mask decreased accuracy for shape judgments significantly more than it did for color judgments.

Accuracy for shape judgments was significantly lower than for color judgments when the delayed offset mask was implemented (see Figure 6). This indicates that color judgments did not require reentrant processes regardless of object number. On the other hand, shape judgments did improve with reentrant processing both when two objects were shown, as predicted, but also when one object was shown. Therefore, shape judgments improved when reentrant processes were not disrupted by delayed dot offset in both one-object and two-object situations.

The results of Experiment #3 indicate that reentrant processes may be necessary in conditions when binding is not needed. Shape judgments improved with reentrant processes regardless of object number even though binding was needed only when two objects were present. This means that reentrant processes aid in the processing of an object’s shape even in situations where the binding of features is not necessary.

It is possible that the perception of a shape itself requires binding. A shape is a collection of edges, so it is possible that, for shapes, separate edges need to be bound to facilitate perception. If binding is required for shape perception, this would explain why reentrant processes were needed for shape judgments regardless of object number. Under this assumption, the results are consistent with the hypothesis that reentrant processes facilitate the binding of features. Color judgments did not require binding for either one or two objects, and they did not require reentrant processes. In contrast, shape judgments required binding for both one and two objects, and they required reentrant processes in both of those conditions.

Wolfe and Bennett (1997) suggest that the perception of a shape requires binding. Their experiments used stimuli characterized by color, orientation, and shape. Participants perceived the color and orientation of an object before they could identify its shape. This was demonstrated by significantly longer reaction times for trials in which shape needed to be identified in comparison with trials in which color or orientation perception was sufficient. Wolfe and Bennett (1997) concluded that participants preattentively perceived color and orientation because these basic features did not require binding. Participants did not preattentively perceive shape, however, because shape perception required binding. This finding indicates that the perception of shape may require binding because it is less automatic than the perception of color or orientation. Therefore, reentrant processes may be necessary for shape perception even when a single shape is present.

Experiment #4

This experiment examined whether reentrant processes were necessary for the perception of shape and orientation. It was hypothesized that the delayed offset mask would significantly decrease performance for the orientation judgment in two-object cases. The stimuli were composed of two objects. Each object was a rectangle, a curvy line, an ellipse, or a triangle, and each could appear either vertically or horizontally (see Appendix for stimuli). Participants made shape judgments, which did not require the binding of shape and orientation information. Still, the perception of a shape itself may, as reported by Wolfe & Bennett (1997), require binding irrespective of the number of objects shown. Participants also made orientation judgments, which required binding when two objects appeared together. Three mask types were used: simultaneous offset, delayed offset, and pattern mask. Participants were instructed to disregard the rectangular object and report the shape and orientation of the non-rectangular object. When two objects were present, binding was needed and reentrant processes should be necessary in the orientation task. To the extent that reentrant processes are always needed to help extract shape information, then binding may also be necessary in the shape task.

Method

Participants. Twenty-one participants completed the study. All were college students attending Bates College. All had normal or corrected-to-normal vision.

Materials. The program E-Prime (Version 2.0) was used to present stimuli and record responses (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The monitors that ran the experiment had a resolution of 1024 x 768 pixels.

Participants viewed objects composed of one or two shapes. The stimuli are shown in the Appendix. When two shapes were presented, one shape was horizontal, and the other was vertical. When only one shape was presented, it could be either horizontal or vertical. A shape could be a rectangle, a curvy line, an ellipse, or a triangle. When two shapes were presented, one was always a rectangle, and the other was a curvy line, an ellipse, or a triangle. The target appeared in one of six locations on the screen, and all of the other locations contained distracting stimuli. In order to indicate which one the target was, four dots surrounded the target stimulus.

Responses were provided by pressing keys on a standard keyboard. Participants pressed ‘j’ for curvy line, ‘k’ for triangle, and ‘l’ for ellipse, and they pressed ‘1’ for horizontal and ‘2’ for vertical.

Procedure. First, participants received instructions about the task and completed 20 practice trials. Then, they completed 560 trials (580 trials in total). Participants took a brief, self-paced break every 100 trials.

Stimuli were presented against a black background. Each trial began with a fixation: a white circle was presented in the center of the screen for 1000 ms, and participants were instructed to fixate on it. Then, the array of six objects was presented for 150 ms, and the target item was surrounded by four dots (see Figure 7). Stimuli were randomly selected and arranged in the display. Afterwards, a randomly selected mask was presented. In the simultaneous offset condition, a 300 ms blank display followed the stimulus array. In the delayed offset condition, the dots remained on the screen following stimulus offset for 300 ms. In the pattern mask condition, a colored grid was displayed in the location of the target and the four dots for 300 ms. Following this, participants were prompted for a shape response and then for an orientation response. The shape and orientation prompts remained on the screen until a response was provided. After responses were made, a blank screen was presented for 1000 ms and served as an intertrial interval. Accuracy data were recorded.

Results and Discussion

Accuracy rates are shown in Figure 8. A 3x2x2 ANOVA was conducted to compare the effects of judgment type, number of objects, and mask type on accuracy. The critical finding was that the three-way interaction was significant, *F*(2, 46) = 4.43, *p* = .017. All of the main effects and interactions along with significance levels are shown in Table 9.

Because there was no significant main effect of judgment type, for both shape and orientation judgments reentrant processes did not facilitate performance when one object was shown but did facilitate performance when two objects were presented. Orientation judgments required the binding of shape information and orientation information, and reentrant processes helped orientation perception. In contrast, shape judgments did not require the binding of shape information with orientation information, but reentrant processes did help shape perception.

Perhaps this suggests that reentrant processes may be necessary even when binding is not needed, as indicated by Experiment #2. Or perhaps the perception of a shape itself requires binding because a shape is a collection of multiple edges. This would entail that the perception of a shape in any condition would require reentrant processes; however, this was not the case for shape judgments when one object was present. Thus, it is difficult to explain why shape judgments necessitated reentrant processes only when two objects were present.

It is also surprising that in Experiments #3 and #4 reentrant processes were employed differently in shape judgments. In Experiment #3, shape judgments required reentrant processes regardless of object number. This suggests that the basic perception of shape necessitates reentrant processes perhaps because multiple edges of different orientations need to be bound into a shape. In Experiment #4, however, shape judgments only required reentrant processes when two objects were present. This does not fit with the understanding that the perception of a single shape necessitates binding (and thus reentrant processes). Therefore, these results do not permit a certain conclusion about the perception of shape. One possible explanation for the contradicting results of Experiments #3 and #4 is that the stimuli used in the two experiments were different. The shapes that participants perceived in Experiment #3 were different from the shapes in Experiment #4 (see Appendix). These differences may have caused shapes to be perceived in distinct ways in the two experiments. Such distinct methods of perception may have employed reentrant processes differently.

Experiment #5

This experiment examined whether reentrant processes were necessary for the perception of color and motion. It was hypothesized that the delayed offset mask would significantly decrease performance for the motion judgment in two-dot cases. Participants were shown dots that were white, red, blue, or green and moved either vertically or horizontally (see Appendix for stimuli). Participants made color judgments, which did not require binding, and motion judgments, which required binding when two moving dots were shown at the same location. Three mask types were used: simultaneous offset, delayed offset, and pattern mask. When two dots were present, binding was necessary and reentrant processes should facilitate performance. Participants were instructed to disregard the white dot and report the color and motion of the non-white dot. When only one dot was shown, binding was not necessary for either task.

Method

Participants. Twenty-three participants completed the study. All were college students attending Bates College. All had normal or corrected-to-normal vision.

Materials. The program E-Prime (Version 2.0) was used to present stimuli and record responses (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The monitors that ran the experiment had a resolution of 1024 x 768 pixels.

Participants viewed objects composed of one or two dots. The stimuli are presented in the Appendix. When two dots were presented, one dot moved horizontally, and the other moved vertically. When only one dot was presented, it could move either horizontally or vertically. A dot could be white, red, blue, or green. When two dots were presented, one was always white, and the other was red, blue, or green. The target appeared in one of six locations on the screen, and all of the other locations contained distracting stimuli. In order to indicate which one the target was, four dots surrounded the target stimulus.

Responses were provided by pressing keys on a standard keyboard. Participants pressed ‘r’ for red, ‘g’ for green, and ‘b’ for blue, and they pressed ‘1’ for moving horizontally and ‘2’ for moving vertically.

Procedure. First, participants received instructions about the task and completed 20 practice trials. Then, they completed 550 trials (570 trials in total). Participants took a brief, self-paced break every 100 trials.

Stimuli were presented against a black background. Each trial began with a fixation: a white circle was presented in the center of the screen for 1000 ms, and participants were instructed to fixate on it. Then, an array of six objects was presented, each object constituting of two dots, and the target item was surrounded by four white dots (see Figure 9). In total, the array was shown for 210 ms and contained seven displays, each presented for 30 ms. In each display, the dots constituting the object were presented in a slightly different location from the previous display. This was done to create the perception of illusory motion. Stimuli were randomly selected to appear in the display. Afterwards, a randomly selected mask was presented. In the simultaneous offset condition, a 300 ms blank display followed the stimulus array. In the delayed offset condition, the dots remained on the screen following stimulus offset for 300 ms. In the pattern mask condition, a colored grid was displayed in the location of the target and the four dots for 300 ms. Following this, participants were prompted for a color response and then for a motion response. The color and motion prompts remained on the screen until a response was provided. After responses were made, a blank screen was presented for 1000 ms and served as an intertrial interval. Accuracy data were recorded.

