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Temporal processing of figures and grounds

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TEMPORAL PROCESSING OF FIGURES AND GROUNDS

by

Lauren Nicole Hecht

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
Philosophy degree in Psychology
in the Graduate College of
The University of Iowa

July 2009

Thesis Supervisor: Professor Shaun P. Vecera

ABSTRACT

Research on figure-ground organization focused primarily on identifying cues that are used to establish regions as figure or ground. Recently, others have demonstrated behavioral consequences of figure-ground assignment, including speeded responses and higher accuracy for figures. However, other outcomes of figure-ground assignment have been demonstrated. For example, figures' spatial resolution is enhanced for figures relative to grounds. Still, the consequences of figure-ground assignment can extend beyond spatial processing to other domains, including temporal processing.

To investigate the consequences of figure-ground assignment for temporal processing, I first examined whether targets could be perceived as appearing temporally earlier on figures than on grounds (i.e., prior entry effect). My results suggest that figural regions are available to perceptual level processes sooner than grounds. Upon confirming a prior-entry-like effect for figures, I then examined other temporal processing differences between figures and grounds. Specifically, I demonstrated that targets presented on figures are perceived as offsetting later than targets appearing on grounds, suggesting that figures receive extended perceptual level processing relative to grounds. Consequently, I found that extended processing of figures degrades temporal resolution compared to ground regions. Finally, I presented a computational model that captures the temporal processing effects of figure-ground assignment, demonstrating that these effects can arise from a single architecture.

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph. D. thesis of

Lauren Nicole Hecht

has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
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ABSTRACT

Research on figure-ground organization focused primarily on identifying cues that are used to establish regions as figure or ground. Recently, others have demonstrated behavioral consequences of figure-ground assignment, including speeded responses and higher accuracy for figures. However, other outcomes of figure-ground assignment have been demonstrated. For example, figures' spatial resolution is enhanced for figures relative to grounds. Still, the consequences of figure-ground assignment can extend beyond spatial processing to other domains, including temporal processing.

To investigate the consequences of figure-ground assignment for temporal processing, I first examined whether targets could be perceived as appearing temporally earlier on figures than on grounds (i.e., prior entry effect). My results suggest that figural regions are available to perceptual level processes sooner than grounds. Upon confirming a prior-entry-like effect for figures, I then examined other temporal processing differences between figures and grounds. Specifically, I demonstrated that targets presented on figures are perceived as offsetting later than targets appearing on grounds, suggesting that figures receive extended perceptual level processing relative to grounds. Consequently, I found that extended processing of figures degrades temporal resolution compared to ground regions. Finally, I presented a computational model that captures the temporal processing effects of figure-ground assignment, demonstrating that these effects can arise from a single architecture.

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CHAPTER I

INTRODUCTION

The human visual system continually establishes a suitable representation of the external world that allows for efficient interaction with the environment. With each movement of the eyes, a wide array of information is received by the visual system, where it must be constructed into a meaningful percept. Because humans' eyes often move about the visual scene quite rapidly, the visual system must work very quickly to construct a coherent representation from a seemingly ambiguous assortment of shapes, colors, and textures. As is the case with all of the senses, vision can offer an interpretation of the environment that can help to clarify the representation generated from other senses or at times generate an interpretation that is not possible through at least one other sense. For example, it may be difficult to adequately determine that the top of a doorway is too short to walk through without having to duck. Aspects of this scenario may be simplified by establishing a visual, as opposed to auditory or tactile, representation of the problem: identifying the doorway as such, determining where it is located, and comparing the height of the individual and the height of the doorway.

Still, each collage of ambiguous information in the retinal image can be interpreted in multiple ways. Thus, the visual system's task of interpreting the external world is not trivial; it could be demanding and daunting, quickly overwhelming the visual system and its resources. Fortunately the visual system utilizes a wide variety of processes in order to form a coherent representation of the world, many of which are heuristics that allow the system to generalize its interpretation of patterns emerging in the image. Heuristics are not always accurate, but they provide a means of organizing, in a timely fashion, the vast amount of information in the visual scene. Some heuristics help interpret aspects of the image, such as depth, while others reflect processes that combine information to be treated as a single perceptual group, designated as more important than the surrounding, irrelevant information (i.e., figure-ground organization).

More precisely, figure-ground assignment is defined as the process by which the visual system forms or groups information together into regions and then segregates those regions into figures that fall in the foreground (i.e., occluding regions) and grounds that fall into the background (i.e., occluded regions; Palmer & Rock, 1994). For instance, this process allows the image of a set of car keys to be treated as a separate object from the papers lying on the desk. Having established the keys as a foreground figure, the papers on the desk fall into the background and may be processed differently from the keys. Figure-ground organization serves two main purposes: 1) to recognize cues that allow features to be perceptually grouped (i.e., features that seemingly belong together) and 2) to use those grouping cues to treat visual information separately (i.e., relevant vs. irrelevant).

Due to the direct influence of perceptual grouping cues on establishing figure-ground assignment, most figure-ground research has focused primarily on identifying and examining the relevant cues. The image-based cues associated with figure-ground organization include area, symmetry, and convexity (Palmer, 1999, 2002; see also Pomerantz & Kubovy, 1986, Rock, 1975, 1995, and Rubin, 1915/1958). Regions established as figure typically have a smaller area than grounds and are often surrounded by grounds, as in the case of a pen placed on the desk. Symmetric regions tend to be perceived as figure and these foreground regions typically contain more convexities than the ground.

Additionally, Vecera, Vogel and Woodman (2002) discovered that lower-regions in a visual scene (i.e., those that fall below the horizon-line) are also more frequently treated as figures. Phenomenologically, figures appear closer to the observer. Given that relative position of an item in the field of view can impact depth perception such that items lower in the visual field tend to be closer in depth, Vecera et al. reasoned that the lower region in a vertically aligned display should be perceived as the closer region (i.e., figure) more frequently.

Other researchers went beyond the image-based cues that influence figure-ground assignment and examined the impact of early perceptual processes. Klymenko, Weisstein, and colleagues extensively studied the impact of spatial perception and temporal perception (e.g., Klymenko & Weisstein, 1986, 1989a, 1989b; Klymenko, Weisstein, Topolski & Hsieh, 1989) on figure-ground organization. Klymenko and Weisstein (1986) first presented participants with two regions varying in their spatial frequency (i.e., the number of sinusoidal grating cycles per degree of visual angle). They found that regions containing higher spatial frequencies were more frequently perceived as the figure. In contrast when two regions varied in their temporal frequency (i.e., rate of on-off flickering), those containing *lower* temporal frequencies were perceived as figure more frequently and for longer durations than were regions of high temporal frequencies (e.g., Klymenko & Weisstein, 1989a, 1989b). In conjunction with their previous work, Klymenko and Weisstein (1989a, 1989b) predicted that there may be an interaction between spatial and temporal frequency channels, giving rise to the tradeoff found within regions preferentially treated as figure.

Klymenko et al. (1989) confirmed an interaction between spatial and temporal frequency by presenting spatially varying stimuli with a constant temporal frequency. This condition replicated their previous results, demonstrating an association between regions of high spatial frequency and figural assignment. Additionally, they again found that regions of low temporal frequencies were associated with the perception of a foreground figure, when spatial frequency was held constant. Critically, they further manipulated both spatial and temporal frequencies, varying both systematically, to determine the extent of the interaction between spatial and temporal frequencies and the impact of that interaction on figure-ground assignment.

As Klymenko et al. (1989) predicted, they found that when spatial frequency was at its highest, this region was perceived as figure regardless of the temporal frequency of the region. Likewise, the lowest temporal frequency region was preferred as figure regardless of the spatial frequency. Interestingly, when the spatial and temporal frequencies were close between the regions, assignment was reliant upon the temporal frequency, suggesting that the temporal channel may play a more critical role in figure-ground organization when spatial frequency is ambiguous.

However, figure-ground assignment is not a strictly bottom-up process that only takes image-based cues and early visual processes into account. Rather, higher-level perceptual processes (e.g., object-recognition and attention) can impact it in a top-down fashion. Peterson (1994, 1999; see also Peterson & Gibson, 1991, 1993, 1994, Peterson, Harvey & Weidenbacher, 1991, Rock, 1975, and Vecera & O'Reilly, 1998, 2000) demonstrated that familiar objects (e.g., the profile contour of a face, tree, or a woman) are treated as foreground figures for longer durations than unfamiliar regions.

Later, Vecera, Flevaris and Filapek (2004) demonstrated that drawing attention to a region prior to its appearance increases its likelihood of being perceived as a figure. Their results contradicted previous claims that attention only operates once figure-ground assignment is complete (i.e., it does not automatically impact figure-ground assignment). Previous researchers believed figure-ground assignment is a preattentive process that operates in parallel across the visual field before focal attention processes are operating (e.g., Julesz, 1984), a view which was supported by Baylis and Driver (1995; Driver & Baylis, 1996). However, Vecera et al. made one critical change in their design that allowed them to find an impact on figure-ground assignment: allocating exogenous attention to a location occupied by the figure or ground.

Moreover, Vecera et al. (2004) found that allocating exogenous attention can begin to override image-based cues to figure ground assignment. From this, they concluded that figure-ground assignment does not require the use of spatial attention and does not need to be complete prior to use of spatial attention: figure-ground assignment and spatial attention are interactive processes implying a close marriage between these two processes that may be dependent upon the current visual stimuli at any situation. Another implication this offers is that figure-ground processes may be able to take advantage of those offered within attention (i.e., they may be able to rely upon the same behavioral mechanisms).

Despite the vast research on the cues used to perform figure-ground organization, less attention has been given to establishing the consequences of figure-ground assignment.

The aforementioned studies have revealed cues and perceptual processes that can distinguish the foreground figure from the background. Nonetheless, it is important to understand what impact figure-ground assignment has on other perceptual processes, if any. Is figure-ground assignment the end result of perceptual organization processes, with its only impact being designation of a region as figure or ground, or are there other behavioral consequences for distinguishing between these regions?

Some researchers moved beyond identification of figural cues and examined the consequences, or effects, of figure-ground assignment. One of the first noted effects of figure-ground assignment, aside from the designation of relative relevance, was a perceived increase in salience and "shape-ness" of the "thing-like" figure (Rubin, 1915/1958). Rubin discussed the role of the shared contour between two overlapping regions. He noted that the contour typically denotes the shape of an object by outlining its boundaries; the ground, however, continues behind the contour leaving an observer without a clear representation of its structure. Other researchers have also claimed figures are "more strongly structured, and more impressive" (Koffka, 1935) and appear closer to the viewer (Palmer & Rock, 1994). Yet the mechanisms behind these perceptions and the behavioral consequences they evoke are now being explored.

Researchers studying the behavioral effects of figure-ground assignment noted figural benefits: faster and more accurate discriminations of targets on the figure relative to those appearing on the ground (e.g., Lazareva, Castro, Vecera & Wasserman, 2006; Nelson & Palmer, 2007), greater sensitivity for detecting high spatial frequency targets on figures (Wong & Weisstein, 1982, 1983), and better memory for figures than grounds both in the long-term spanning several minutes or longer (see Dutton & Traill, 1933, and Rubin, 1915/1958) and in the short-term spanning a few hundred milliseconds (see Driver & Baylis, 1996). The speed and accuracy figural benefits are robust and generalize across species. Lazareva et al. (2006) found that pigeons were able to peck at a target on a figure more rapidly than when it appeared on a background, but only when the pigeons also had to report if the target was on an object (the figure) or the background. Pigeons were also more accurate to report which region was figure after learning to distinguish between the two regions.

A similar result is seen in humans. Nelson and Palmer (2007; also see Lazareva et al., 2006) showed participants two-region displays containing a clear figural assignment due to the presence of a familiarity cue (e.g., the profile contour of a face). Then they presented a target on either the figure (i.e., face region) or the ground, near the contour shared between the regions. They found that when the target fell on the figure, participants were faster and more accurate at discriminating the target's identity than when the target was located on the background.

Wong and Weisstein (1982) reported a similar result. They compared observers' ability to detect and discriminate targets within the foreground figure and the background. Wong and Weisstein presented face-vase stimuli to observers, and a tilted line would appear either on the face or the vase region. Observers maintained one region (e.g., face) as figure for an entire block of trials because these stimuli are ambiguous in regards to figure-ground assignment. Weisstein and Wong found that tilted lines were better detected and discriminated on figures than on grounds and on neutral backgrounds (i.e., regions that are not in competition for contour assignment). These results were consistent with previous research that found differences in processing by figures and grounds, specifically that figures are processed to a higher degree of resolution than grounds (Julesz, 1978).

However, Wong and Weisstein's (1982) results could have been attributed to attention: targets appearing at the attended location (i.e., figure) are discriminated with higher accuracy. To rule out explanations of attention, Wong and Weisstein (1983) further examined target processing within figure and ground regions by manipulating the targets that participants detected (i.e., sharp versus blurry). They found that sharp targets were more readily detected within figures, but blurry targets were more readily detected within the background, aligning with previous work indicating that figures tend to have higher spatial frequencies (Klymenko & Weisstein, 1986, 1989a, 1989b; Klymenko et al., 1989) and higher degrees of resolution (Julesz, 1978). Consideration of other research on spatial frequency channels indicates that low spatial frequencies have temporal constraints. Specifically, these channels have a shorter latency (Breitmeyer, 1975; Lupp, Hauske & Wolf, 1976; Vassilev & Mitov, 1976) and shorter integration of time constants (Nachmias, 1967; Tolhurst, 1975). If grounds are processed via low spatial temporal frequency channels (Klymenko & Weisstein, 1986; Klymenko et al., 1989; Weisstein, Maguire & Brannon, 1982), then figure-ground assignment may have consequences that reflect the interaction with spatial and temporal processing. In other words, more complex and structured consequences may result from assigning regions as figures or grounds, rather than the observed salience or response benefits.

Given the influence temporal and spatial perception each have on figure-ground assignment (see above), a reverse impact of assignment on temporal and spatial perception may also exist. The spatial frequency processes that impact figure-ground assignment may also be impacted once assignment is complete, even if spatial frequency is not directly used in establishing figural assignment. However, Weisstein and Wong's (1982, 1983) experiments establish figure-ground assignment by instructing participants to explicitly hold one region as figure; they used an endogenous manipulation of attention. Therefore, the benefits for high spatial frequency on the figure region may reflect a consequence of endogenous attention, which enhances spatial resolution (Liu, Abrams & Carrasco, 2009) relative to unattended locations (e.g., the ground).

Consequently, performance benefits and the reported enhanced salience for figures may reflect a change in spatial processing, though attention effects must be ruled out. To examine this potential consequence of figure-ground assignment, Cosman, Hecht and Vecera (in review) conducted a series of experiments that not only ruled out attentional effects but also demonstrated a change in spatial resolution for figures relative to grounds. More specifically, Cosman et al. demonstrated that the benefit for figures was a result of perceptual enhancement and not processing priority.

In a perceptual enhancement account, establishing the region as figure can increase the gain of the input channels' processing relative to the ground's input channels. In contrast, the processing priority account suggests that figure-ground assignment biases the order in which the regions are processed. Specifically, figures are processed before grounds, providing the impression that they are also more salient than grounds. In their experiments, participants viewed two-region displays containing a figure region (i.e., a convex, symmetric shape) and a ground region (i.e., a concave shape). By holding processing priority constant, they were able to assess the perceptual enhancement account.

To hold priority constant, they assigned processing priority to a feature that was orthogonal to the figure-ground assignment (e.g., the color of the region containing the target information). Participants then completed a difficult spatial judgment regarding the angles forming the convexity or concavity of the region of matching color. Prior to beginning the experiment, participants were informed which color region would contain the relevant target information. They used the apex of the angle at the center of the display to compare to the outer angle forming the convexity or concavity of the colored region for which they were reporting. Participants discriminated the height of these angles relative to one another by indicating which angle (left or right) was higher (or lower) than the other.

Cosman et al. (in review) found that figures were perceptually enhanced: accuracy was higher for apex judgments on figures than on grounds at all but the smallest apex offsets. Moreover, this enhancement was present when the figure and ground regions were abutting, but not when the regions were separated or presented individually, demonstrating that the shared contour between the regions used to complete figure-ground assignment was critical in producing the effect on spatial resolution. In other words, removing figure-ground assignment eliminated the effect. Thus, Cosman et al. demonstrated that within the spatial domain, processing priority alone could not account for figural benefits: figures were perceptually enhanced compared to other regions. Therefore, the increased spatial resolution of figures enhances the perception of the figure and targets on its surface resulting in not only increased salience but also in faster and more accurate target discriminations on this region.

In spite of this, as the work of Weisstein and colleagues suggests (see above), the consequences of figure-ground assignment may extend beyond that of the spatial domain and impact temporal processing. As mentioned above, targets appearing on figures are afforded quicker and more accurate discriminations than non-figural targets (e.g., Lazareva et al., 2006; Nelson & Palmer, 2007; Wong & Weisstein, 1982, 1983). Although perceptually enhanced spatial resolution of figures may be able to account for the accuracy results, it is not necessarily the only way to account for the speed of response. Increased spatial resolution may not speed the processing duration for perception (i.e., figures and grounds are processed for the same duration but at different levels or amounts of processing). Instead there may be temporal consequences resulting from figure-ground assignment: figures may begin processing earlier than grounds, allowing participants to make faster and more accurate judgments.

As noted by Vecera et al. (2004) figure-ground assignment may be afforded use of the same mechanisms used by spatial attention. Supporting this perspective, researchers have found that allocating visual spatial attention can enhance spatial resolution at that location in order to facilitate target discrimination (e.g., Yeshurun & Carrasco, 1998, 1999, 2000) and that it generally facilitates perceptual processing, such that events at the attended region are perceived as occurring earlier than those at unattended regions (e.g., Schneider & Bavelier, 2003; Shore & Spence, 2005; Shore, Spence & Klein, 2001; Stelmach & Herdman, 1991; see also Frey, 1990). The spatial enhancement results parallel those found by Cosman et al. (in review) in which figure-ground assignment also yielded perceptual enhancement, possibly due to use of the same mechanism. Since there is an apparent interaction between spatial attention and figure-ground assignment and a demonstrated influence of both spatial and temporal processing on figure-ground assignment, I conjectured that the temporal consequences of spatial attention might also extend to figure-ground assignment by way of a shared or similar mechanism, providing evidence that response benefits for figures can also be explained by a change in temporal processing (i.e., a consequence of figure-ground assignment on temporal perception).

In this dissertation, I investigated the impact of figure-ground assignment on temporal perception. In Chapter II (Experiments 1-4), I examined whether establishing figure-ground organization affects temporal processing. Specifically, I asked whether perceptual processing is initiated earlier on figures than on grounds. To answer this question, participants made temporal order judgments (TOJs) for the onset of target events on the figure compared with onsets on the ground. TOJs were more accurate when onset targets appeared on the figure than on the ground, such that in order to perceive the onsets as occurring simultaneously, the ground target would need to lead (i.e., onset earlier than) the target on the figure.

The experiments in Chapter III then assessed the duration of perceptual processing for figures relative to grounds (Experiments 5-7). The increased salience effect and the response benefits for figures may not only be attributed to early perceptual processing but also to the duration of processing. In particular, figures may be afforded extended processing durations relative to grounds. To examine this, participants performed TOJs for the offset of targets within the figure and ground regions. In accordance with the extended duration hypothesis, offset detections were more accurate for the ground.

In Chapter IV, I examined a prediction made from an extended processing duration account: if figures are afforded extended processing durations, then the temporal resolution within this region should be decreased relative to the ground. Establishing a region as ground enhances the temporal resolution of this region relative to figures, aligning with the finding that higher temporal frequencies tend to be perceived as ground (e.g., Klymenko et al., 1989; Klymenko & Weisstein, 1989a, 1989b). In a modified flicker-fusion task, reports were more accurate at discriminating a target's feature when the flickering target was on the ground rather than the figure, suggesting that there was an increased temporal resolution within the ground allowing the flicker to be perceived more accurately. The results of this experiment further support the conclusion from Experiment 6-8: extended processing of figures.

Finally, in Chapter V, I present a neurally plausible model (i.e., dynamic field theory: DFT) of a mechanism that accounts for both the onset and offset performance for figure-ground organization and the temporal effects of spatial attention. This model posits that neural populations processing the figure are more active, resulting in a peak of activation that is building toward piercing threshold, which it easily does first when the onset of a target is presented. However, this same enhanced activation for the figures is sustained when the target is present, creating difficulties in the perception of the target's offset. This model was used to successfully simulate the behavioral data collected in Experiments 1-8. Taken together, these studies demonstrate that figure-ground assignment can impact temporal perception, resulting in processing differences between figures and grounds.

CHAPTER II

PRIOR ENTRY FOR FOREGROUND FIGURES

Current figure-ground research is beginning to move beyond examining the bottom-up and top-down cues of figure-ground assignment (see Chapter I for discussion) and is focusing on the consequences establishing this assignment has on other perceptual processes. For example, Cosman et al. (in review) demonstrated that designating a region as the foreground figure results in its perceptual enhancement, providing finer spatial resolution within the figure relative to the resolution of the background. In the current chapter, I present a series of experiments that further examined the consequences of figure-ground assignment by focusing on differences in temporal processing within the figure and ground regions. Specifically, these experiments were designed to determine whether figures become available for perceptual processing earlier than grounds.

Phenomenologically, figures appear more shape-like and more salient than grounds (Rubin, 1915/1958). One possible source for the increased perceptibility of figures over grounds is that figures might be processed faster than grounds, allowing figures to become available for perceptual processing earlier than grounds. Numerous studies of visual attention have suggested that attended events are perceived before unattended events, a finding termed the 'doctrine of prior entry' (Shore & Spence, 2005; Shore, Spence & Klein, 2001; Titchener, 1908). The current experiments asked if non-attentional factors, such as scene properties that affect figural status, produce prior-entry-like effects. In short, do some portions of scenes (figures) receive perceptual processing ahead of others (grounds)?

Prior entry is typically studied using temporal order judgment (TOJ) tasks in which participants report which of two targets appeared first. The delay between the targets' onsets varies (the stimulus onset asynchrony, SOA), and attention is directed to one of the targets before it appears. Targets at attended locations are perceived as occurring earlier than targets at unattended locations. Although early studies of prior entry were subject to alternative explanations, such as response bias (see Pashler, 1998), more recent studies have ruled out response biases.

For example, Shore et al. (2001) had participants report a target dimension that was orthogonal to the direction of attention and included a condition in which participants reported which stimulus appeared second. They implemented these changes to avoid two potential sources of response bias. The first methodological change addressed the possibility that individuals were reporting which target appeared at the location of the cue, regardless of their perception of the events' timing.

In previous experiments (e.g., Schneider & Bavelier, 2003; Stelmach & Herdman, 1991) participants reported the location (left, right) of the target that onset first. Given that the cue also appeared to the left or right of fixation, the response of left could either indicate that the target on the left was perceived to onset first or that participants responded to the cued target's location regardless of the perception of the onsets. The latter would shift the results such that it appeared that the unattended item would need to appear earlier in order to be perceived as occurring first since responses would be biased toward the attended region, mimicking the results that would be found if the cued target was in fact perceived to occur earlier then the unattended (i.e., uncued) target. By having individuals report a dimension orthogonal to the direction of attention (e.g., horizontal or vertical), these two possibilities could be disentangled.

The second methodological change made by Shore et al. (2001) was implemented to determine whether participants preferentially responded to the attended target, regardless of whether they respond to its location or another orthogonal dimension. Put another way, participants' tendency may be to always report the attended item as appearing first. If this is the case, then participants would still report the attended target item when asked to report which item appeared second.

Shore et al. (2001) were not the first to use this procedure. Frey (1990) had participants provide both reports and found that participants did in fact have a response bias: regardless of which question they were answering ('which first?' or 'which second?'), participants always reported the target at the attended location. Consequently, the results were contradictory, with the 'which first?' procedure yielding a prior entry effect, and the 'which second?' procedure yielding the reverse (i.e., that attended targets must lead unattended targets for both events to be perceived as simultaneous). It is important to note, however, that an orthogonal cuing procedure (i.e., responses not linked to the direction of cuing; see above) was not used in this study. Still, Shore et al., observed prior entry effects under these more stringent conditions, suggesting that attention speeds perception (Shore et al., 2001).

To determine if a prior entry effect exists for figure-ground processes, I followed previous work and used a TOJ task that eliminated response biases. Participants viewed displays containing two regions (Figure 1); two targets, an 'x' and an 'o,' then appeared, one on each region. The interval between the targets' onset varied, and participants reported which target, x or o, appeared first or which appeared second. Any bias in responding first to targets on figures would be eliminated when reporting which target appeared second (Shore et al., 2001).

This procedure allowed me to compute the point of subjective simultaneity (PSS), a common statistic used to examine prior entry (see Shore & Spence, 2005). The PSS reflects the time at which participants discriminate the temporal onsets with 50% accuracy; that is, the PSS is the point at which participants would perceive the stimuli as simultaneous, though this is not typically tested directly. I computed the percentage of time the target (x or o) was judged as occurring first or second in order to calculate the PSS for each observer. If targets on the figure were perceived as occurring earlier than targets on the ground, then targets on the ground would need to appear before those on the figure for the two targets to be perceived as occurring at the same time. Thus, if targets on figures are perceived as occurring earlier than those on grounds, the PSS should be significantly different from zero.

Experiments 1 and 2

Method

Participants. Thirty-two University of Iowa undergraduates with normal or corrected-to-normal vision volunteered for course credit. Sixteen volunteers participated in each experiment.

Stimuli. Figure 1 depicts the two different display types, one with a strong figure-ground assignment (Figure 1A) and the other with an ambiguous figure-ground assignment (Figure 1C). Each display contained a green region (RGB = 0, 132, 0) and a red-orange region (RGB = 238, 83, 15). Each color occurred equally on the left and right regions. Displays appeared against a black background.

In figure-ground displays, the symmetric, convex figure subtended approximately 3.73º by 4.60º of visual angle; the concave, shaded ground region subtended approximately 3.34º by 3.73º. Both regions were equally likely to appear on either side of fixation. There were two types of ambiguous displays, one with two convex regions and another with two concave regions. Each region in a convex display measured 3.58º by 4.60º, and each region in a concave display measured 3.42º by 3.80º. The ambiguous displays lacked the depth cues present in the figure-ground displays, thereby eliminating strong figure-ground assignment.

Two targets were presented in each display, with one target appearing on each shape. The targets were a small ‘x’ and ‘o’ that subtended approximately 0.40º by 0.40º of visual angle. The targets were the same color as the region on which they were presented, thereby eliminating the appearance of the targets being superimposed over the displays. Across trials, each target appeared equally on each region of the display and appeared 1.80° from fixation.

Procedure. Figure 2 illustrates events and their durations in a single trial. Each trial began with a 500 ms fixation point that participants were instructed to fixate throughout each trial. The fixation point appeared on the contour between the two regions. A figure-ground display was then presented for 500 ms, followed by the two targets, presented at differing onsets. The targets appeared to grow out of the middle of the displays and then recede by varying the shadow lengths cast by the targets. The targets grew and receded across 225 ms. One target appeared and started its movement before the second target; the second target appeared and began moving with stimulus onset asynchronies (SOAs) of 26, 50, 100, and 150 ms; SOAs were randomized throughout the experiment. The target on the figure moved ahead of that on the ground on half of trials and conversely on the other half of trials. Negative SOAs corresponded to targets on the figure as moving first; positive SOAs corresponded to targets on the ground as moving first.

Participants judged which target (x or o) appeared to move first (Experiment 1) or judged which target appeared to move second (Experiment 2). Participants performed 512 trials and responded via key press.

Results and Discussion

The results appear in Figures 3A (Experiment 1) and 3B (Experiment 2), which depict the proportion of the time the target on the ground was judged as moving first or second averaged across all participants. The curves shown in Figure 3 are the best-fitting logistic functions fitted to the average data. All statistical analyses, however, were based on the best fitting logistic curves fitted to each participant's data (see Figures 4 and 5 for Experiments 1 and 2, respectively). The curve fits for individual observers produced R^2 values of 0.95 or higher.

As is evident from Figures 3A and 3B, the percentage of trials in which the target on the ground was perceived as moving first increased as SOA increased. More importantly, however, is the rightward shift in the PSS for the figure-ground stimuli compared to the ambiguous stimuli: Participants required the target to move earlier on the ground to perceive the targets as moving simultaneously. This pattern of results was observed in a majority (70%) of participants.

To quantify these observations, I calculated a PSS for each observer based on that observer's best fitting logistic function; the PSS was computed as the point at which the observer reported seeing each target as moving first equally. For both experiments, accuracy of reports for the concave ambiguous displays (Experiment 1: 83%; Experiment 2: 84%) was higher than for convex ambiguous displays (Experiment 1: 65%; Experiment 2: 74%). Although this difference was significant (Experiment 1: $t(15) = 9.03$, $p < 0.05$; Experiment 2: $t(15) = 3.71$, $p < 0.05$), higher accuracy for concave regions in the figure-ground displays would result in a ground advantage, rather than the predicted figural advantage. Therefore, despite the difference in accuracy between these ambiguous displays types, performance was averaged across these displays for the remaining analyses.