Results and Discussion

Accuracy rates are shown in Figure 10. A 3x2x2 ANOVA was conducted to compare the effects of judgment type, number of dots, and mask type on accuracy. The critical finding was that there was no significant three-way interaction, $F(2, 44) = 1.43$, $p = .250$. A significant interaction emerged, however, between type of judgment and number of dots, $F(1, 22) = 22.42$, $p < .001$. Another significant interaction emerged between type of judgment and mask type, $F(1.40, 30.72) = 5.50$, $p = .017$. All the main effects and interactions along with significance levels are shown in Table 10.

It is crucial to note that accuracies for motion judgments were all close to .5. This most likely indicates a floor effect for motion judgments: the task was so difficult that participants could not determine the direction of motion at rates greater than chance. Thus, the results of the motion judgment are inconclusive, and the two significant interactions only indicate that participants could discriminate the color of the objects but could not discriminate the direction of motion.

General Discussion

Summary of Findings

The series of experiments undertaken for this thesis studied whether reentrant processes are necessary for binding. Bouvier and Treisman’s (2010) hypothesis was that reentrant processes facilitate performance when binding is required, but they did not make predictions about reentrant processes’ involvement when binding is not necessary. The current results showed that reentrant processes are needed for binding, but they may also aid perception in some cases where binding is not required.

Experiment #1 replicated Bouvier and Treisman’s (2010) results. Color judgments did not require binding and did not necessitate reentrant processes regardless of the number of bars present. Orientation judgments required binding when two bars were present and necessitated reentrant processes in two-bar trials. These findings suggest that reentrant processes facilitate the binding of features.

Experiment #2 reversed Bouvier and Treisman’s (2010) design by presenting color judgments that require binding and orientation judgments that did not require binding. Color judgments required binding when two bars were present and necessitated reentrant processes in two-bar trials. Orientation judgments did not require binding regardless of bar number, but results indicated that reentrant processes improved performance in two-bar trials. Perhaps orientation is perceived less automatically than color and thus necessitates reentrant processes even when binding is not required (Treisman & Gormican, 1988; Erlikhman et al., 2013). The noteworthy finding here is that reentrant processes may help build an object representation even in cases when binding is not required in addition to cases when binding is required.

Experiment #3 examined binding and reentrant processes when color and shape information was being sought. Color judgments did not require binding and did not necessitate reentrant processes regardless of object number. Shape judgments required binding when two objects were present, but the results indicated that reentrant processes helped to extract shape information irrespective of the number of objects shown. Perhaps the perception of shape, similarly to orientation, requires reentrant processes even when no binding is needed. Alternatively, perhaps multiple edges of different orientations need to be integrated for shape perception. This could explain why shape perception itself may require binding (Wolfe & Bennett, 1997) and thus may require reentrant processes. The outcome of this experiment may suggest that reentrant processes are necessary even in cases when binding is not required, or it may suggest that shape perception requires binding and reentrant processes.

Experiment #4 investigated binding and reentrant processes when shape and orientation information was being sought. Here, orientation judgments required the binding of shape information with orientation information when two objects were shown. As such, orientation judgments required reentrant processes when two objects were shown but not when one object was shown. Shape judgments, on the other hand, did not require the binding of shape information and orientation information regardless of object number, but the results indicated that reentrant processes did facilitate performance in two-object trials. This may again suggest that shape perception requires binding and thus reentrant processes. It is difficult to understand, however, why shape judgments did not necessitate reentrant processes in one-bar trials, when they did necessitate reentrant processes in one-bar trials in Experiment #3. Thus, the results of this experiment are difficult to interpret with certainty.

Experiment #5 examined binding and reentrant processes in color and motion. Color judgments did not require binding, while motion judgments did. Unfortunately, the motion task was quite difficult and accuracy for it was low, so the motion results are inconclusive due to a floor effect. Therefore, this experiment does not advance the field's understanding of binding and reentrant processes.

Implications

These experiments contribute to the debate about the binding problem: they suggest that how the brain achieves feature binding is a relevant question for current research. Di Lollo (2012) argues that feature binding is achieved via feed-forward processes and thus does not require reentrant processes. If this were true, then feature perception that requires binding should be as easily accomplished as feature perception that does not require binding because the two would share the same mechanism. However, the experiments for this thesis demonstrate that binding visual features is more demanding than the perception of features alone. The results show that accuracy is lower for trials that require binding than for trials that do not require binding. This indicates that feature binding requires resources that are not necessary for single feature perception, such as reentrant processes. Thus, Di Lollo's (2012) position is not supported. Rather, feature binding does not seem to be accomplished via the same mechanism as single feature perception.

The experiments undertaken for this thesis demonstrate that reentrant processes may sometimes be necessary even when binding is not required, which supplements the understanding that reentrant processes are required when binding is necessary. It is important here to note the unique role of color. It has been suggested that color is processed more automatically than other features (Treisman & Gormican, 1988; Erlikhman et al., 2013). This could explain why color did not necessitate reentrant processes when binding was not needed, while orientation did necessitate reentrant processes in some cases when binding was not needed.

The experiments that include shape raise important questions about the visual processing of shape. The evidence can be interpreted in at least two ways. The first possible explanation is that reentrant processes are sometimes necessary even when binding is not required, as is the case for orientation. Thus, for shape judgments which did not require binding, reentrant processes may have still been necessary. The second possible explanation is that shape perception itself requires binding and thus reentrant processes. Wolfe and Bennett (1997) propose that the perception of shape may be more demanding than the perception of color and orientation, which is why shape perception may require binding. Also, a shape is formed by multiple edges of different orientations, which makes it plausible that binding and reentrant processes may be necessary for shape perception.

Future Directions

A simple but important manipulation for future research is to replicate Experiment #1 but change the color of the bar that participants are asked to ignore. For instance, instead of white, the bar being disregarded could be any other color that is not white or black. This is a critical manipulation because white is often considered a neutral color, which may make it easy to ignore. If participants are asked to ignore a non-neutral color, this may increase the task's difficulty and decrease their accuracy. The pattern of results may resemble that of the orientation task, in which case reentrant processes may improve color judgments even when binding is not required. Alternatively, the pattern of results may not change, which would strongly demonstrate that reentrant processes are not necessary in color judgments when binding is not needed.

These experiments could not determine how motion is bound with other features. Unfortunately, in Experiment #5, the direction of motion was too difficult to discern, so the experiment did not yield interpretable results. Future research should examine the binding of motion in an experiment where the task is made easier. This could be done by decreasing the number of distractors. Another way the task could be made easier is to present the dots for longer periods of time. In Experiment #5, each dot was presented for 30 ms, so each array was presented for a total of 210 ms. Perhaps if each dot were presented for 50 ms or even 70 ms, the direction of motion might become easy enough for participants to discern. However, the rate of presentation must still encourage illusory motion. Researchers must be careful with the extent to which they slow down stimulus presentation because this could make the color task too easy. Color accuracy was relatively high in Experiment #5, so if the task became much easier, accuracies might rise substantially and reach a ceiling effect. Therefore, the amount of time for which stimuli would be presented should be carefully determined.

Looming and receding motion is another area of research to which the current studies are relevant. Kahan, Colligan, and Wiedman (2011) examined how the features of looming and receding objects are processed. They found that the visual system is biased to process such motion. The design of Experiment #5 can be employed to study looming and receding motion in order to determine whether such motion is perceived differently from 2D motion. Looming motion may be more salient from an evolutionary standpoint (Kahan et al., 2011), so perhaps its perception is more automatic than that of 2D motion. If this is the case, it would be interesting to compare the processing of looming motion to the processing of color, as they may both be perceived more automatically than other features. Specifically, looming motion, like color, may not require reentrant processes when binding is not needed. In addition, if looming motion is processed more automatically than color, reentrant processes may not be required when processing looming objects even when binding is needed.

Furthermore, neural studies can also greatly enhance the field's understanding of binding and reentrant processes. Cortese, Bernstein, and Alain (1999) examined the neural mechanism of binding using event-related potentials (ERPs). The stimuli they used were characterized by a color, an orientation, or a conjunction of color and orientation. They identified ERP components related to feature perception. They also established that the perception of a single feature and the perception of a conjunction of features occur simultaneously. Applying the ERP technique to Bouvier and Treisman's (2010) design could remarkably aid the understanding of feature binding. It can be examined how the delayed offset mask affects ERPs for different features in comparison with the simultaneous offset condition and the pattern mask condition. This would elucidate the temporal dynamics of reentrant processes in the way they facilitate feature binding.