Analysis of the PSSs indicated that the PSS for the figure-ground displays (Experiment 1: 10.1 ms; Experiment 2: 8.8 ms) differed significantly from zero both when participants reported 'which onset first?', $t(15) = 2.22$, $p < .05$, and 'which onset second?', $t(15) = 2.25$, $p < .05$. Importantly, these PSSs were shifted rightward, toward a positive SOA indicating that the figure target must *lead* the ground target in order for the events to be perceived as simultaneous. In comparison, the PSSs for ambiguous displays (Experiment 1: -2.7 ms; Experiment 2: -2.4 ms) did not differ significantly from zero, regardless of whether participants reported which target offset first, $t(15) < 1$, *ns*, or second, $t(15) < 1$, *ns*, indicating no temporal processing advantage for either region in these displays. Moreover, the PSS for figure-ground displays was significantly different from the PSS for ambiguous displays in Experiment 1, $t(15) = 2.87$, $p < .05$, and in Experiment 2, $t(15) = 2.23$, $p < .05$.

An additional, combined analysis of the accuracy of reports from the 'which first?' and 'which second?' experiments revealed less accurate responses in the 'which first?' condition than the 'which second?' condition (79.5% versus 83.7%), $F(1, 30) = 12.10$, $p < .05$. This three-factor ANOVA on experiment task ('which first?' or 'which second?') by display type (figure-ground or ambiguous) by SOA (26, 50, 100, 150) was computed with the latter two conditions as within-subjects variables, and the former as a between-subjects variable. I found that task did not interact with the remaining factors, so I collapsed across task and again analyzed the PSSs.

Analysis of the PSSs revealed a PSS of 9.5 ms for the figure-ground displays, which differed significantly from zero, $t(31) = 3.20$, $p < .05$. This positive PSS indicates that targets on grounds must occur, on average, 9.5 ms ahead of those on figures for the two targets to be perceived as occurring simultaneously. For ambiguous displays, the PSS was -2.6 ms, which did not differ significantly from zero, $t(31) = 1.24$, $p > .20$, indicating that the targets in neither of the regions in these displays had a temporal processing advantage over the other region. The PSS for the figure-ground displays was significantly larger than the PSS for the ambiguous displays, $t(31) = 3.63$, $p < .05$.

An additional analysis was then computed after examining the curve fits: just noticeable difference (JND). The figure-ground and ambiguous-displays produced performance curves that were either shifted rightward or are centered, respectively, along the x-axis (i.e., SOA). However, the logistic functions also have noticeably different slopes (see Figures 3A and 3B). Thus, the JND was calculated because it shares a monotonic relationship with the slope of the logistic function. It determines the least amount of separation in time between two events that is required to accurately order the events with 75% accuracy. The JNDs in the current experiment were defined as half of the temporal interval between the SOA values at 75% and 25% accuracy on the psychometric function. As the JND increases, a longer amount of time is needed between target onsets to reliably order the events and the slope of the function is becoming shallower (i.e., increasing more slowly). Hence, smaller JNDs can also indicate a higher sensitivity to temporal differences in the onset events.

As Figures 3A and 3B suggest, the JND for figure-ground displays (Experiment 1: 41.6 ms; Experiment 2: 31.9 ms) was smaller than the JND for ambiguous displays (Experiment 1: 82.0 ms; Experiment 2: 52.8 ms) when participants responded 'which first?', $t(15) = 6.87$, $p < .05$, and when they responded 'which second?', $t(15) = 3.14$, $p < .05$. These results suggest that the figure-ground displays result in greater sensitivity for temporal perception than the ambiguous displays. Still, it was those same displays that also shifted perception of the order of events as evidenced by the positive PSS (see above).

The current findings support a prior entry effect of figure-ground assignment. Targets presented on figures were perceived as occurring earlier than targets appearing on grounds or on ambiguous regions. For the two targets to be perceived as occurring simultaneously, targets on the ground needed to onset earlier than those on the figure. Importantly, my procedures rule out biases to respond first to figures because I continue to find a figural advantage when participants report which target appeared second.

Although the results of Experiments 1 and 2 are straightforward, there are three issues to discuss. One concern is that the figure-ground displays were visible for 500 ms before the targets appeared to allow the regions to be fully segregated, and participants might have made eye movements and fixated one of the regions, allowing targets on figures to be processed more quickly than those on grounds. However, preferential eye fixation of one of the regions is not a straightforward alternative to my results because in temporal perception, targets in the periphery (i.e., more distant from fixation) are processed faster than central targets (e.g., Carrasco, McElree, Denisova, & Giordano, 2003). Although there are numerous differences between the current procedure and Carrasco et al.'s (2003), their results would suggest that for my results to show a temporal advantage for figures, the *ground* region—not the figural region—would need to be fixated. Such a preferential eye fixation of the ground is problematic because typically the eyes are directed toward objects (i.e., figures). Nevertheless, to address this concern, I tested an additional seven participants in the 'which first' task while monitoring eye position and excluding trials in which fixation was not maintained (less than 3% of trials). The results from this control study were similar to those from Experiments 1 and 2 (see Figure 3D; individual curve-fits are plotted in Figure 6), with a PSS on figure-ground displays of 8.8 ms, indicating that targets on the ground needed to lead those on the figure by an average of 8.8 ms to be perceived as simultaneous. For ambiguous displays, there was no systematic shift in the PSS; these displays produced a PSS of -2.3 ms. These PSS values did not differ significantly from those observed in Experiments 1 and 2: $t(37) < 1$ for the figure-ground displays and $t(37) < 1$ for the ambiguous displays. Also, when eye position was monitored, the difference in PSSs between the figure-ground and ambiguous conditions approached significance, $t(6) = 1.63$, $p = .07$ (one-tailed). Thus, my findings from Experiments 1 and 2 do not seem to be caused by participants preferentially fixating either region.

A second issue for discussion is response bias. My procedure carefully follows previous work in ruling out response bias; participants respond to target features that are orthogonal to figure-ground assignment, and I control for the order of report across Experiments 1 and 2. However, one might express the concern that with figure-ground displays a response bias is more complex. Specifically, the response bias might be to respond 'first' to targets on figures and 'second' (or, more generally, 'later') to targets on grounds. However, there are no data to support this more complex response bias; response bias need not be different for temporal order judgments following figure-ground manipulations than following attentional manipulations.

Moreover, the 'which first' and 'which second' control procedure produces more reliable results than other attempts to rule out response bias. For example, one possible procedure to rule out such a sophisticated response bias might be to include a 'simultaneous' response alternative for participants; such a response alternative would reduce a response bias by freeing participants from responding to the target on the figure when the SOAs were short and participants were uncertain about which response to make (for discussion, see Stelmach & Herdman, 1991). However, previous studies that provided a 'simultaneous' response suggest that this response is chosen inconsistently across studies. For example, Stelmach and Herdman's (1991) participants used a 'simultaneous' response infrequently (less than 5% of trials), whereas Jaskowski's (1993) participants used this response alternative on a majority of trials. Based on the results in the literature, and my own pilot work using a 'simultaneous' response, adding such a response might not conclusively rule out response bias.

A third issue concerns an alternative interpretation of my results: Attention could be attracted more to regions that contain figural cues (e.g., convexity, symmetry) than regions that lack these cues. Thus, my findings could be produced by attention, not figure-ground assignment per se. To address this alternative, in Experiment 3 participants performed the TOJ task used in Experiment 1 with displays that separated the two regions in the figure-ground displays. Separating the regions eliminates the regions' competition for figural status and assignment of the shared edge to the figure. If my previous results are produced by attention to convex, symmetric regions only, not figure-ground assignment, then separating the regions should have no effect. Attention would be drawn to convex, symmetric regions ('figures' in Experiments 1 & 2), and targets on such regions should be perceived as occurring earlier than targets on other regions. In contrast, if my results depend on figure-ground assignment itself, then there should be no differences in temporal perception between targets on the two regions because the regions do not compete for the assignment of a shared edge.

Experiment 3

Method

Participants. Sixteen University of Iowa undergraduates with normal or corrected vision volunteered for course credit.

Stimuli and Procedure. The stimuli and procedure were identical to Experiment 1, with the following exceptions. First, participants only viewed figure-ground displays; ambiguous displays were not presented. Second, the regions in these displays were separated by 0.5° of visual angle and did not share an edge. To compensate for the fact that the targets appeared further in the periphery than those in Experiment 1, the targets in the current experiment were increased in size in accordance with the cortical magnification factor (Rovamo & Virsu, 1979) suggested by Wolfe et al. (1998) for discriminations tasks. The scaled targets measured 0.50° by 0.50°.

Results and Discussion

The data were treated as those in Experiment 1. The results for Experiment 3 appear in Figure 3C, with individual curve-fits depicted in Figure 7. Analysis of the PSS computed from the fitted logistic functions revealed a PSS of -0.53 ms, which did not differ significantly from zero, $t(15) < 1$. Moreover, the magnitude of the PSS in Experiment 3 was significantly smaller than the PSS from the figure-ground displays in Experiment 1, $t(46) = 2.14$, $p < .05$. These findings suggest that competition for figural status, which is increased by having two regions share a contour, was important in determining temporal perception differences between the two regions.

Analysis of the JNDs indicated that the slopes of the logistic function for the separated figure-ground displays (39.8 ms) did not differ significantly from the slope for the figure-ground trials in Experiment 1, $t(30) < 1$, *ns*, or in Experiment 2, $t(30) = 1.34$, $p = .19$. In contrast, the JND for the separated displays was significantly smaller than the JND for the ambiguous displays in Experiment 1, $t(30) = 5.17$, $p < .05$, and marginally smaller than the ambiguous displays in Experiment 2, $t(30) = 1.91$, $p = .07$. This pattern of results matches the comparison between figure-ground and ambiguous displays in Experiments 1 and 2, indicating that the figure-ground displays (Experiments 1 & 2) and the separated displays (Experiment 3) have the same, narrow slope relative to the ambiguous displays (Experiments 1 & 2). Thus, the sensitivity for ordering onsets is equivalent between figure-ground displays with regions that share a contour and those with the regions separated, removing competition for figural assignment.

The current results indicate that the prior-entry-like effect observed in Experiments 1 and 2 critically depends on the assignment of one region as a foreground figure. When regions do not share an edge and do not compete for figural status, temporal perception does not differ significantly between the two regions. The separation between the regions in Experiment 3 likely prevents the convex region ('figure') from speeding perceptual processes consistently on most trials. The current findings indicate that figural status, similar to attentional cuing, affects the time at which targets are available for perceptual processing.

Although the current experiments strongly support a prior entry effect for foreground figures, this conclusion depends on participants assigning figural status to the convex region that shares a contour with a concave region, as in Experiments 1 and 2, but not assigning figural status to the same region when it is separated from another region, as in Experiment 3. As a validity check to ensure that this assumed figure-ground assignment (or lack thereof) does result from my displays, I conducted a control experiment. In Experiment 4, participants performed a target discrimination task in which a single target appeared on a region and participants reported if the target was an 'x' or an 'o.' Nelson and Palmer (2007) reported that such a discrimination task is sensitive to figure-ground assignment; their participants were faster to discriminate targets that appeared on figures than those that appeared on grounds (also see Lazareva, Castro, Vecera, & Wasserman, 2006). If my displays produce figure-ground assignment consistent with the results of Experiments 1-3, I would expect that targets would be discriminated fastest on figures in figure-ground displays in which the regions shared an edge and competed for edge assignment. Targets on other regions should be discriminated relatively slowly because of the absence of a strong figure-ground interpretation.

Experiment 4

Method

Participants. Ten University of Iowa undergraduates with normal or corrected vision volunteered for course credit.

Stimuli and Procedure. The stimuli were the three display types used in Experiments 1-3, namely figure-ground displays that shared a contour, ambiguous displays, and the separated displays from Experiment 3. The procedure involved presenting a single target on one of the two regions in a display. Participants were instructed to report if the target was an 'x' or an 'o' as quickly and accurately as possible. Following a 500 ms fixation point, a display with a single target already grown out to its furthest position appeared for 200 ms. The display then disappeared while participants responded.

Results and Discussion

Reaction times longer than 2000 ms and shorter than 150 ms were excluded from the analyses; this trimming removed less than 5% of the data. The mean reaction times (RTs) appear in Table 1. The results indicated that targets on a 'figure' were discriminated faster than those on a 'ground' only when the two regions shared a contour. I analyzed the RTs with a two-factor ANOVA, with display type (figure-ground, ambiguous, or separated) and target location ('figure' or 'ground') as factors. ('Figure' and 'ground' were chosen arbitrarily for ambiguous displays, and for separated displays the 'figures' were convex regions and 'grounds' were concave regions.) I conducted planned comparisons on the RT for 'figures' and 'grounds' for each of the three display types.

My analysis revealed neither a main effect for display type, $F(2, 18) < 1$, *n.s.*, nor a main effect for target location, $F(1, 9) < 1$, *n.s*. There was a significant interaction, $F(2, 18) = 4.54$, $p < .05$, suggesting that the target location depended on the display type. The planned comparisons indicated that this was indeed the case. Figures were discriminated faster than grounds when the two regions shared a contour, $t(9) = 2.32$, $p < .05$, but not when the 'figure' and 'ground' regions were part of an ambiguous display, $t(9) = 2.03$, $p = .07$, or when the regions were separated, $t(9) < 1$, *n.s.* Accuracy was high (> 94% in all conditions) and showed no statistically significant effects between targets on figures and those on grounds.

Consistent with previous findings, target discrimination was faster when targets appeared on a figure than on a ground, indicating a processing preference for figures over grounds. Importantly, this same figural advantage did not appear for my ambiguous stimuli or for separated regions. These findings verify that participants assign figural status to the convex regions in my display, but only when those regions share a contour with another region, consistent with the figure-ground effects based on TOJs from Experiments 1-3.

Discussion of Experiments 1-4

These experiments demonstrate a prior-entry-like effect for figure-ground assignment in which targets appearing on figures are perceived as occurring earlier than targets appearing on non-figural regions. The findings are not likely due to a response bias favoring targets on figures because temporal processing remains better for figures over grounds when participants report which of two targets appeared second. Most important, the results depend on figural assignment: When regions are separated and do not share an edge, no differences in temporal perception appear between the regions.

The current results are part of an increasing number of studies that find figure-ground processes show effects similar to the effects of attention. In addition to the temporal perception advantages of figures that I have demonstrated, others have shown that visual targets appearing on figures are discriminated faster and more accurately than those on grounds (Lazareva et al., 2006; Nelson & Palmer, 2007; Wong & Weisstein, 1982). Although these latter studies have reported an RT difference between targets on figures and grounds, the cause of this figural advantage is not known. The figural advantage could be due to better spatial perception of targets on figures than on grounds or to improved temporal perception of targets on figures than on grounds. My results point to a specific source of the figural advantage: figures might alter temporal perception, allowing targets on figures to be perceived as occurring earlier than those on grounds. In a speeded discrimination task (e.g., Nelson & Palmer, 2007), this change in temporal perception might produce faster RTs to targets on figures than to those on grounds.

Importantly, my results also demonstrate that competition among regions is critical for inducing processing differences between figures and grounds. Separated regions do not produce the same perceptual consequences as figure-ground assignment. This latter finding suggests that attention to a region may not fully explain the perceptual differences between figures and grounds I have reported. Instead, as recent neurophysiological findings have suggested, attention might depend on figure ground assignment; attentional effects are stronger when attention is directed to a figure than to a ground (see Qiu, Sugihara, & von der Heydt, 2007). Thus, figure-ground assignment and spatial attention may be highly interactive and produce similar effects, although they can remain distinct, dissociable processes (e.g., Kimchi & Peterson, 2008; Vecera & Behrmann, 1997).

Beyond the current results, there might be other temporal consequences of figure-ground assignment. For example, temporal information influences figure-ground assignment. Regions that flicker at higher temporal frequencies tend to be perceived as grounds and those that flicker at lower frequencies tend to be perceived as figures (Klymenko et al., 1986; Klymenko & Weisstein, 1989a, 1989b). Also, figures might hold perceptual processes longer than grounds, in which case detecting the offset of a target might be slower for figures than for grounds (cf. Rolke, Ulrich, & Bausenhart, 2006).

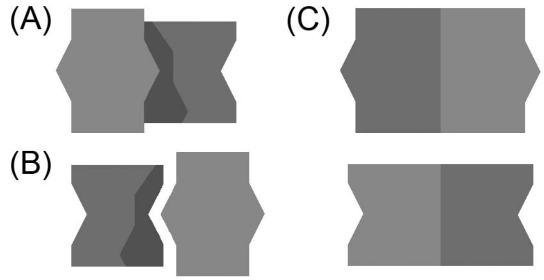

Figure 1. Stimuli used in Experiments 1-4. (A) Figure-ground display in which the symmetric convex region (depicted in light gray) appeared as the foreground region. (B) Separated figure-ground displays that do not contain a strong figural assignment. (C) Two types of ambiguous displays that did not produce a strong figure-ground segregation.

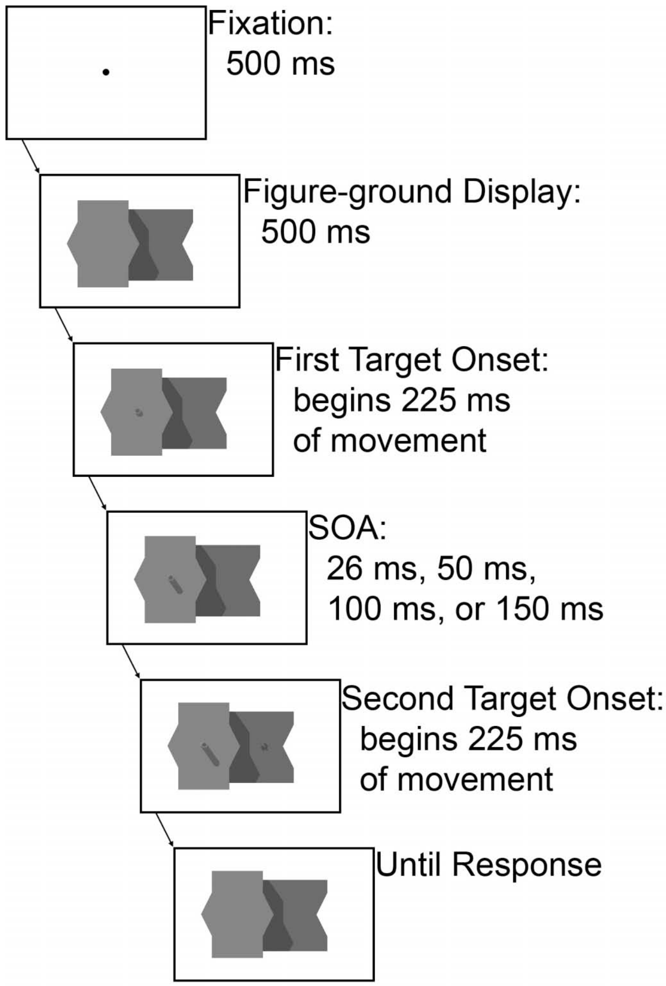

Figure 2. Events and their durations for a single trial in Experiments 1-3.

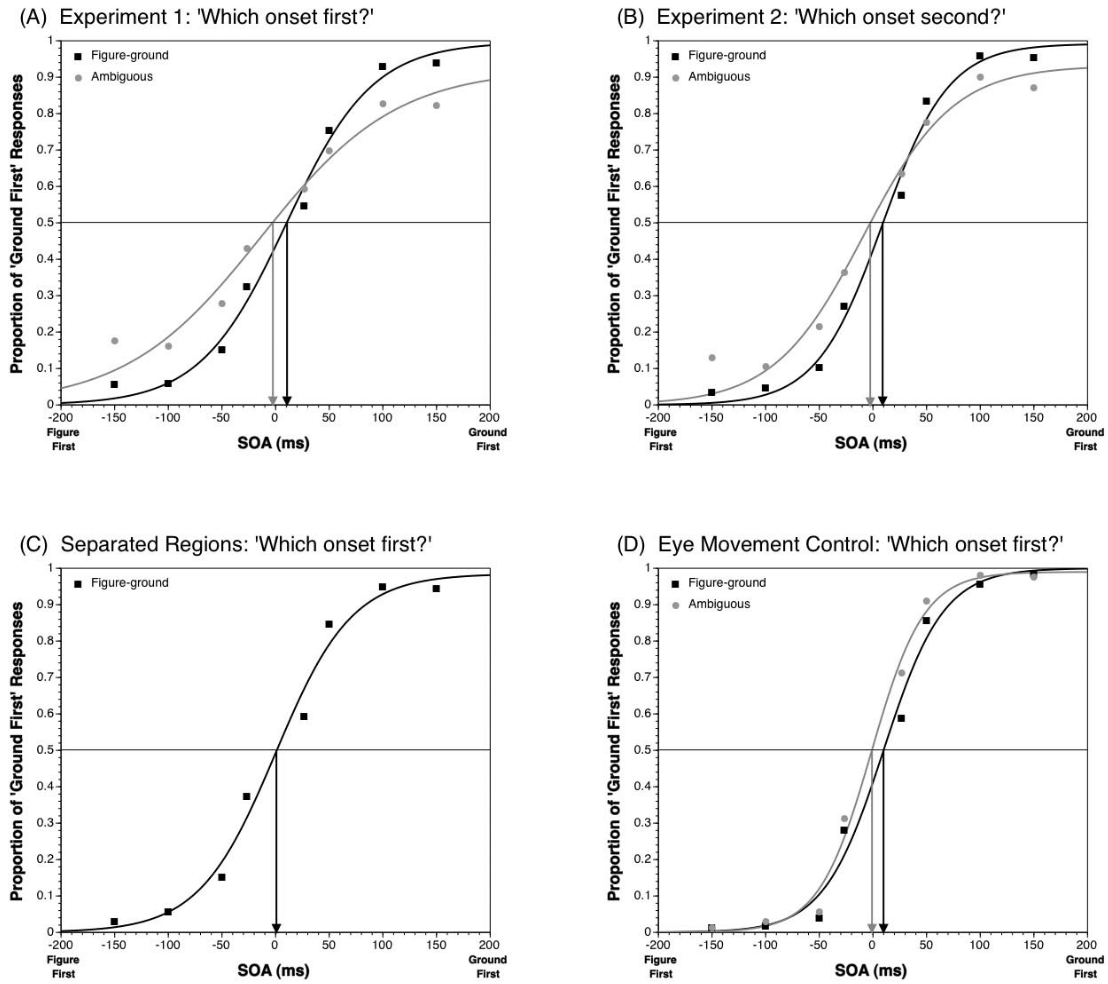

Figure 3. Results from Experiments 1 and 2. (A) Results from Experiment 1 in which participants judged the target that was perceived to move first and (B) in which participants judged the target that was perceived to move second. The figure-ground displays exhibited a rightward shift in the PSS (black arrow) compared to ambiguous regions in which either region could be perceived as figure (grey arrow). No such figural advantage appears in (C) Experiment 3, in which the regions are separated spatially. (D) Results from a control experiment monitoring eye movements. The graphs plot the proportion of trials in which the target on the ground was judged to occur first as a function of SOA. Negative SOAs are for targets on figures that move first and positive SOAs are for targets on grounds that move first. All error bars are within-subject 95% confidence intervals.

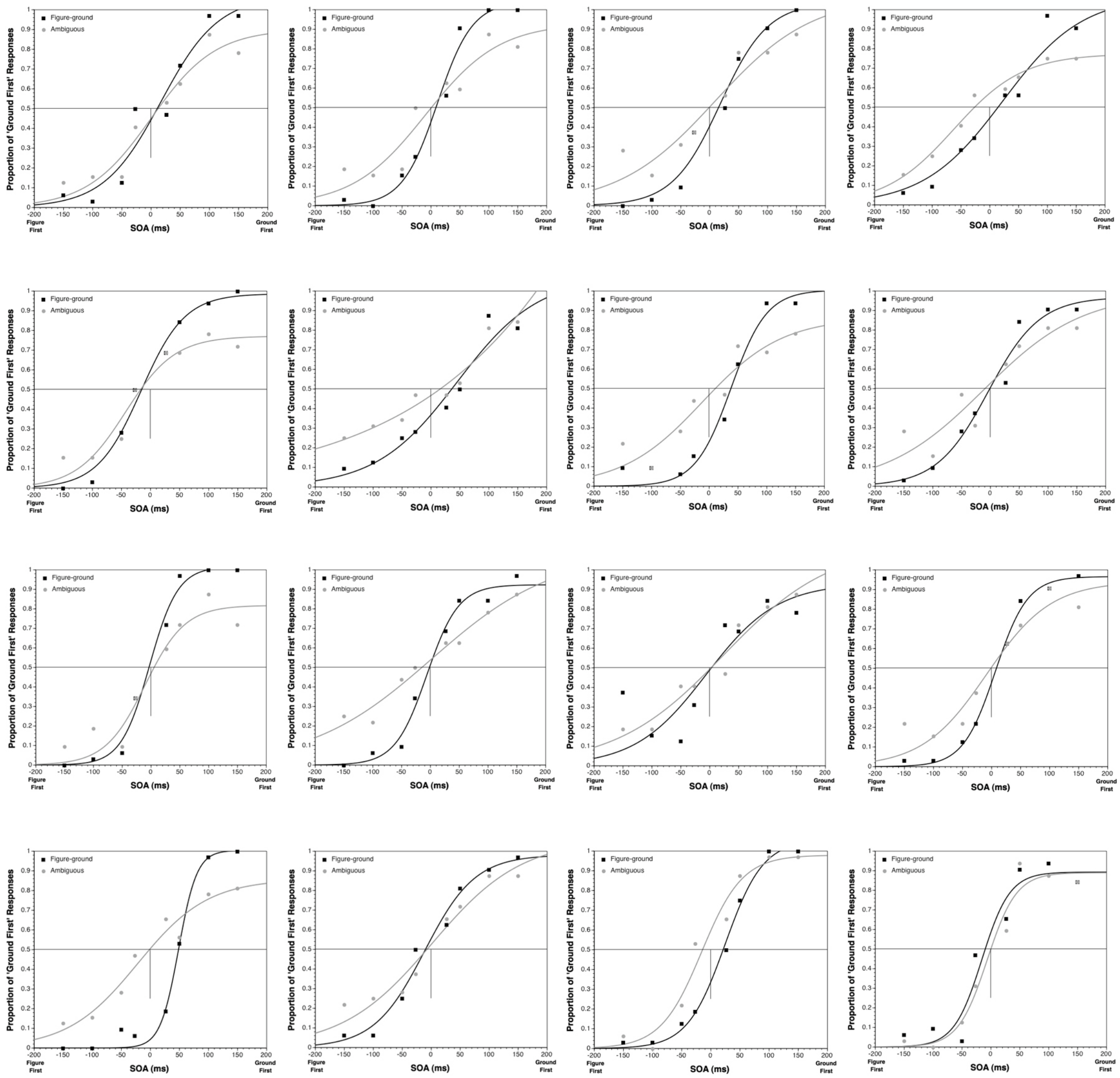

Figure 4. Individual results and curve fits from the sixteen participants in Experiment 1.