Transcranial magnetic stimulation (TMS) may also be a useful tool in studying feature binding. Braet and Humphreys (2009) examined the effect of TMS on illusory conjunctions among features. They found that when activity in the right posterior parietal cortex was inhibited by TMS, there was an increase in the number of illusory conjunctions participants reported. In contrast, inhibiting activity in the occipital cortex did not lead to an increase in illusory conjunctions. In addition, in order to induce a large number of illusory conjunctions, TMS had to be applied during a critical, slightly delayed time window. This demonstrated that the right posterior parietal cortex is probably involved in a late stage of feature binding (Braet &

Humphreys, 2009). Incorporating TMS into Bouvier and Treisman’s (2010) design could lead to specific conclusions about which brain areas are involved with the binding of different features. Multiple brain regions contribute to the perception of different features, and the same may be true for the binding of different features. Applying TMS to distinct brain regions may reveal the brain areas involved in the binding of particular features.

Conclusion

In conclusion, the experiments described here demonstrated that reentrant processes are necessary when binding is required, but they also indicated that in some cases reentrant processes facilitate perception of features when binding is not required. The results further suggest that color may be processed more automatically than orientation. They also indicate that shape perception may require binding and reentrant processes even when only one shape is being perceived. The findings advance the field’s understanding of feature binding and reentrant processes. In addition, they suggest multiple directions and possible experimental designs for future research on feature binding.

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Footnotes

[1] For all cases when the assumption of sphericity was violated, Greenhouse-Geisser correction factor was applied.

Table 1

Experiment #1: 3x2x2 ANOVA on Judgment Type (Color or Orientation), Number of Bars (One or Two), and Mask Type (Simultaneous Offset Mask, Delayed Offset Mask, or Pattern Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 23	78.96	< .001
Number of bars	1, 23	130.56	< .001
Mask type ^	1.46, 33.49	249.46	< .001
Judgment type * Number of bars	1, 23	133.98	< .001
Judgment type * Mask type ^	1.29, 29.71	6.87	.009
Number of bars * Mask type	2, 46	8.29	.001
Judgment type * Number of bars * Mask type	2, 46	19.28	< .001

Note. ^ = Greenhouse-Geisser test results are reported because the assumption of sphericity was violated.

Table 2

Experiment #1: 2x2 ANOVA on Number of Bars (One or Two) and Mask Type (Simultaneous Offset or Delayed Offset) in Orientation Judgments

Variables	Degrees of freedom	F value	P value
Number of bars	1, 23	102.48	< .001
Mask type	1, 23	25.25	< .001
Number of bars * Mask type	1, 23	6.97	.015

Table 3

Experiment #1: 2x2 ANOVA on Number of Bars (One or Two) and Mask Type (Simultaneous Offset or Delayed Offset) in Color Judgments

Variables	Degrees of freedom	F value	P value
Number of bars	1, 23	9.48	.005
Mask type	1, 23	6.92	.015
Number of bars * Mask type	1, 23	.28	.601

Table 4

Experiment #2: 3x2x2 ANOVA on Judgment Type (Orientation or Color), Number of Bars (One or Two), and Mask Type (Simultaneous Offset Mask, Delayed Offset Mask, or Pattern Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 25	5.86	.023
Number of bars	1, 25	147.72	< .001
Mask type ^	1.43, 35.77	225.23	< .001
Judgment type * Number of bars	1, 25	187.74	< .001
Judgment type * Mask type	2, 50	28.00	< .001
Number of bars * Mask type ^	1.42, 35.55	8.13	.003
Judgment type * Number of bars * Mask type ^	1.57, 39.29	1.35	.268

Note. ^ = Greenhouse-Geisser test results are reported because the assumption of sphericity was violated.

Table 5

Experiment #2: 2x2x2 ANOVA on Judgment Type (Orientation or Color), Number of Bars (One or Two), and Mask Type (Simultaneous Offset Mask or Delayed Offset Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 25	26.88	< .001
Number of bars	1, 25	125.30	< .001
Mask type	1, 25	76.16	< .001
Judgment type * Number of bars	1, 25	112.04	< .001
Judgment type * Mask type	1, 25	.008	.930
Number of bars * Mask type	1, 25	41.65	< .001
Judgment type * Number of bars * Mask type	1, 25	3.69	.066

Table 6

Experiment #2: 2x2 ANOVA on Judgment Type (Orientation or Color) and Mask Type (Simultaneous Offset or Delayed Offset) in Trials with Two Bars

Variables	Degrees of freedom	F value	P value
Judgment type	1, 25	67.79	< .001
Mask type	1, 25	108.16	< .001
Judgment type * Mask type	1, 25	.87	.361

Table 7

Experiment #3: 3x2x2 ANOVA on Judgment Type (Color or Shape), Number of Objects (One or Two), and Mask Type (Simultaneous Offset Mask, Delayed Offset Mask, or Pattern Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 19	328.69	< .001
Number of objects	1, 19	154.53	< .001
Mask type ^	1.38, 26.25	170.69	< .001
Judgment type * Number of objects	1, 19	123.98	< .001
Judgment type * Mask type ^	1.30, 24.66	6.91	.010
Number of objects * Mask type	2, 38	.02	.981
Judgment type * Number of objects * Mask type	2, 38	.11	.898

Note. ^ = Greenhouse-Geisser test results are reported because the assumption of sphericity was violated.

Table 8

Experiment #3: 2x2x2 ANOVA on Judgment Type (Color or Shape), Number of Objects (One or Two), and Mask Type (Simultaneous Offset Mask or Delayed Offset Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 19	165.92	< .001
Number of objects	1, 19	169.78	< .001
Mask type	1, 19	139.11	< .001
Judgment type * Number of objects	1, 19	117.04	< .001
Judgment type * Mask type	1, 19	27.10	< .001
Number of objects * Mask type	1, 19	.05	.823
Judgment type * Number of objects * Mask type	1, 19	.13	.720

Table 9

Experiment #4: 3x2x2 ANOVA on Judgment Type (Shape or Orientation), Number of Objects (One or Two), and Mask Type (Simultaneous Offset Mask, Delayed Offset Mask, or Pattern Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 23	1.71	.204
Number of objects	1, 23	58.68	< .001
Mask type ^	1.57, 36.13	56.06	< .001
Judgment type * Number of objects	1, 23	11.71	.002
Judgment type * Mask type	2, 46	4.27	.020
Number of objects * Mask type	2, 46	14.00	< .001
Judgment type * Number of objects * Mask type	2, 46	4.43	.017

Note. ^ = Greenhouse-Geisser test results are reported because the assumption of sphericity was violated.

Table 10

Experiment #5: 3x2x2 ANOVA on Judgment Type (Color or Motion), Number of Dots (One or Two), and Mask Type (Simultaneous Offset Mask, Delayed Offset Mask, or Pattern Mask)

Variables	Degrees of freedom	F value	P value
Judgment type	1, 22	14.22	.001
Number of dots	1, 22	1.05	.317
Mask type ^	1.46, 32.14	7.60	.004
Judgment type * Number of dots	1, 22	22.42	< .001
Judgment type * Mask type ^	1.40, 30.72	5.50	.017
Number of dots * Mask type	2, 44	.06	.943
Judgment type * Number of dots * Mask type	2, 44	1.43	.250

Note. ^ = Greenhouse-Geisser test results are reported because the assumption of sphericity was violated.