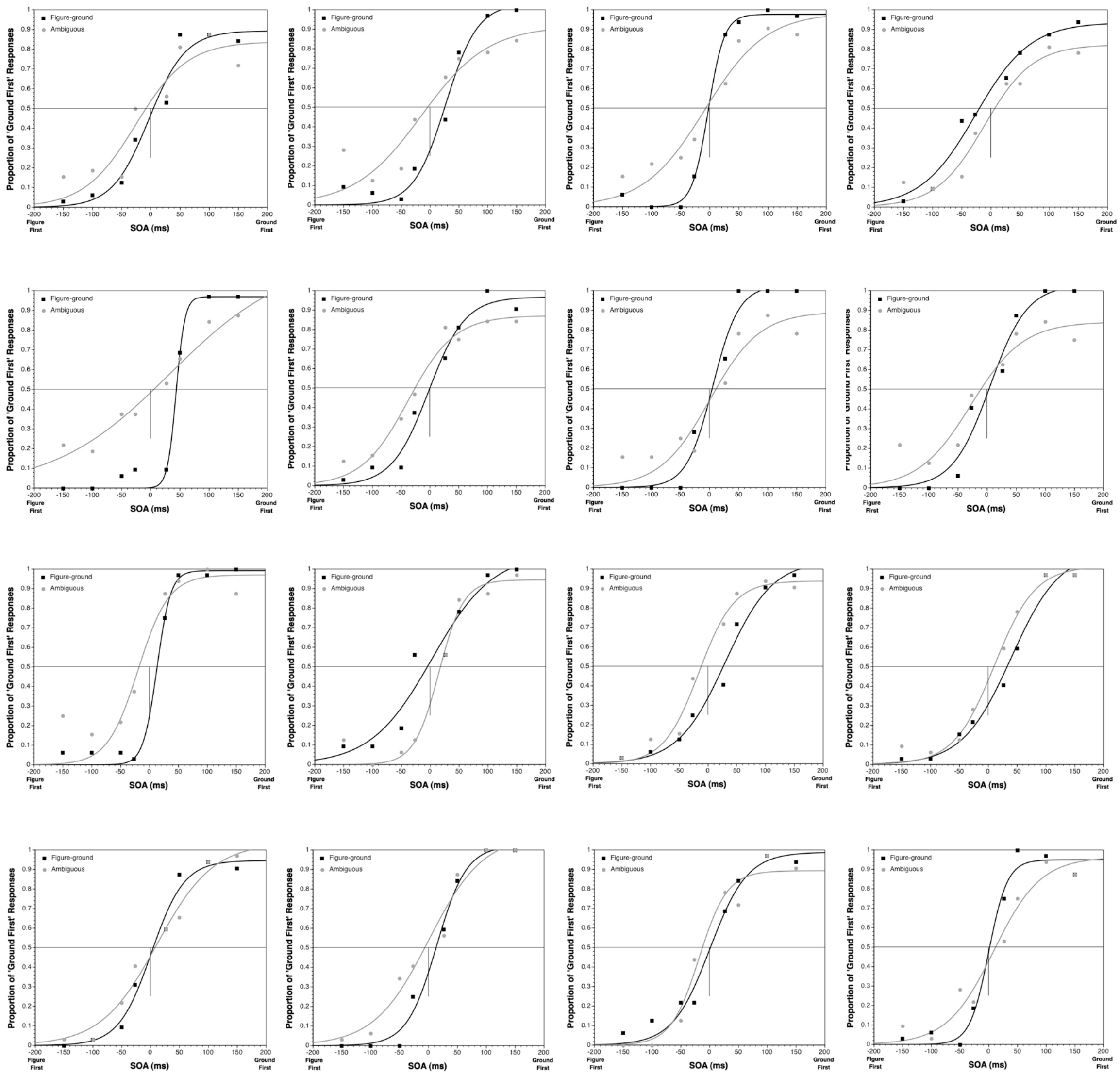

Figure 5. Individual results and curve fits from the sixteen participants in Experiment 2.

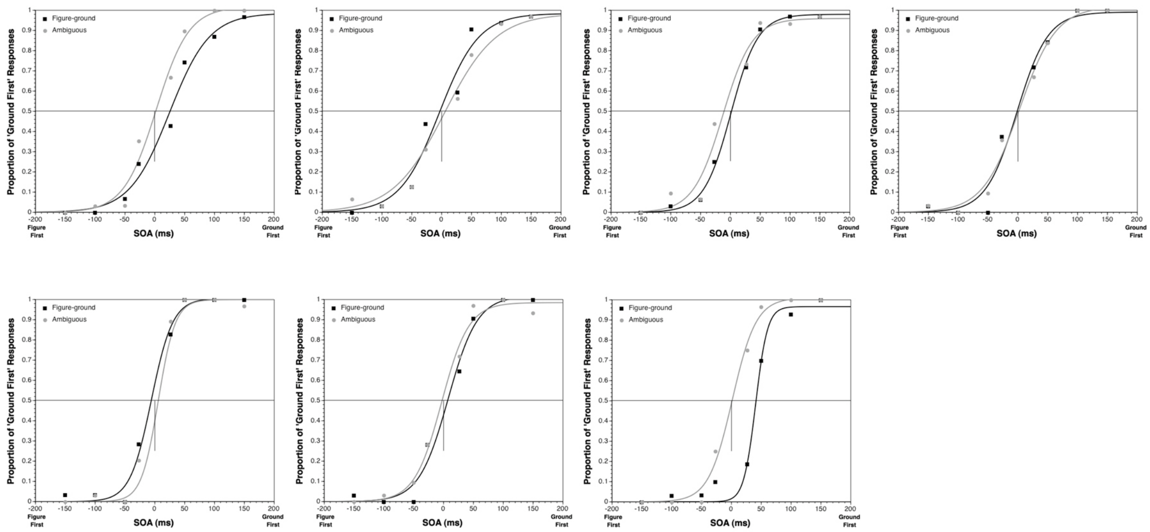

Figure 6. Individual results and curve fits from the seven participants in the eye movement control experiment.

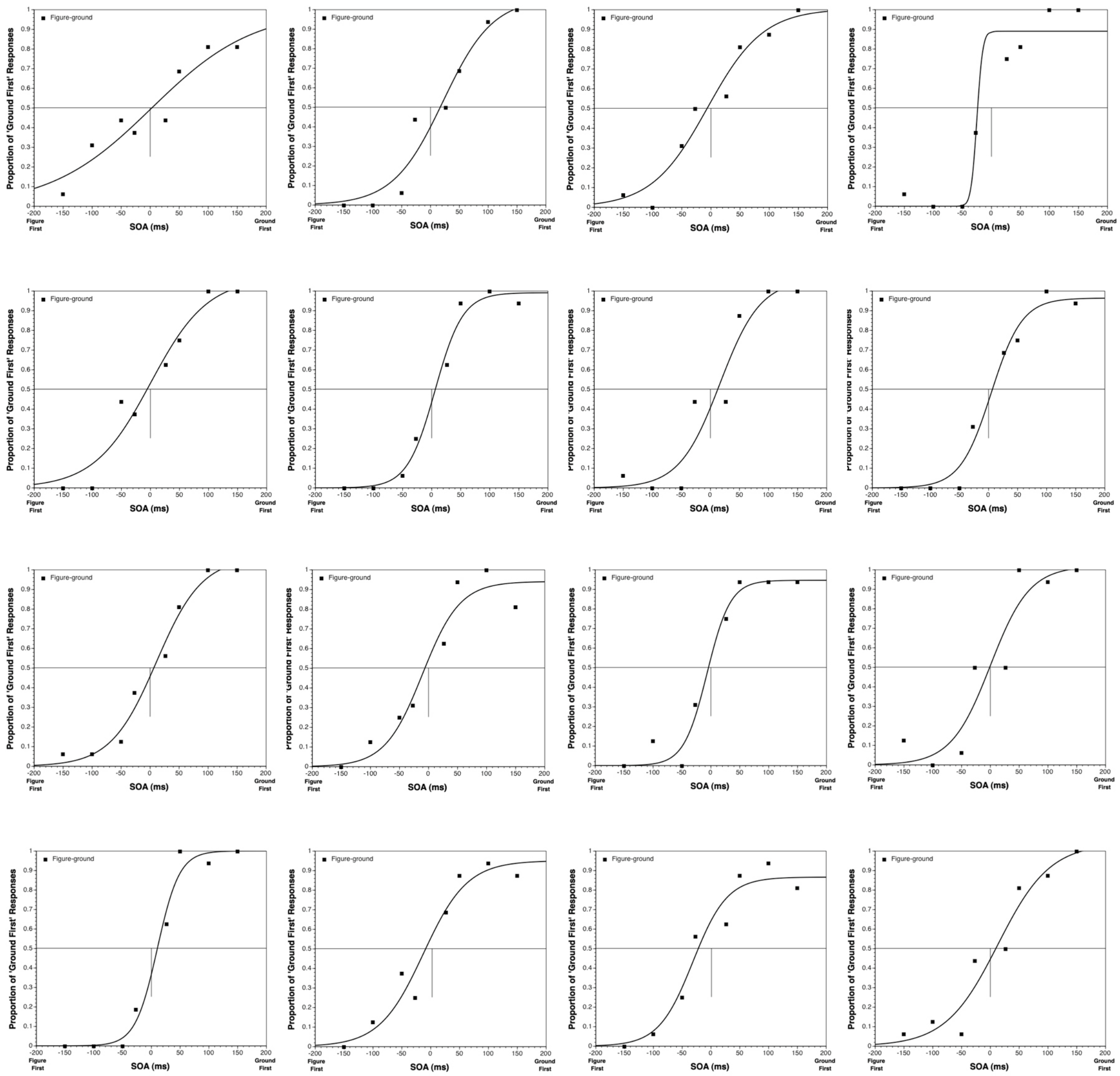

Figure 7. Individual results and curve fits from the sixteen participants in Experiment 3.

Table 1. Mean RTs and Accuracy for Perceptual Discrimination Task (Experiment 3).

Display Type	Target on 'Figure'	Target on 'Ground'
Shared contour	581.0 (14.9)	611.5 (14.9)
	94.4% (1.8)	96.7% (1.8)
Ambiguous	597.7 (9.8)	580.2 (9.8)
	94.8% (1.0)	95.4% (1.0)
Separated contour	598.8 (9.3)	597.0 (9.3)
	95.8% (1.5)	97.3% (1.5)

Note: Parentheses indicate 95% confidence intervals on the 'figure' versus 'ground' comparisons for each display type.

CHAPTER III

TEMPORAL EXTENSION OF FOREGROUND FIGURES

Temporal processing differs between figures and grounds. When monitoring these regions for the onset of new information, information appearing within the figure is perceived earlier than information appearing within the ground, demonstrating a prior entry effect of figure-ground assignment (see Chapter II). This demonstration offers an explanation for the common response benefits in accuracy and reaction time for targets appearing on figures (e.g., Lazareva et al., 2006; Nelson & Palmer, 2007). However, this is not the only change in temporal processing that may result in accuracy and reaction time benefits, figures may be processed for longer durations than grounds. This potential consequence of figure-ground assignment was examined in the experiments presented in this chapter.

A series of experiments examining a 'prior entry' effect for figure-ground displays demonstrated that figures receive processing ahead of grounds (Lester, Hecht & Vecera, 2009). The 'prior entry' effect is characterized by attended events being perceived before unattended events (e.g., Shore & Spence, 2005; Titchener, 1908). Using a temporal order judgment (TOJ) task, Lester et al. (2009) varied the delay between the onset of two targets. They found that targets appearing on the backgrounds needed to onset earlier than targets appearing on the foreground figures in order for the two targets to be perceived as occurring simultaneously (i.e., a 'prior-entry-like' effect). These results imply that figure targets were perceived to lead ground targets, suggesting that figures are afforded early perceptual processing over grounds.

Although figures are available for perceptual processing earlier than grounds, another temporal consequence of figure-ground assignment might account for the perceived salience of foreground figures: extended processing of figures compared to grounds. Previous research has demonstrated that attended locations often undergo processing for extended durations relative to unattended locations (e.g., Hein, Rolke & Ulrich, 2006; Rolke, Ulrich & Bausenhart, 2006; Yeshurun & Levy, 2003). In these studies, attention is drawn to a particular spatial location, and a target offset is detected. This modification to the TOJ procedure (i.e., offset rather than onset detections) provides a relative comparison of the duration of time an item is processed. In contrast to onsets receiving a processing benefit at attended locations, offsets were less accurately perceived at an attended location than at an unattended location. Targets appearing at an attended location had to offset earlier to be perceived as offsetting simultaneously with targets at an unattended location.

Research on the effects of figure-ground organization points to similarities between attention and figure-ground processes. For example, targets are discriminated faster on figures and at attended regions. Also, targets on figures and at attended locations show a 'prior entry' effect and are perceived as occurring earlier than targets on grounds or at unattended locations. Based on these similarities, I hypothesized that figure-ground organization might exhibit a temporal extension effect similar to that shown by attention. Namely, figures might hold perceptual processing longer than grounds. If this is the case, then detecting the offset of a target would be more difficult when it is located on a figure than on a ground, producing a ground advantage for target offsets.

To test my temporal extension hypothesis, I used a TOJ task to measure processing duration. Participants viewed bipartite figure-ground displays containing two regions (Figure 8), each with a target protruding from its surface. The interval between the targets' offset (i.e., receding into the region) varied at one of four stimulus offset asynchronies (SOAs), and participants reported which target receded first (Experiment 5) or which receded second (Experiment 6). Any bias in responding first to targets on figures or on grounds would be eliminated by including these report order conditions (see Shore et al., 2001). For instance, a participant preferentially responding to the figure would be *less* accurate when the ground target offsets first, especially at short SOAs; this same result is indicative taken to suggest figure targets were perceived to offset earlier than ground targets. However, if participants have this response bias, it would be evident when reporting which target offset second; their reports would now be opposite of those found when reporting which offset first. Increased responses to the figure would suggest that it was offsetting second more often than the ground; the ground target was perceived to lead the figure target, conflicting with the earlier result.

I assessed temporal discrimination by calculating the point of subjective simultaneity (PSS). The PSS reflects the temporal delay between target offsets that produces the most uncertainty for participants, resulting in 50% discrimination accuracy; that is, the PSS is the point at which participants perceive the stimuli as receding (offsetting) simultaneously. If figures are afforded extended processing relative to grounds, then targets appearing on the figure would be perceived as withdrawing *later* than targets on the ground. Thus, the targets on the figure would need to recede *before* those on the ground for the two targets to be perceived as withdrawing at the same time, shifting the PSS away from zero. Alternatively, if figures are not processed for extended durations compared to grounds, then the PSS should fall at zero, indicating the events must occur at the same time to be perceived as simultaneous.

Experiments 5 and 6

Method

Participants. Thirty-two University of Iowa undergraduates with normal or corrected-to-normal vision volunteered for course credit.

Stimuli. Figure 8 depicts the two different display types: strong figure-ground assignment (Figure 8A) and ambiguous figure-ground assignment (Figure 8C). Each display contained a green region (RGB = 0, 132, 0) and a red-orange region (RGB = 238, 83, 15) displayed against a black background. Each color occurred equally often on the left and right regions.

In figure-ground displays, the symmetric, convex figure subtended approximately 3.73º by 4.60º of visual angle; the concave, shaded ground region subtended approximately 3.34º by 3.73º. Both regions were equally likely to appear on either side of fixation. There were two types of ambiguous displays: two convex regions and two concave regions. Each region in a convex display measured 3.58º by 4.60º, and each region in a concave display measured 3.42º by 3.80º. The ambiguous displays lacked the depth cues present in the figure-ground displays, thereby eliminating strong figure-ground assignment.

Two targets, a small ‘x’ and ‘o’ that subtended approximately 0.40º by 0.40º of visual angle, were present in each display, with one target on each shape. The targets were the same color as the region on which they were presented, thereby eliminating the appearance of the targets being superimposed over the displays (see Richard, Lee & Vecera, 2008, for discussion). Across trials, each target appeared equally often on each region of the display and appeared 1.80° from fixation.