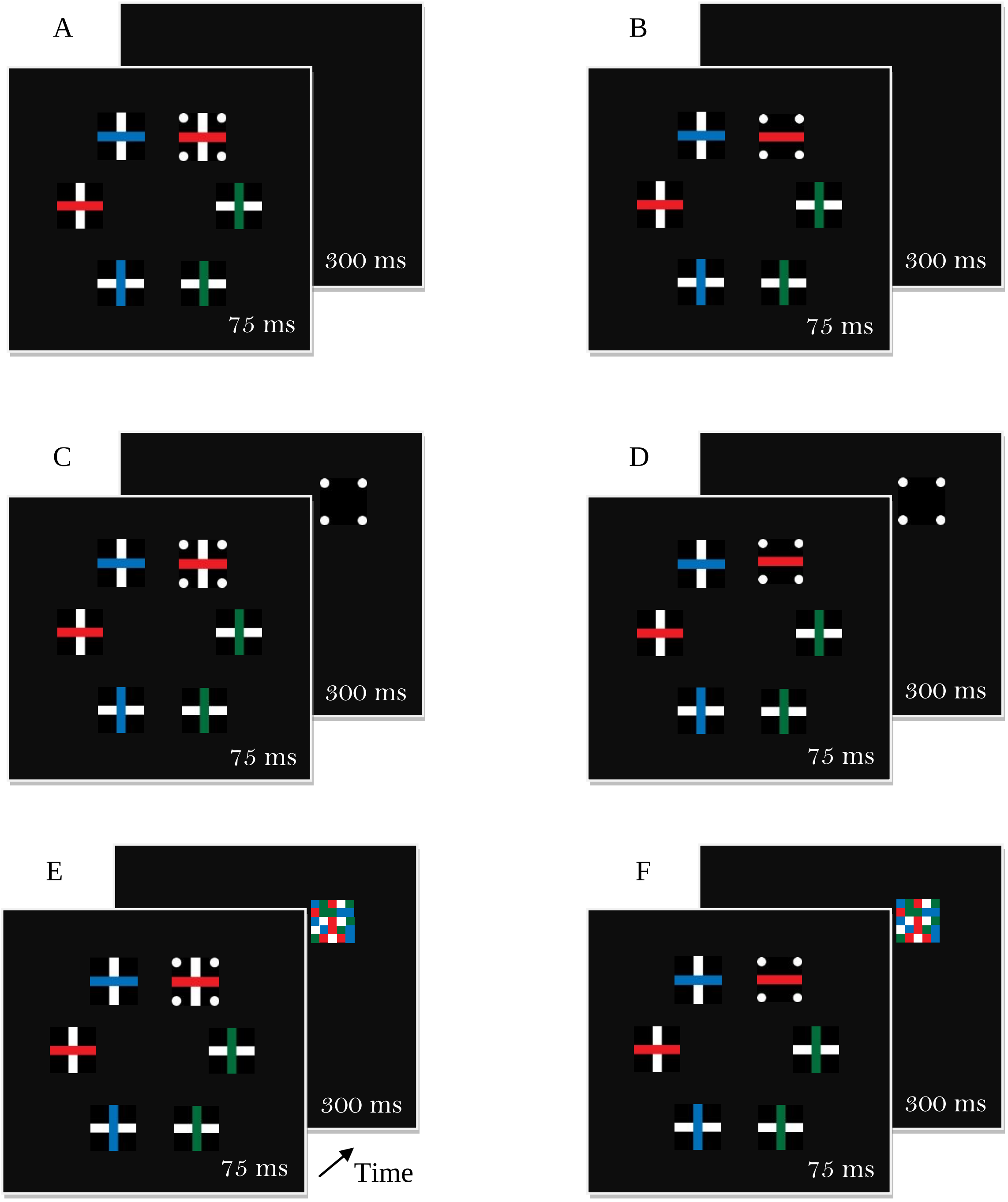


Figure 1. Based on Bouvier and Treisman's (2010) design. Experiment #1. Stimuli arrays and possible masks. For each trial, an array of six stimuli appears on the screen for 75 ms. In (A), (C), and (E), the targets have two bars, while in (B), (D), and (F), the targets have one bar. Then, a mask follows for 300 ms. In (A) and (B), the mask consists of four dots with simultaneous offset (so no image remains on the screen after the stimuli disappear), in (C) and (D) the mask consists of four dots with delayed offset, and in (E) and (F) the mask is a pattern mask.

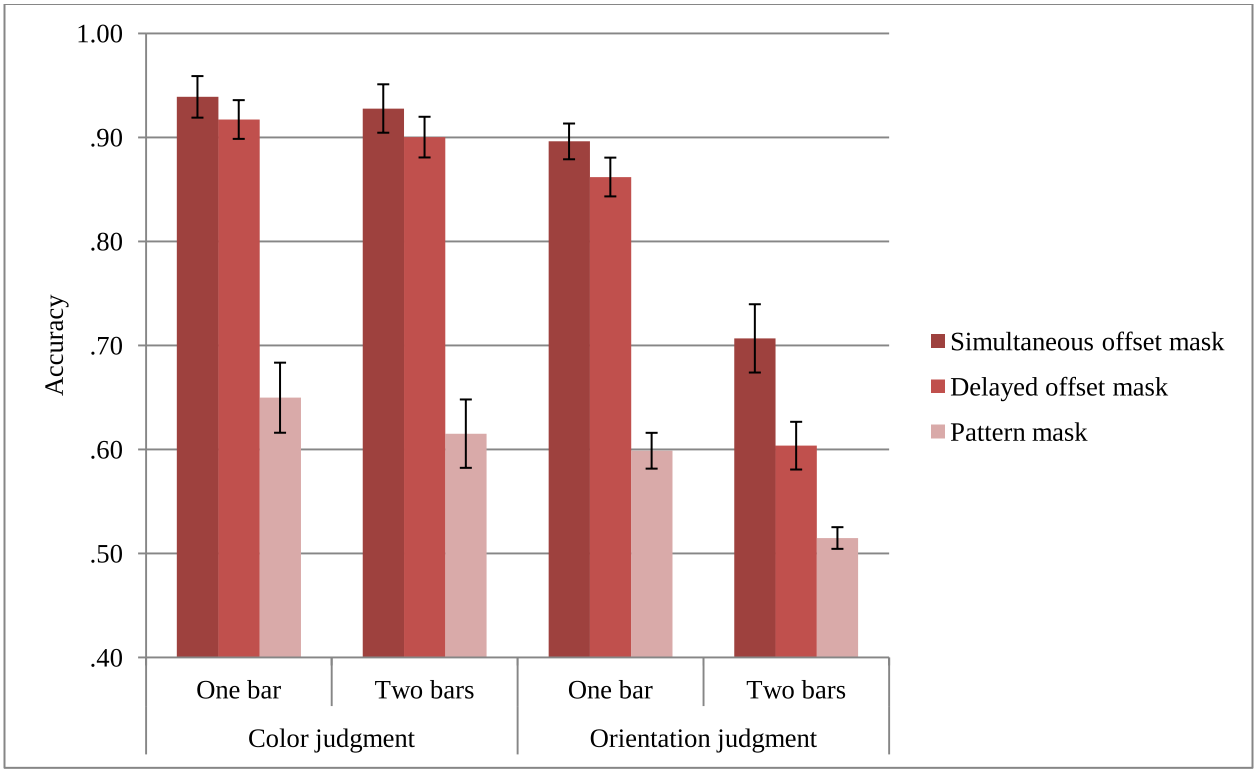


Figure 2. Results of Experiment #1. Accuracy as it is affected by judgment type (color or orientation), number of bars (one or two), and mask type (simultaneous offset, delayed offset, or pattern mask). Error bars represent ±1 SE. The delayed offset mask significantly decreased accuracy for the orientation judgment when two bars were shown.

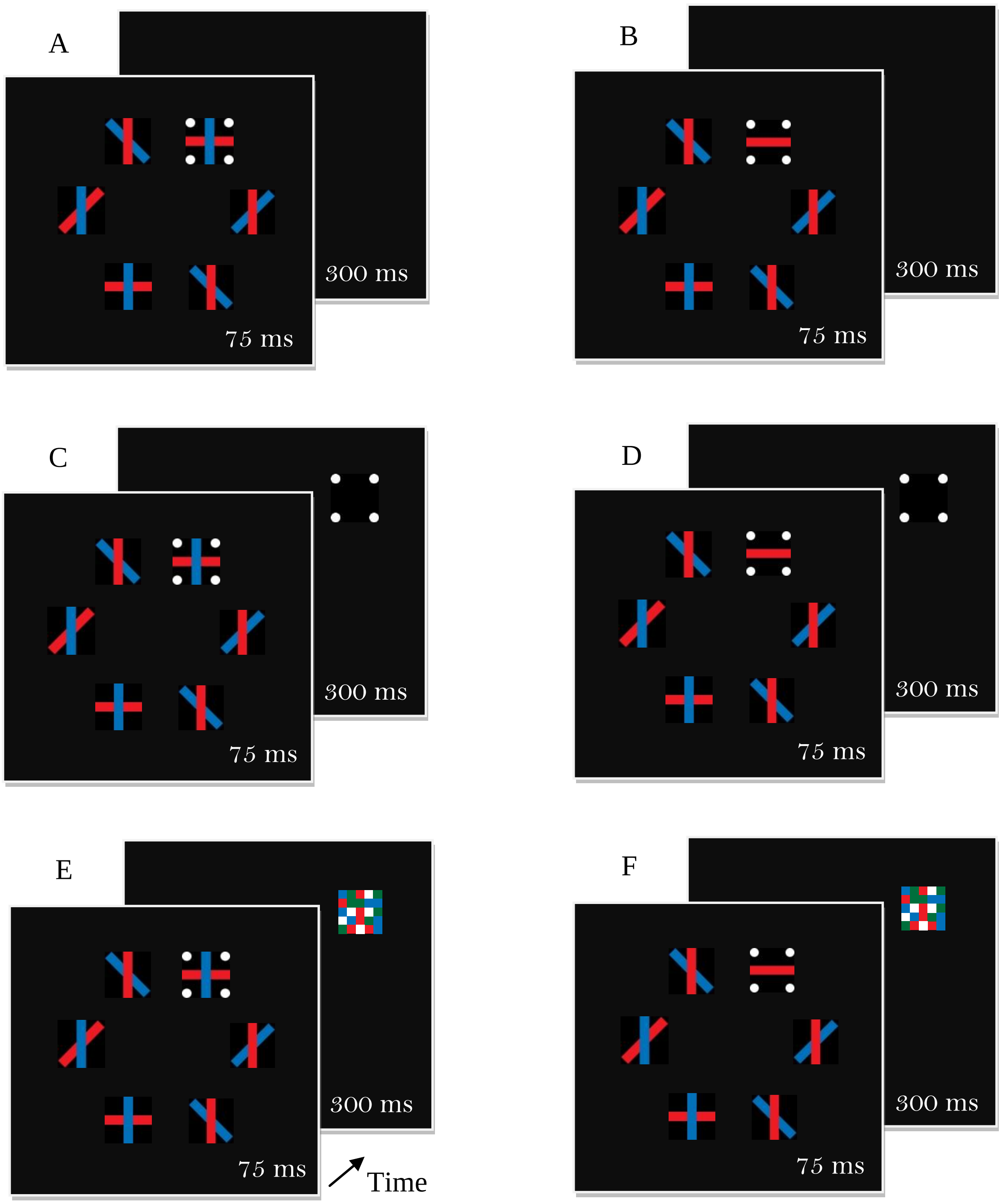


*Figure 3.*Experiment #2. Stimuli arrays and possible masks. For each trial, an array of six stimuli appears on the screen for 75 ms. In (A), (C), and (E), the targets have two bars, while in (B), (D), and (F), the targets have one bar. Then, a mask follows for 300 ms. In (A) and (B), the mask consists of four dots with simultaneous offset (so no image remains on the screen after the stimuli disappear), in (C) and (D) the mask consists of four dots with delayed offset, and in (E) and (F) the mask is a pattern mask.