Procedure. Each trial began with a 500 ms central fixation point that participants were instructed to fixate throughout the trial. The fixation point appeared at a location that was later occupied by the contour between the two regions. Either a figure-ground or ambiguous display was then presented for 400 ms; this display contained two targets (x and o) each protruding from one region (figure and ground). Following this display, and after a variable amount of time (35-75 ms), these targets began receding at various offsets into their respective regions over a duration of 110 ms; varying the shadow lengths cast by the targets reinforced this movement. Once the first target began to withdraw (i.e., once the shadow began to recede), the second target began to offset after one of four randomly selected SOAs: 26, 50, 100, and 150 ms. The target on the figure moved ahead of that on the ground on half of trials (negative SOAs) and conversely on the other half of trials (positive SOAs). Following the recession of the targets, the figure-ground display remained on screen until participants responded. Figure 9 illustrates the order of events in a trial. Half of the participants indicated which target began to offset first (Experiment 5) and the other half indicated which offset second (Experiment 6). Participants completed 512 trials and responded via key press.

Results and Discussion

The proportion of time the ground's target was perceived as moving first or second, averaged across all participants, is plotted in Figure 10. The curves plotted in Figure 10 represent the best-fitting logistic function to the averaged data. However, all statistical analyses were based on the best-fitting logistic curves fitted to each individual participant's data. All curve fits converged to a tolerance of $R^2 \geq 0.92$.

As shown in Figures 10A and 10B, the proportion of trials in which the ground target was perceived as offsetting first (or second) increased as SOA increased. Critically, the PSS was shifted leftward for figure-ground displays relative to the ambiguous displays such that the figure target needed to move *earlier* than the ground target in order to perceive them as offsetting simultaneously. This pattern was observed in a majority (75%) of participants as can be seen in their individual data and curve fits, plotted in Figures 11 and 12. For both experiments, the two types of ambiguous displays, convex (Experiment 5: 85.8%; Experiment 6: 80.2%) and concave (Experiment 5: 84.9%; Experiment 6: 79.9%), did not yield differences in accuracy of reports (Experiment 5: $t(15) = 1.10$, $p > .2$; Experiment 6: $t(15) < 1$, *ns*); thus, I averaged results across these displays for the remaining analyses.

Analysis of the PSSs indicated that the PSS for the figure-ground displays shifted significantly leftward, indicating that the figure's target needed to recede ahead of the ground's target. The PSS in Experiment 5 was -10.1 ms, and the PSS in Experiment 6 was -9.9 ms. Both of these PSS values differed significantly from zero, $t(15) = 3.02$, $p < .05$ for Experiment 5 and $t(15) = 2.67$, $p < .05$ for Experiment 6.

In contrast to the PSS values from the figure-ground displays, the PSSs for ambiguous displays (Experiment 5: -1.3 ms; Experiment 6: -1.6 ms) did not exhibit significant, systematic shifts from zero. The PSS for ambiguous displays in Experiment 5 was -1.3 ms, and that in Experiment 6 was -1.6 ms, $t(15) < 1$, *ns* for the Experiment 5 PSS and $t(15) < 1$, *ns* for the Experiment 6 PSS. Moreover, the PSS for figure-ground displays was significantly different from the PSS for ambiguous displays in Experiment 5, $t(15) = 2.46$, $p < .05$, and this difference was marginally significant in Experiment 6, $t(15) = 2.06$, $p = .06$.

An additional, combined analysis of the accuracy of reports from the 'which first?' and 'which second?' experiments revealed slightly more accurate responses in the 'which first?' experiment than the 'which second?' experiment (85.1% versus 81.6%), $F(1, 30) = 3.56$, $p = .07$. A three-factor ANOVA on task ('which first?' or 'which second?') by display type (figure-ground or ambiguous) by SOA (26, 50, 100, 150) was computed with the latter two conditions as within-subjects variables, and the former as a between-subjects variable. I found that task did not interact with the remaining factors, so I collapsed across task and again analyzed the PSSs.

Analysis of the PSSs revealed a PSS of -10.0 ms for the figure-ground displays, which differed significantly from zero, $t(31) = 4.07$, $p < .05$. This negative PSS indicates that targets on figures must occur, on average, 10 ms ahead of those on grounds for the two targets to be perceived as occurring simultaneously. For ambiguous displays, the PSS was -1.5 ms, which did not differ significantly from zero, $t(31) = 1.01$, p > .30, indicating that the targets in neither of the regions in these displays had a temporal processing advantage over the other region. The PSS for the figure-ground displays was significantly larger than the PSS for the ambiguous displays, $t(31) = 3.22$, $p < .05$.

In addition to calculating the PSS, I calculated the just noticeable difference (JND) for each individual's best-fitting logistic function. The JND indicates the least amount of separation in time between two events (i.e., SOA) that is required to accurately order the events with 75% accuracy. This value also shares a monotonic relationship with the slope of the function, providing an assessment of the sensitivity of observers' perceptions. For example, a function as the JND decreases (i.e., shorter SOAs), less time is required between target offsets to reliably order the events. In other words, the slope of the function is becoming steeper (i.e., increasing more rapidly). Hence, smaller JNDs can also indicate a higher sensitivity to temporal differences in the offset events. In the current experiment, the JND was defined as half of the temporal interval between the SOA values at 75% and 25% accuracy on the best-fitting logistic function.

As Figures 10A and 10B suggest, the JND for figure-ground displays in Experiment 5 (36.4 ms) was not significantly different from the JND for ambiguous displays (39.6 ms), $t(15) = 1.56$, $p > .10$. However, the JND was smaller for figure-ground displays in Experiment 6 (40.5 ms) than for ambiguous displays (53.1 ms), $t(15) = 1.99$, $p = .07$. These results suggest that the figure-ground displays did not consistently result in greater sensitivity for temporal perception than the ambiguous displays, as has been found in previous studies (see Lester et al., 2009), though there was a trend toward greater sensitivity for figure-ground displays as evidenced by the steeper slopes (i.e., smaller SOAs). Still, these displays shifted perception of the order of events as evidenced by the positive PSS (see above).

These results support my temporal extension hypothesis under which figures are afforded extended perceptual processing, but which impairs one's ability to detect offsets on a figure's surface relative to offsets on a background. Importantly, the PSSs in both experiments were shifted leftward for displays containing strong figure-ground assignment but not for ambiguous assignment: figure targets must begin to offset *prior to* ground targets in order for the offsets to be perceived as simultaneous, suggesting a shorter processing duration for grounds. In other words, a consequence of figure-ground assignment is lengthened processing of figures—that is, an extension of temporal processing.

Importantly, my procedures also rule out response biases by examining reports of 'which offset first?' and 'which offset second?'. Assessment of such complimentary reports is a technique that has been used in previous research (e.g., Carrasco, Ling & Read, 2004; Shore, Spence & Klein, 2001) to rule response bias accounts (see Pashler, 1998). If a response bias were present in the current experiments, then the PSS would have been shifted in opposite directions for each experiment; the PSS may have shifted leftward in Experiment 5 (i.e., figures must offset before grounds) and rightward in Experiment 6 (i.e., figures must offset after figures), or vice versa. Because neither outcome was present, response biases cannot account for my results.

Although the results of Experiments 5 and 6 are straightforward, my findings could have been produced by attentional processes, rather than by figure-ground processes. Specifically, attention may have been drawn toward the region containing figural cues (e.g., convexity, symmetry). As a result, shifting attention to the convex, symmetric regions, rather than figure-ground organization, impaired the detection of offsets. To address this alternative, in Experiment 7 participants performed the TOJ task used in Experiment 1 with displays that separated the two regions. By separating the convex and concave regions, competition for figural status and assignment of the shared edge of the figure is eliminated. If the results from Experiments 5 and 6 were produced by attention being directed to convex, symmetric regions, then separating the regions should not impact offset judgments, and I should replicate the results of Experiment 5. Attention would still be drawn to the 'figure' (i.e., convex region), and targets withdrawing from this region should still be perceived as moving later than targets on the 'ground' (i.e., concave region). In contrast, if my results depend on completion of figure-ground assignment, then the temporal perception of the offsets should be accurate and unbiased. That is, the PSS for the convex region should not be shifted negatively away from zero because figure-ground competition has been weakened or eliminated by separating the two regions.

Experiment 7

Method

Participants. Sixteen University of Iowa undergraduates with normal or corrected-to-normal vision volunteered for course credit.

Stimuli and Procedure. The stimuli and procedure were identical to Experiment 5, with the following exceptions. First, participants only viewed figure-ground displays; ambiguous displays were not presented. Second, the regions in these displays were separated by 0.50° of visual angle and did not share an edge. To compensate for the fact that the targets appeared further in the periphery than those in Experiment 5, the targets in the current experiment were increased in size to 0.50° by 0.50° in accordance with the cortical magnification factor (Rovamo & Virsu, 1979) suggested by Wolfe et al. (1998) for discrimination tasks.

Results and Discussion

The best-fitting logistic function of the averaged data is plotted in Figure 10C. Logistic functions were fit to each individual's data (see Figure 13), as in Experiments 5 and 6, and were used to compute a PSS for each participant. Analysis of the averaged PSSs revealed a PSS of 1.8 ms, which did not differ significantly from zero, $t(15) < 1$, *ns.* Moreover, the magnitude of the PSS was significantly smaller than the PSS from the figure-ground displays in Experiments 5 and 6 combined, $t(46) = 2.17$, $p < .05$. Because the current experiment and Experiment 5 used the same report ('which first?'), an additional comparison was made between the PSS in each of these experiments: the PSS was marginally smaller than the PSS in Experiment 5, $t(30) = 1.74$, $p = .09$. These findings suggest that competition for figural status, which is increased by having two regions share a contour, was important in determining temporal perception differences between the two regions. When regions do not share an edge and do not compete for figural status, temporal perception does not differ significantly between the two regions.

I also calculated the JND for each individual's best-fitting logistic function. The JND for the separated displays (36.4 ms) was not significantly different from the JND for ambiguous displays (42.6 ms), $t(15) = 1.56$, $p > .10$. However, the JND was smaller for figure-ground displays in Experiment 6 (40.5 ms) than for ambiguous displays (42.6 ms), $t(15) = 1.99$, $p = .07$. These results suggest that the sensitivity for temporal perception in figure-ground displays was not consistently different from that of the separated regions, replicating previous studies (see Lester et al., 2009).

Analysis of the JNDs indicated that the slopes of the psychometric function for the separated figure-ground displays (42.6 ms) did not differ significantly from the slope for the figure-ground trials in Experiment 5, $t(30) < 1$, *ns*, or in Experiment 6, $t(30) < 1$, *ns*. Likewise, the JND for the separated displays was not different from the JND for the ambiguous displays in Experiment 5, $t(30) < 1$, *ns*, and Experiment 6, $t(30) = 1.23$, $p = .20$. This pattern of results indicates that the slopes were equivalent across the displays. In other words, all three functions (see Figures 10A, 10B, and 10C) increased by the same amount across displays. Therefore, the sensitivity for ordering offsets is equivalent between figure-ground, ambiguous and separated displays.

Importantly, this conclusion depends on the convex region receiving figural status only when it shares a contour with a concave region, as in Experiments 5 and 6, and not when the two regions are separated, as in Experiment 7. Furthermore, Lester et al. (2009) verified the validity of the figure-ground displays used in the current experiments. In their third experiment, participants discriminated targets appearing on the figure and ground regions. In accordance with previous research (e.g., Lazareva et al., 2006; Nelson & Palmer, 2007), discrimination performance was sensitive to figure-ground assignment:

targets on figures in figure-ground displays in which the regions shared an edge and competed for edge assignment were discriminated fastest, whereas targets on other regions were discriminated relatively slowly due to the absence of a strong figure-ground interpretation. Thus, I can conclude that the processing duration effect observed in Experiments 5 and 6 depends on the assignment of one region as a foreground figure, and the separation between the regions in Experiment 7 prevents extended processing of the convex region ('figure') on most trials.

Discussion of Experiments 5-7

If figures are afforded extended perceptual processing relative to grounds, more lead-time would be required for targets that offset on the figure, as was found in Experiments 5 and 6. An offsetting target on a foreground figure could not be detected as readily as targets on other regions. Thus, a greater delay was needed between the offset of the lingering target (i.e., the figure target) and the other target (i.e., the ground target). Moreover, this duration effect is a consequence of completing figure-ground assignment, as evidenced by accurate temporal perception of events on separated 'figure' and 'ground' regions (Experiment 7).

The current results, in conjunction with previous research (e.g., Lester et al., 2009), demonstrate that the consequences of figure-ground assignment on temporal perception parallel those found in the spatial attention research (e.g., Hein et al., 2006; Rolke et al., 2006; Shore & Spence, 2005; Shore et al., 2001; Yeshurun, 2004; Yeshurun & Levy, 2003). This raises the concern of whether the prior-entry-like effect and the processing duration effect for figures are a corollary of figure-ground processes or simply reflect a shift of spatial attention, in which attention is drawn to figural regions. I argue that the effects observed here are consequences of figure-ground assignment and not merely to attention to a convex region that has been separated from other regions, as in Experiment 7. There is likely a tightly linked interaction between figure-ground assignment and attention (e.g., Qiu, Sugihara & von der Heydt, 2007; Vecera et al., 2004), and it will be difficult to disentangle the effects of attention and figure-ground processes. Some research has indicated that figure-ground assignment and attention can be dissociated (e.g., Kimchi & Peterson, 2008; Vecera & Behrmann, 1997), but further work will be required to fully understand the relationship between these visual processes.

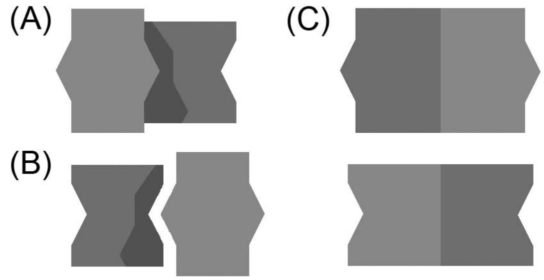

Figure 8. Stimuli used in Experiments 5-7. (A) Figure-ground display in which the symmetric convex region (depicted in light gray) appeared as the foreground region. (B) Separated figure-ground displays that do not contain a strong figural assignment. (C) Two types of ambiguous displays that did not produce a strong figure-ground segregation.