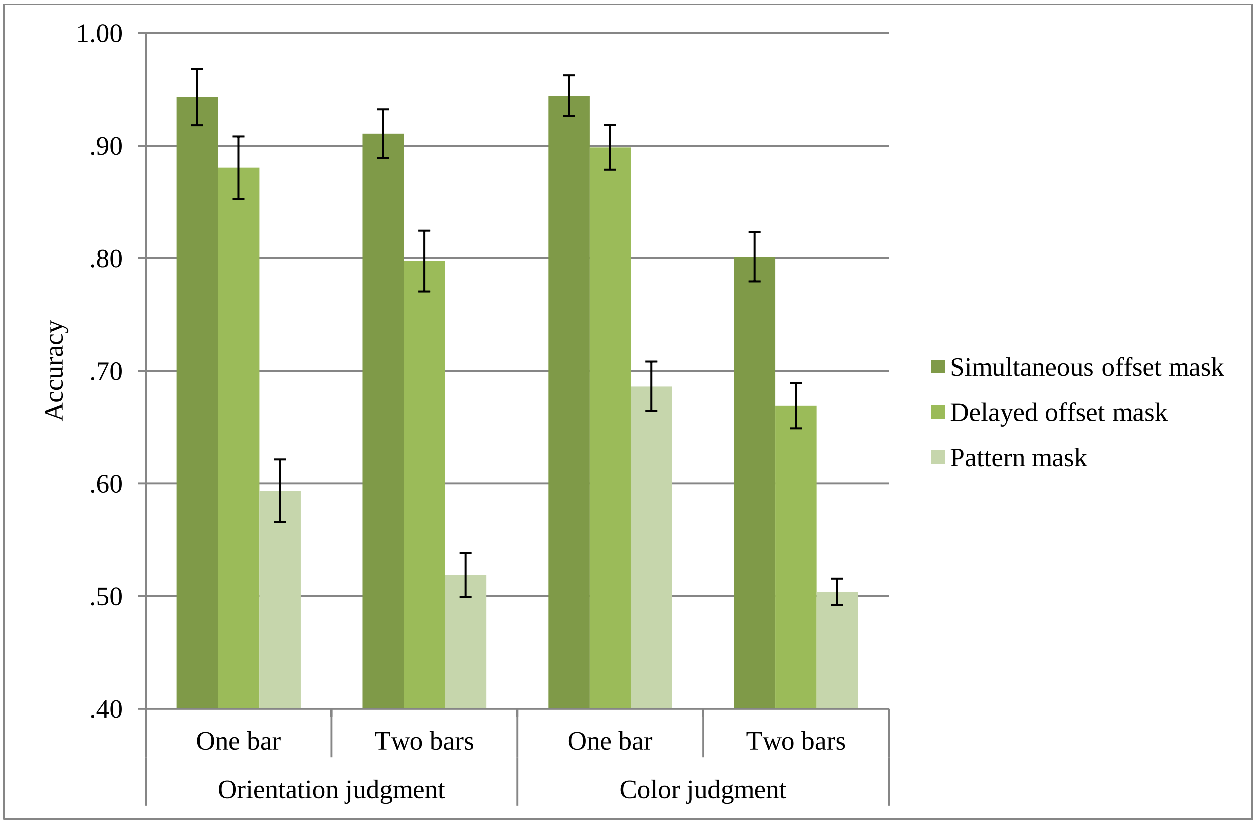


Figure 4. Results of Experiment #2. Accuracy as it is affected by judgment type (orientation or color), number of bars (one or two), and mask type (simultaneous offset, delayed offset, or pattern mask). Error bars represent ±1 SE. The delayed offset mask significantly decreased accuracy for the color judgment when two bars were shown as well as for the orientation judgment when two bars were shown.

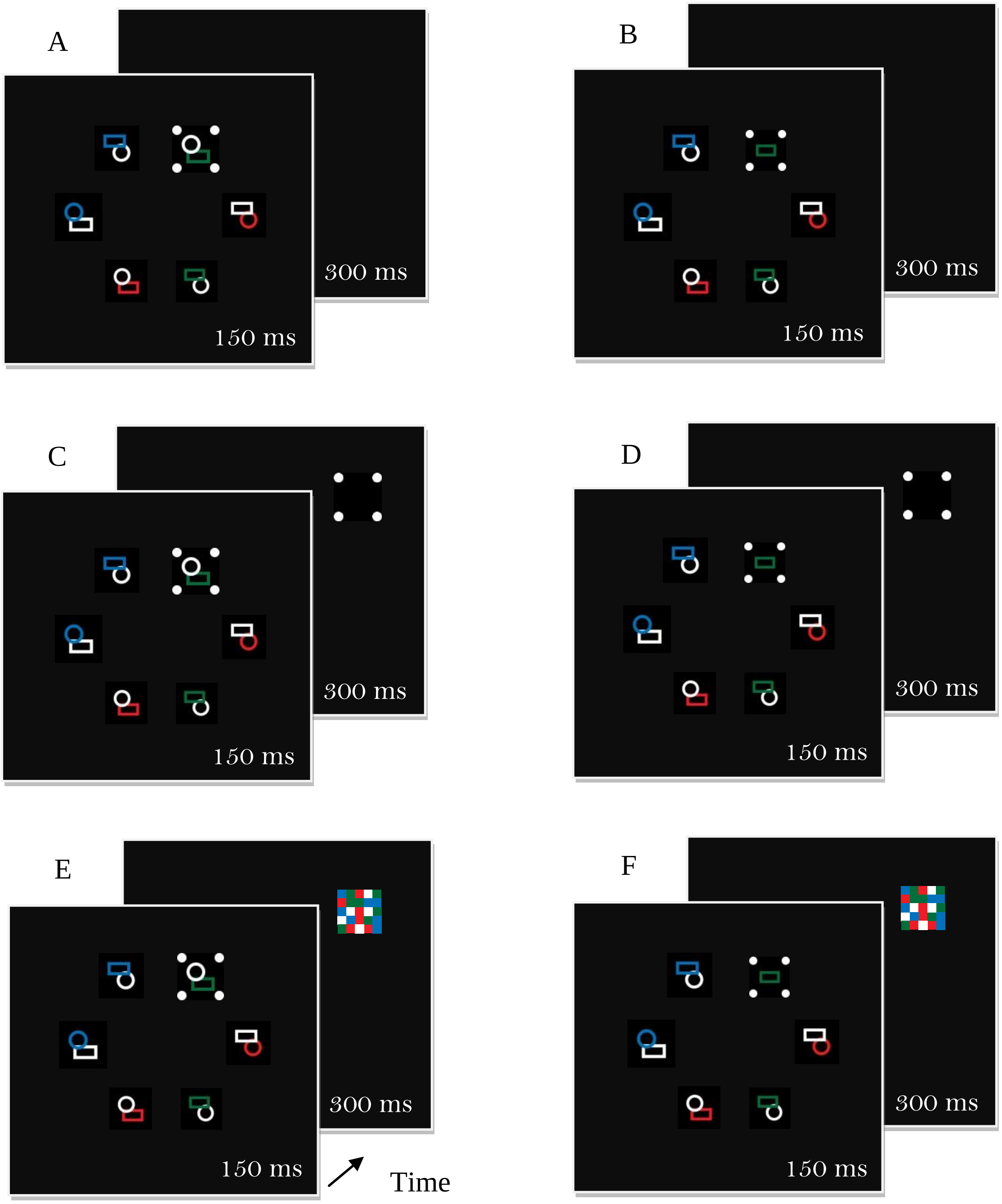


Figure 5.Experiment #3. Stimuli arrays and possible masks. For each trial, an array of six stimuli appears on the screen for 150 ms. In (A), (C), and (E), the targets have two shapes, while in (B), (D), and (F), the targets have one shape. Then, a mask follows for 300 ms. In (A) and (B), the mask consists of four dots with simultaneous offset (so no image remains on the screen after the stimuli disappear), in (C) and (D) the mask consists of four dots with delayed offset, and in (E) and (F) the mask is a pattern mask.

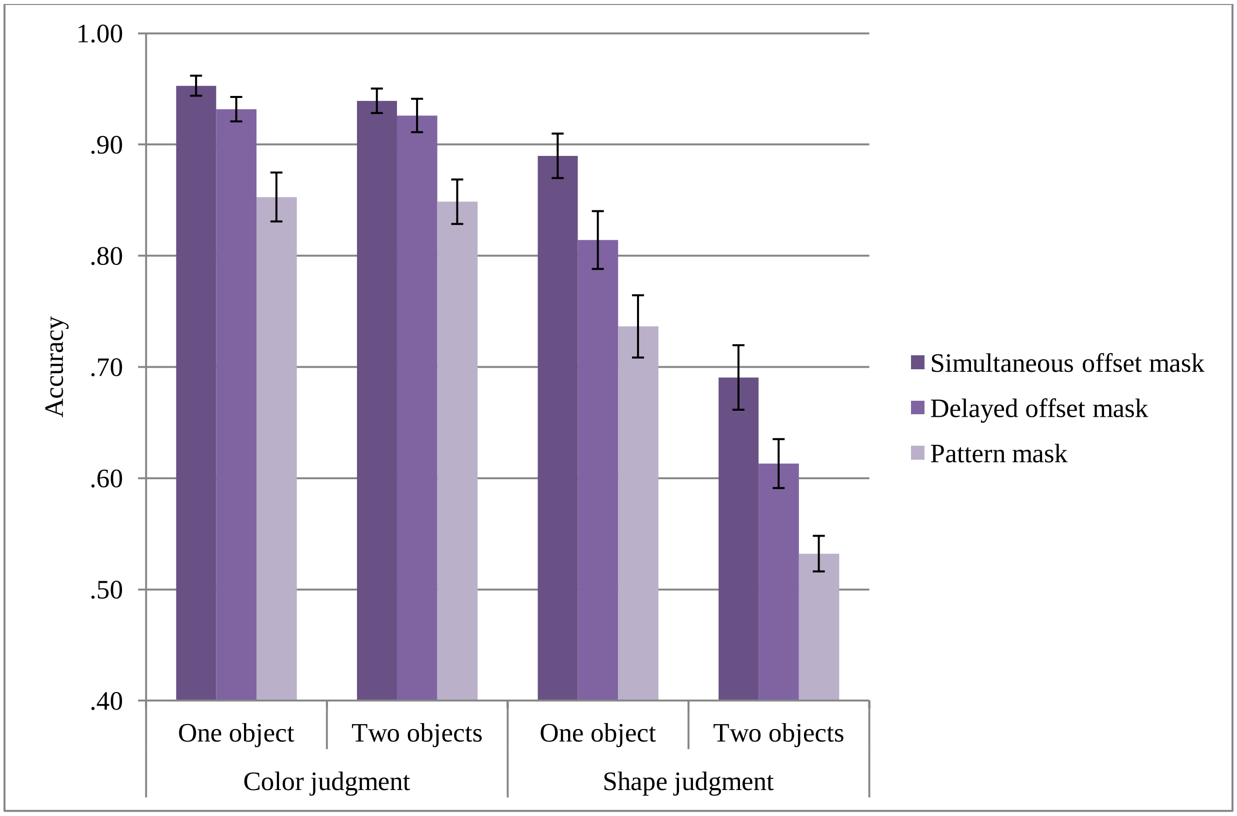


Figure 6. Results of Experiment #3. Accuracy as it is affected by judgment type (color or shape), number of objects (one or two), and mask type (simultaneous offset, delayed offset, or pattern mask). Error bars represent ±1 SE. The delayed offset mask significantly decreased accuracy for the shape judgment when two objects were shown as well as when one object was shown.

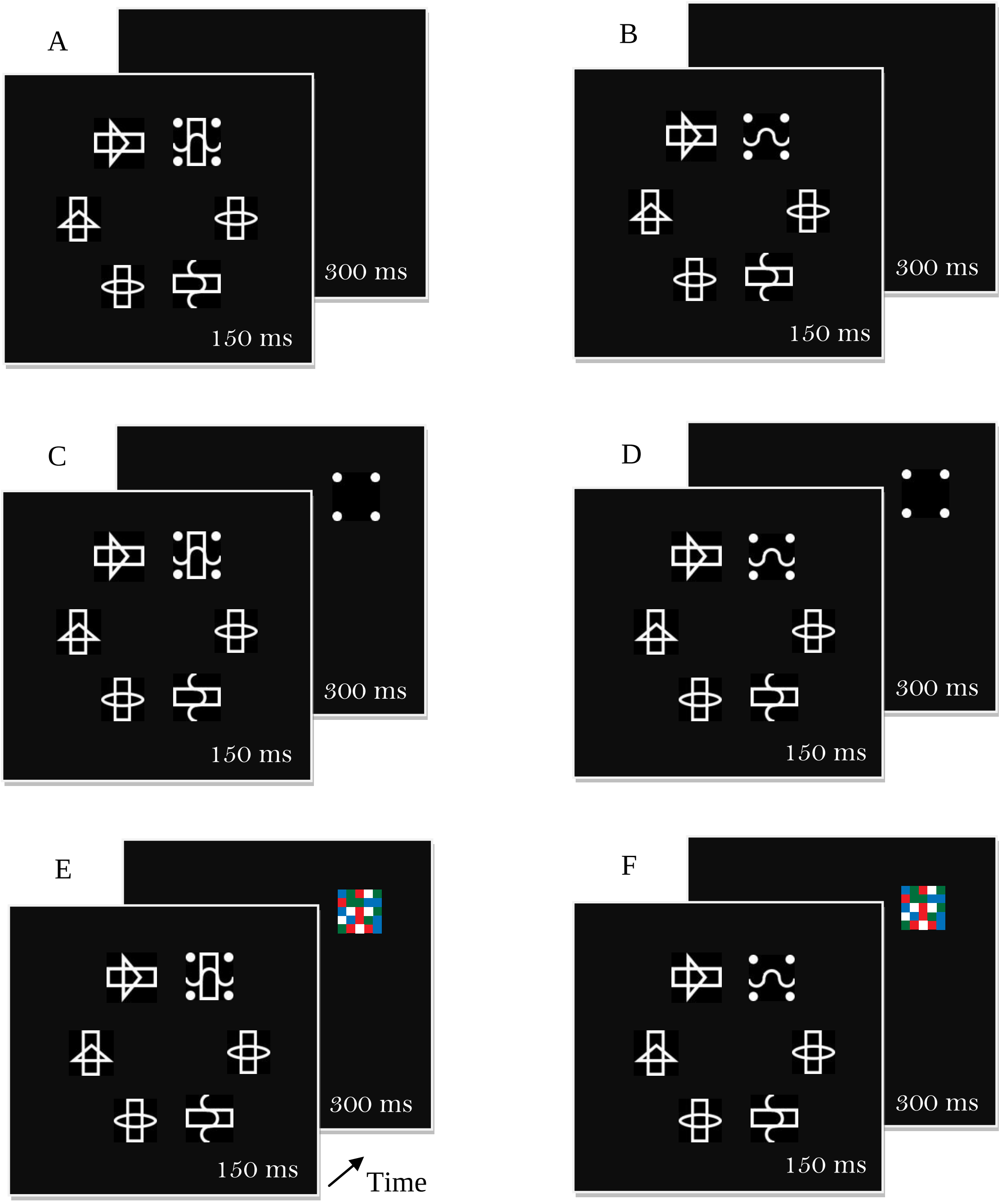


Figure 7. Experiment #4. Stimuli arrays and possible masks. For each trial, an array of six stimuli appears on the screen for 150 ms. In (A), (C), and (E), the targets have two shapes, while in (B), (D), and (F), the targets have one shape. Then, a mask follows for 300 ms. In (A) and (B), the mask consists of four dots with simultaneous offset (so no image remains on the screen after the stimuli disappear), in (C) and (D) the mask consists of four dots with delayed offset, and in (E) and (F) the mask is a pattern mask.