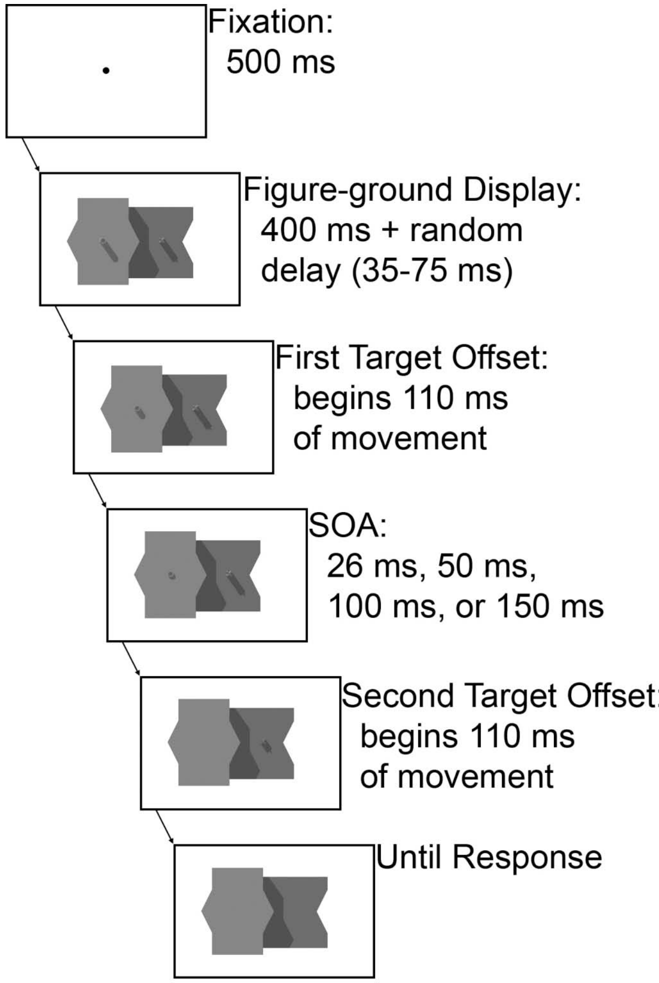

Figure 9. Events and their durations for a single trial in Experiments 5-7.

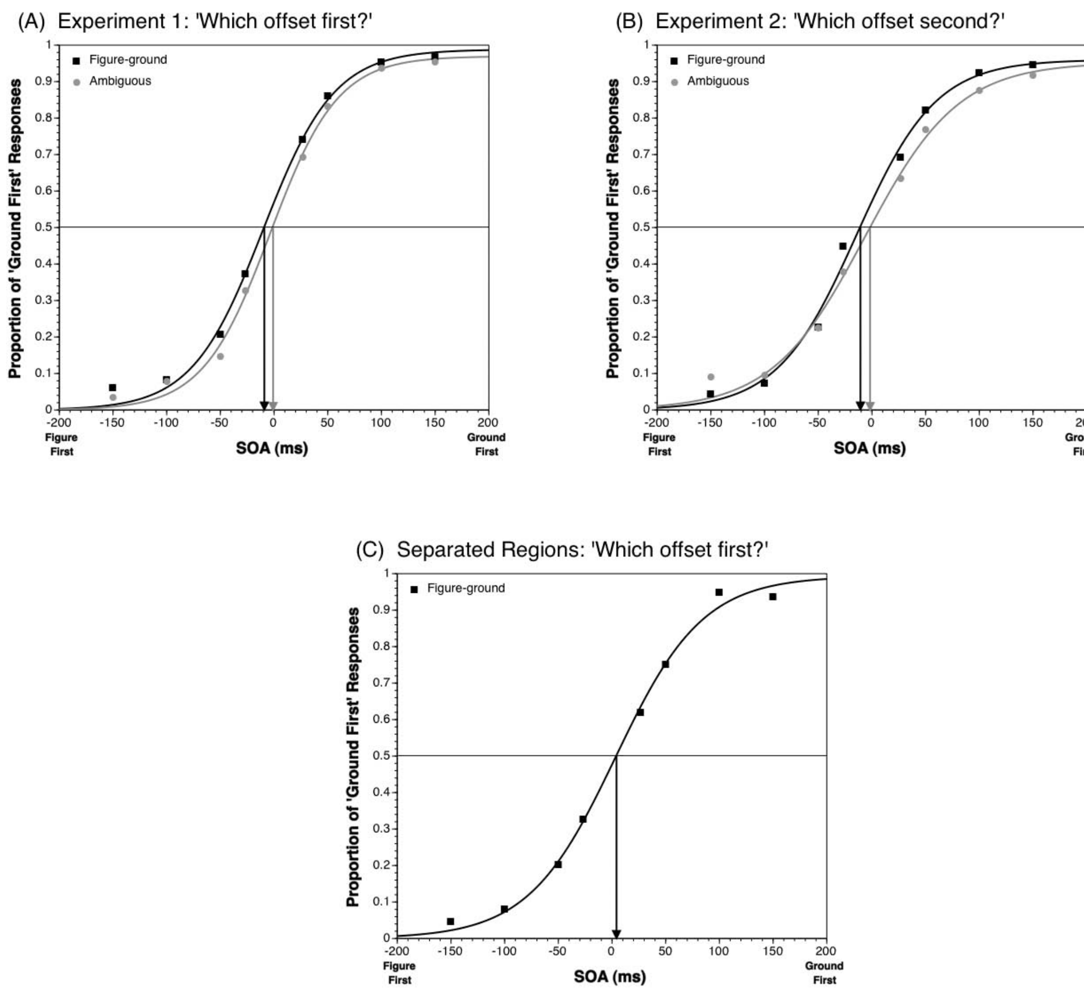

Figure 10. Results from Experiments 5-7. (A) Results from Experiment 5 in which participants determined the target that was perceived to offset first and (B) Experiment 6 in which participants determined the target that was perceived to offset second. The figure-ground displays exhibited a leftward shift in the PSS (black arrow) compared to ambiguous regions in which either region could be perceived as figure (grey arrow). No such shift appears in (C) Experiment 7, in which the regions are separated spatially. The graphs plot the proportion of trials in which the target on the ground was judged to offset first as a function of SOA. Negative SOAs are for targets on figures that move first and positive SOAs are for targets on grounds that move first.

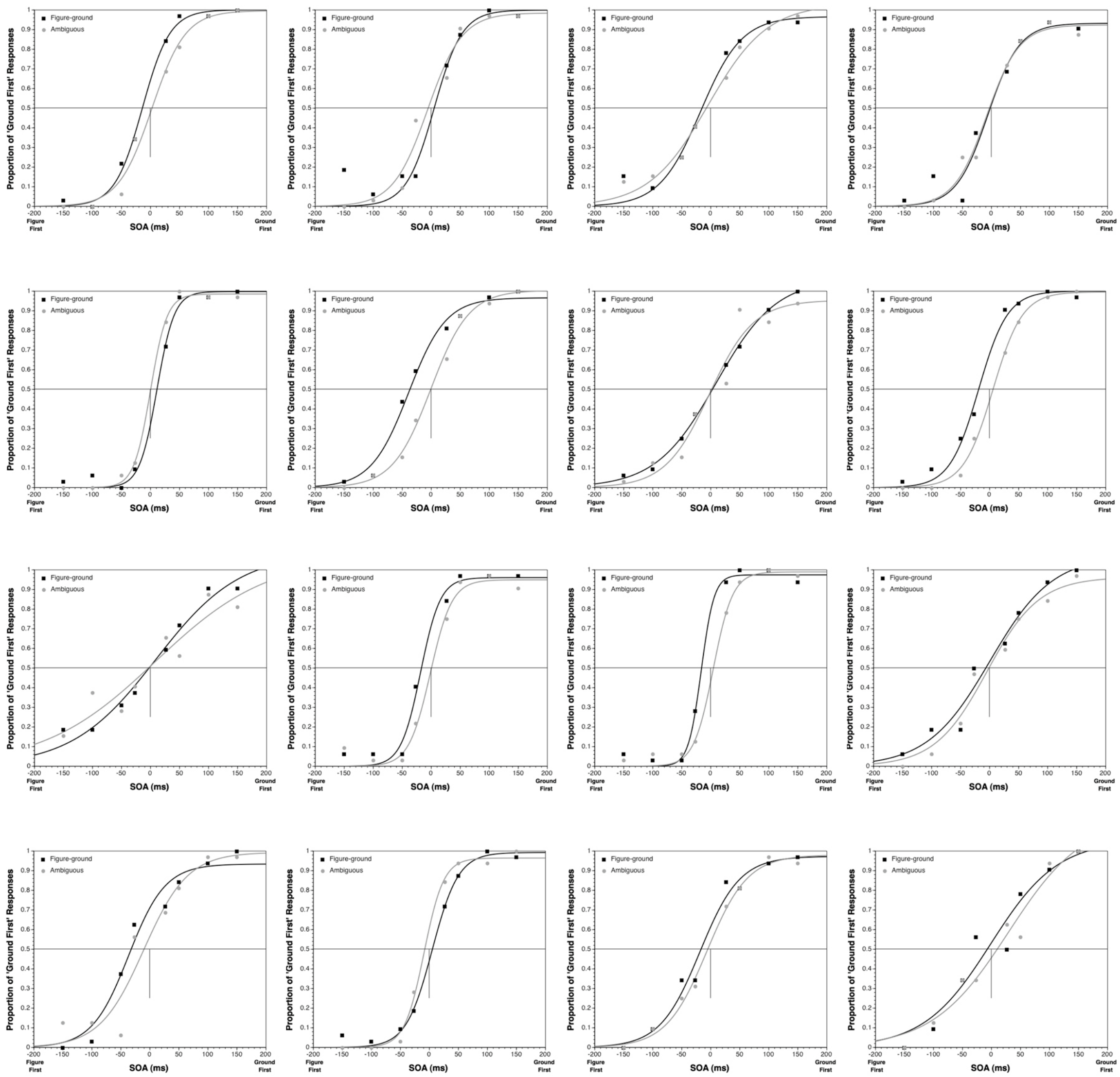

Figure 11. Individual results and curve fits from the sixteen participants in Experiment 5.

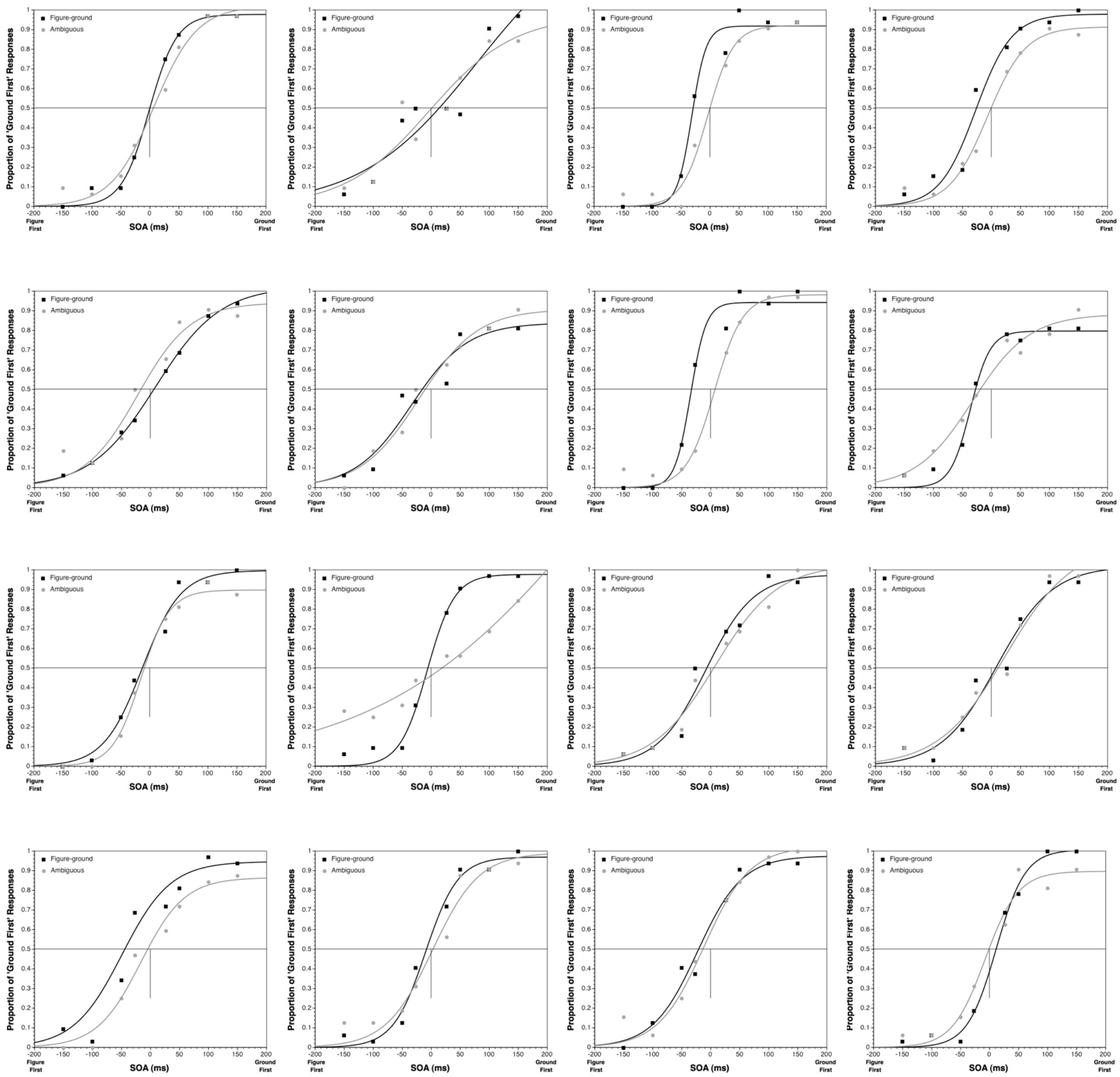

Figure 12. Individual results and curve fits from the sixteen participants in Experiment 6.