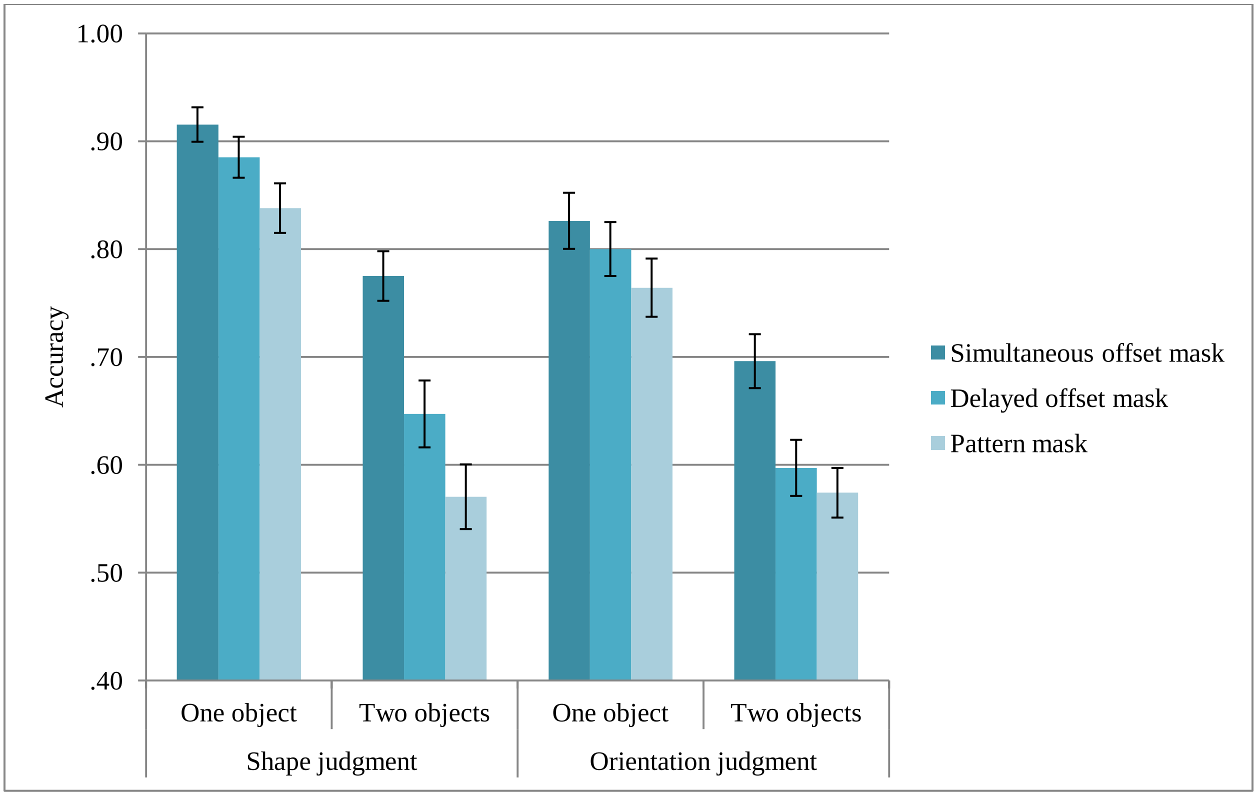


Figure 8. Results of Experiment #4. Accuracy as it is affected by judgment type (shape or orientation), number of objects (one or two), and mask type (simultaneous offset, delayed offset, or pattern mask). Error bars represent ±1 SE. The delayed offset mask significantly decreased accuracy for the orientation judgment when two objects were shown as well as for the shape judgment when two objects were shown.

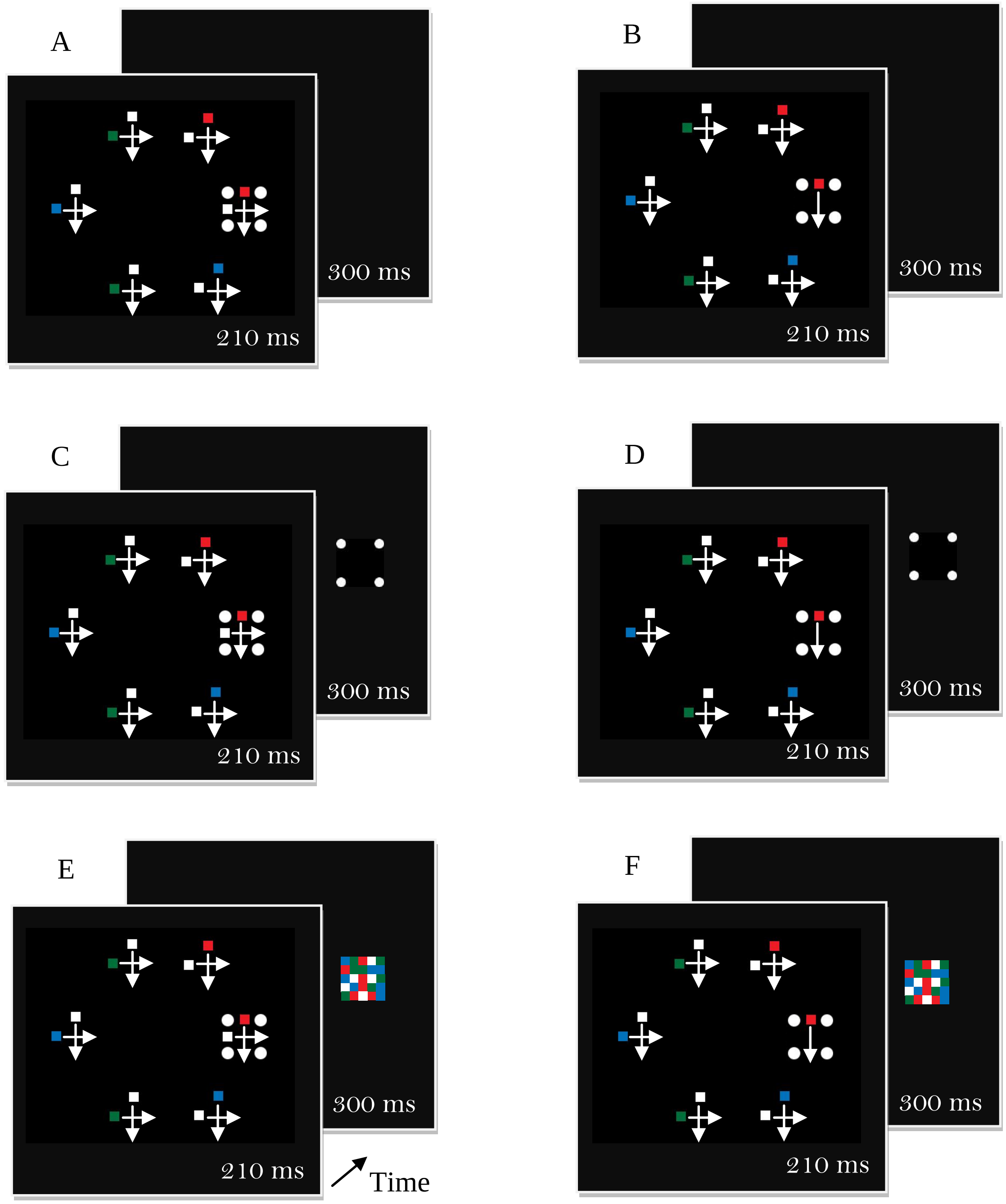


*Figure 9.*Experiment #5. Stimuli arrays and possible masks. The arrows indicate motion; they were not shown in the experimental display. For each trial, an array of six stimuli appears on the screen for 210 ms. In (A), (C), and (E), the targets have two dots, while in (B), (D), and (F), the targets have one dot. Then, a mask follows for 300 ms. In (A) and (B), the mask consists of four dots with simultaneous offset (so no image remains on the screen after the stimuli disappear), in (C) and (D) the mask consists of four dots with delayed offset, and in (E) and (F) the mask is a pattern mask.

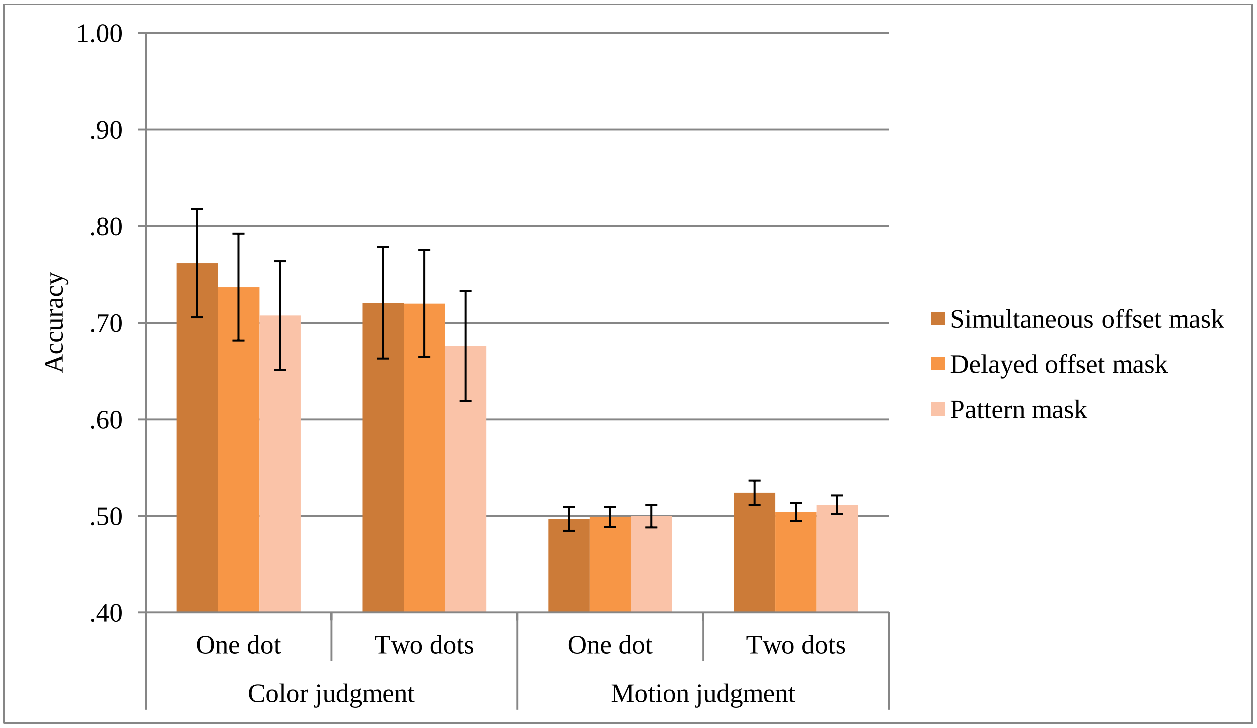


Figure 10. Results of Experiment #5. Accuracy as it is affected by judgment type (color or motion), number of dots (one or two), and mask type (simultaneous offset, delayed offset, or pattern mask). Error bars represent ±1 SE. The accuracy for the motion judgment exhibited a floor effect.

Appendix

Stimuli for Experiment #1

Horizontal blue bar

With white bar

Horizontal green bar

With white bar

Horizontal red bar

With white bar

Vertical blue bar

With white bar

Vertical green bar

With white bar

Vertical red bar

With white bar

Horizontal blue bar

Horizontal green bar

Horizontal red bar

Vertical blue bar

Vertical green bar

Vertical red bar

Stimuli for Experiment #2

Red horizontal bar

With vertical bar

Red diagonal right bar

With vertical bar

Red diagonal left bar

With vertical bar

Blue horizontal bar

With vertical bar

Blue diagonal right bar

With vertical bar

Blue diagonal right bar

With vertical bar

Red horizontal bar

Red diagonal right bar

Red diagonal left bar

Blue horizontal bar

Blue diagonal right bar

Blue diagonal left bar

Stimuli for Experiment #3

Blue circle on top

With rectangle

Green circle on top

With rectangle

Red circle on top

With rectangle

Blue circle on bottom

With rectangle

Green circle on bottom

With rectangle

Red circle on bottom

With rectangle

Blue circle

Green circle

Red circle

Stimuli for Experiment #3

(continued)

Blue rectangle on top

With circle

Green rectangle on top

With circle

Red rectangle on top

With circle

Blue rectangle on bottom

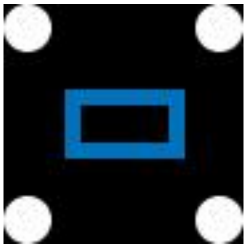
With circle

Green rectangle on bottom

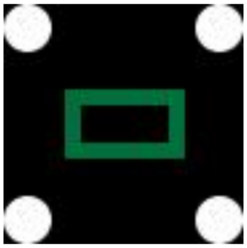
With circle

Red rectangle on bottom

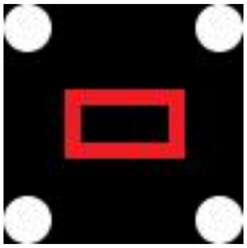
With circle



Blue rectangle



Green rectangle



Red rectangle

Stimuli for Experiment #4

Horizontal curvy line

With rectangle

Horizontal ellipse

With rectangle

Horizontal triangle

With rectangle

Vertical curvy line

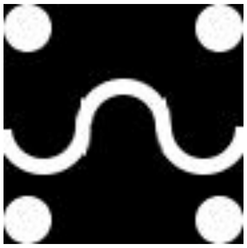
With rectangle

Vertical ellipse

With rectangle

Vertical triangle

With rectangle

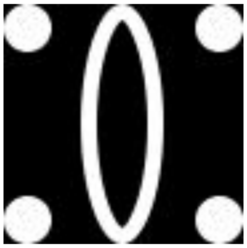


Horizontal curvy line

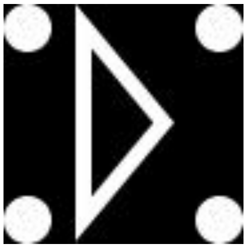
Horizontal ellipse

Horizontal triangle

Vertical curvy line

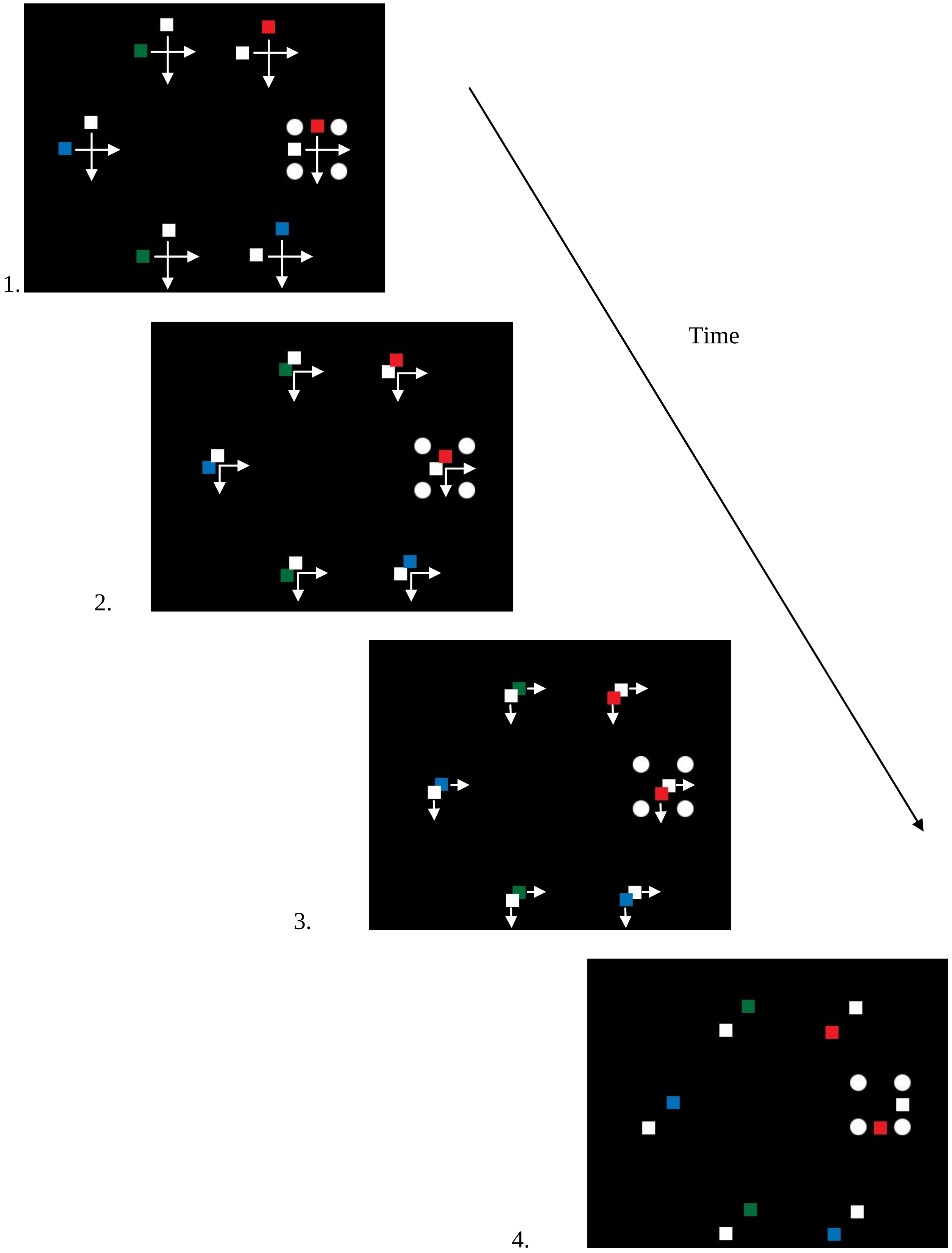


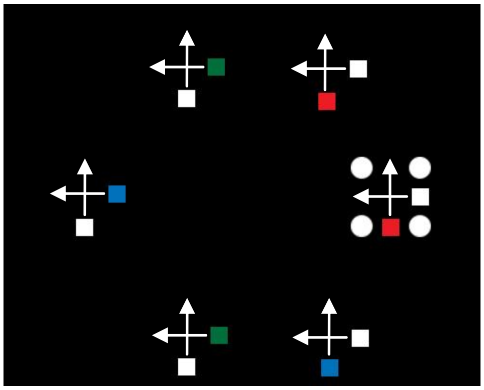
Vertical ellipse



Vertical triangle

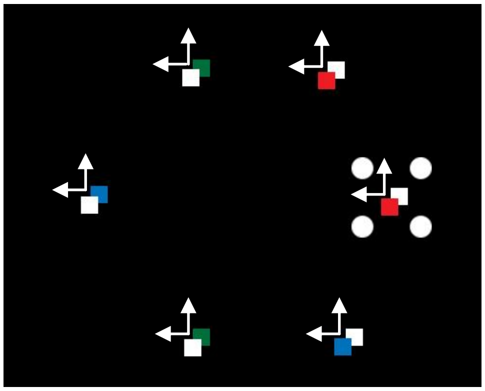
Stimuli for Experiment #5



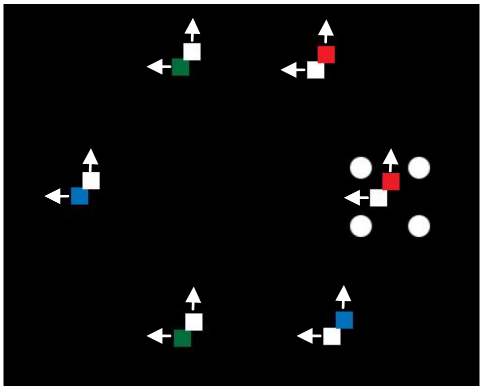


4. (Continued)

Time



5.



6.

Note: The arrows were not displayed in the experiment.

7.