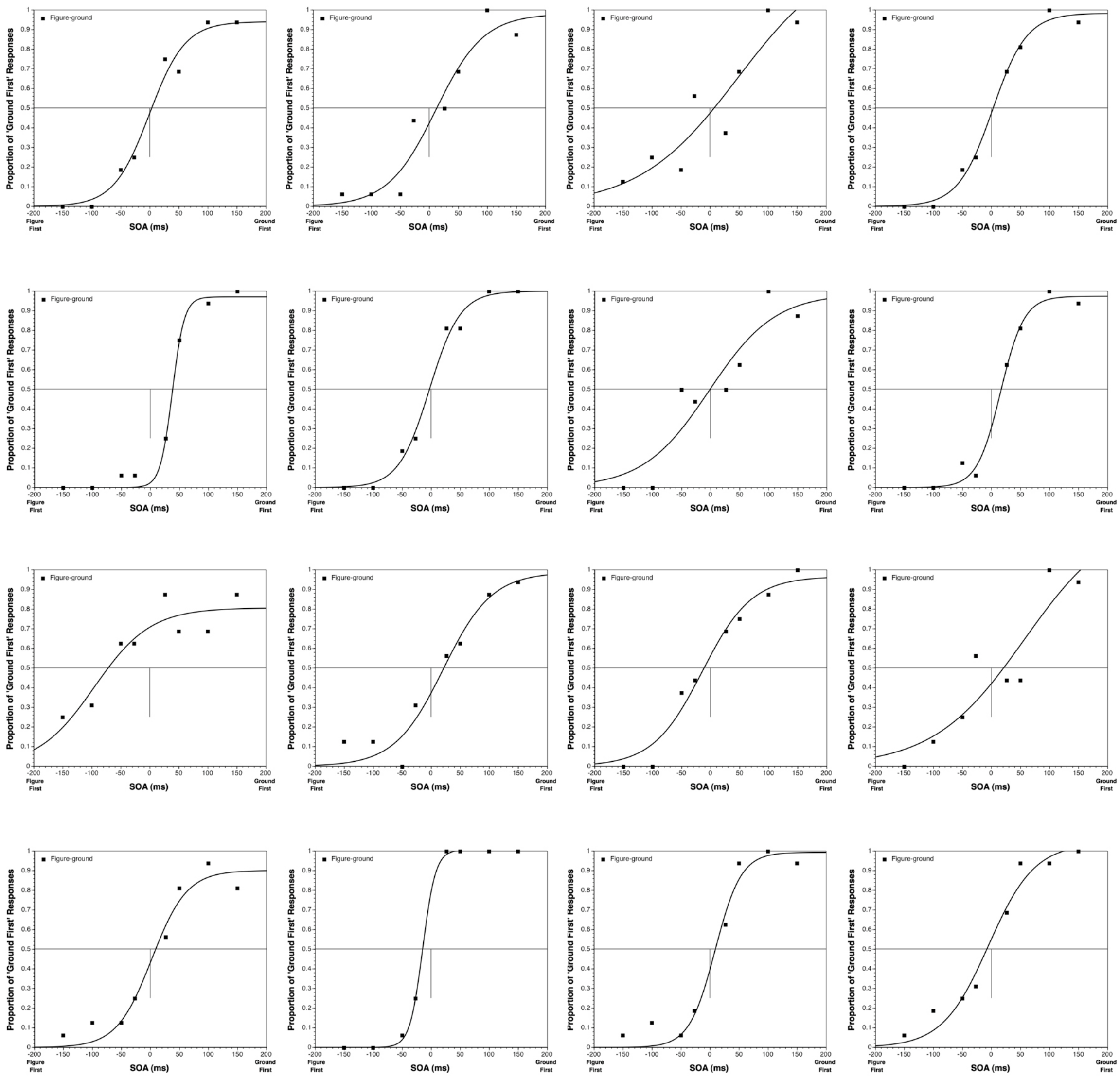

Figure 13. Individual results and curve fits from the sixteen participants in Experiment 7.

CHAPTER IV

INCREASED TEMPORAL RESOLUTION OF BACKGROUNDS

Given that figures are afforded extended durations of perceptual processing, a further implication of this change in temporal processing arises. An extended duration of perceptual processing degrades temporal resolution, the ability to resolve temporal details (e.g., Levine, 2000). As temporal resolution decreases, it can become more difficult to discriminate the duration between two closely spaced events (e.g., Reeves, 1996). Therefore, if the first of two events is processed for an extended duration of time, for example, then it would be difficult to readily perceive a second item appearing close in time at the same or a nearby spatial location. Thus, an implication of the temporal extension effect for figures is that temporal resolution within grounds is higher than resolution within figures.

Evidence for this consequence of the temporal extension effect has been presented within the domain of spatial attention; attending to a spatial location can impair temporal resolution (e.g., Hein et al., 2006; Rolke et al., 2006; Yeshurun, 2004; Yeshurun & Levy, 2003). Some of these studies have used a flicker-fusion paradigm to examine temporal resolution of spatially attended versus unattended regions (e.g., Yeshurun, 2004; Yeshurun & Levy, 2003). In flicker-fusion tasks, two items are presented in rapid succession at the same spatial location and the delay between them (i.e., inter-stimulus interval: ISI) is varied. As the ISI approaches zero, phenomenologically only one item is perceived as being presented, rather than two. In other words at very brief delays, the two items become "fused" together and appear as a single item.

Two items are more readily fused into the percept of a single item at attended locations than at unattended locations (e.g., Yeshurun, 2004; Yeshurun & Levy, 2003). Put another way, longer delays (i.e., high flicker fusion thresholds) were required between two items presented at an attended location in order to reach equivalent discriminability to items at unattended locations. Presumably, the fusion results from extended processing of the first, attended item. This shortens the perceptibility of the delay between items because the first item's offset is not efficiently detected, degrading the ability to detect the delay and onset of the second item. Thus, a flicker-fusion procedure provides a general assessment of temporal resolution.

Applying a flicker-fusion procedure to figure-ground displays allows us to assess the temporal resolution of figure and ground regions. If two items are more readily fused (i.e., have higher fusion thresholds) on figures than on grounds, then it can be concluded that ground regions have higher temporal resolution. In the current experiment, I implemented a modified flicker-fusion task on strong figure-ground and ambiguous displays (see Figures 14A & 14B). Participants viewed one static and one flickering target on each trial and discriminated a critical feature of the flickering target. I measured participants' accuracy for target feature discriminations using *d*' in accordance with other tasks examining flicker fusion (e.g., Yeshurun, 2004; Yeshurun & Levy, 2003). If backgrounds have higher temporal resolution, then accuracy should be higher when flickering targets appear within these ground regions as opposed to when these targets appear within the figure.

Experiment 8

Method

Participants. Twenty University of Iowa undergraduates with normal or corrected-to-normal vision volunteered for course credit.

Stimuli. Participants viewed the same figure-ground displays with strong or ambiguous assignment used in the temporal extension experiments (see Experiments 5-7 in Chapter III). However, we changed the color of the stimuli because assessment of temporal resolution is underestimated when stimuli are red, due to the inhibition of magnocellular pathways (see Yeshurun, 2004). To avoid underestimation of the temporal resolution, the figure and ground regions were green (RGB = 108, 217, 152) or blue (RGB = 121, 199, 238).

The targets presented to participants were Landolt squares, embossed onto the surface of the figure and ground regions in order to promote the sensation of targets that bulge from the surface of the region (see Figure 15). These squares subtended 0.90º by 0.90º of visual angle, and each contained a 0.16º gap on its top or bottom.

Procedure. Figure 15 (right panel) illustrates the sequence of events in a trial. Participants viewed a white central fixation point (500 ms) on a black background and were instructed not to move their eyes from this location. Next, the figure-ground display was presented for 40-60 ms, followed by the presentation of two targets. In each trial, only one target appeared in each region (figure and ground), and one target had a gap on its top while the other had a gap on its bottom. These targets were presented for 40 ms before one of the targets (i.e., the flicker target) was removed for an inter-stimulus interval (ISI) of 10, 20, or 30 ms, while the other target remained visible. After this ISI, the flicker target reappeared, and both targets remain visible for an additional 40 ms. Finally, the targets were removed and the figure-ground display remained visible until participants responded which target (gap on top or on bottom) was the target that flickered. Participants completed 384 trials and responded via key press.

<u>Results and Discussion</u>

Participants' accuracy (d') was calculated using the following formula (Macmillan & Creelman, 1991): $d' = z(\text{hit rate}) - z(\text{false alarm rate})$. For ambiguous displays, a two-factor ANOVA between shape (convex, concave) and ISI (10, 20, 30 ms) revealed a significant main effect of ISI, $F(2, 38) = 10.96$, $p < .05$, in which accuracy increased as ISI increased. However, there was no difference in accuracy for targets on convex and concave shapes, $F(2, 38) < 1$, *ns*, and no interaction between shape and ISI,

$F(1, 19) = 2.50$, $p = .10$. Hence, accuracy for both shapes was combined for the remaining analyses.

We used a two-factor ANOVA on trial type (figure, ground, ambiguous) and ISI (10, 20, 30 to analyze the *d*' data. The mean *d*' values across these conditions appear in Figure 16. The main effect of trial type was significant, $F(2, 38) = 5.92$, $p < .05$, with lowest sensitivity when the flicker target appeared on the figure (*d*' = 2.5) than on either the ground (*d*' = 2.6) or the ambiguous displays (*d*' = 2.7). The main effect of ISI was also significant, $F(2, 38) = 17.10$, $p < .05$, with an increase in *d*' as the ISI increased. Finally, the interaction between trial type and ISI was not significant, $F(4, 76) = 1.06$, $p > .30$.

We used planned pairwise comparisons to investigate flicker fusion performance across the different display types. The *d*' values were significantly lower when the flickering target appeared on the figure than on the ground, $t(19) = 1.92$, $p = .07$, and lower when the flickering target appeared on the figure than on the ambiguous regions, $t(19) = 3.60$, $p < .05$. The *d*' values did not differ when the flickering target appeared on the ground from when it appeared on the ambiguous regions, $t(19) = 1.36$, $p > .10$.

These findings suggest that there is a heightened sensitivity to flickering targets appearing within ground regions, compared to figure regions. In other words, these results support the temporal extension hypothesis, which proposes that figures hold processing longer than grounds. One consequence of this extended figural processing is that figures have poorer temporal resolution than grounds.

Although the current results support the temporal extension effect for figures, differences in the degree of temporal resolution between figure and ground regions may have been underestimated. Our modified flicker-fusion task instructed participants to detect a flicker within the display. In previous experiments, participants viewed a single, static or flickering target and reported how many items were present in the display (e.g., Yeshurun, 2004; Yeshurun & Levy, 2003). Thus, previous research assessed observers' reports of their perceptual experience of the flicker target. Not only were participants in the current experiment instructed to specifically search for a flickering target, but they also viewed a static target that could be used as a comparison. These two aspects of the current design may have raised observers' sensitivities (i.e., lowered flicker-fusion thresholds), resulting in higher accuracy overall and diminished differences between the temporal resolution of figures and grounds.

Discussion of Experiment 8

Temporal processing is modified based on the perceptual organization of the scene, where figures receive extended durations of perceptual processing (i.e., temporal extension effect; se Chapter III). The current experiment tested a strong prediction generated from the temporal extension effect: figures should be less sensitive to, and thus worse at detecting, a flickering target appearing within its borders. I found that figures are disadvantaged by the temporal extension effect, resulting in accuracy impairments in discriminating a flickering target.

Examination of the experiments demonstrating the temporal extension effect (see Experiments 5-7 in Chapter III) raises an alternative explanation for their results: participants may have made eye movements and fixated one of the regions during this presentation duration. The figure-ground displays were visible for 400 ms before the targets appeared in order to allow the regions to be fully segregated. Since figures tend to be fixated, this is particularly problematic because peripheral targets are processed faster than central targets (e.g., Carrasco, McElree, Denisova & Giordano, 2003). Their results suggest that preferential eye fixation of the figure can result in a temporal advantage for grounds. However, Experiment 8 addressed this concern. The figure-ground displays and targets were presented for up to 180 ms, at which point the figure-ground displays remained visible until response. Participants would not have had time to fixate either region prior to the presentation of the targets. Therefore, the differences found in

Experiment 8 indicated that the results in Experiments 5-7 were not due to preferential eye fixation by providing converging evidence for the temporal extension effect.

One account for the effects of both attention and figure-ground assignment on temporal processing is that processing figures (or attended locations) enhances activation of neurons relative to those processing grounds (or unattended locations). Some researchers have predicted higher amounts of activation for the neural representations of figures than for the neural representations of grounds (see Vecera & O'Reilly, 1998, 2000; see also Peterson, 1999, and Peterson & Skow, 2008). This increased activation for figures (or attended locations) may allow for increased sensitivity to targets' onsets and account for the temporal extension effect that decreases sensitivity to targets' offsets. In the next chapter, I present a computational model that was used to examine the plausibility of such a mechanism.

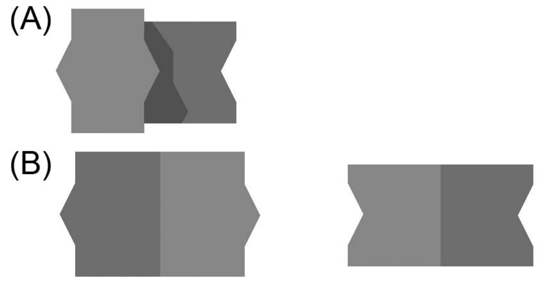

Figure 14. Stimuli used in Experiment 8. (A) Figure-ground display in which the symmetric convex region (depicted in light gray) appeared as the foreground region. (B) Two types of ambiguous displays that did not produce a strong figure-ground segregation.

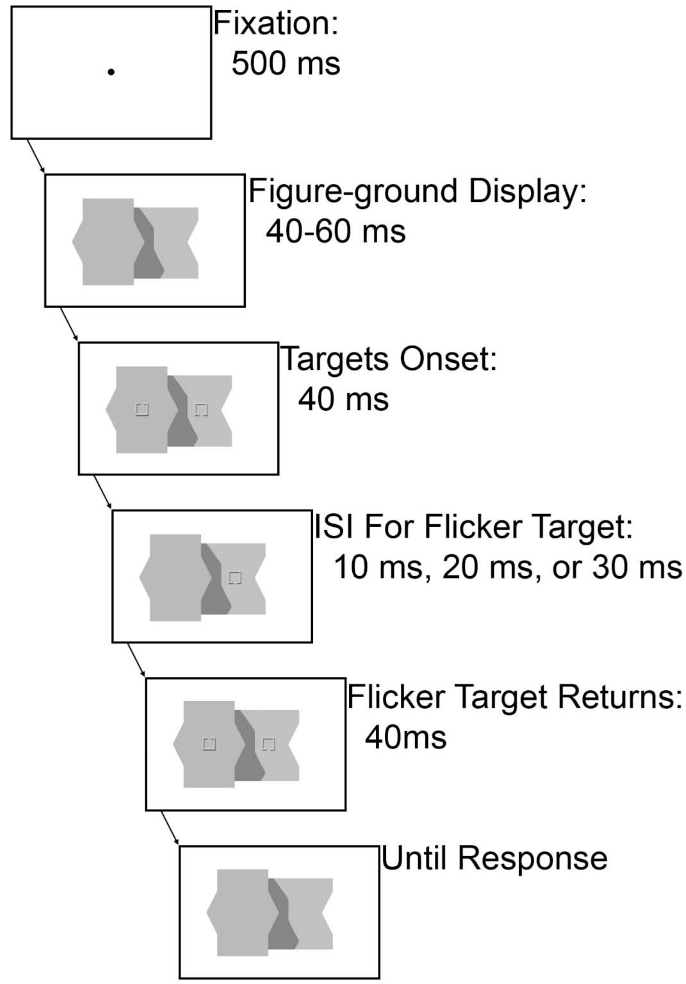

Figure 15. Events and their durations for a single trial in Experiment 8.

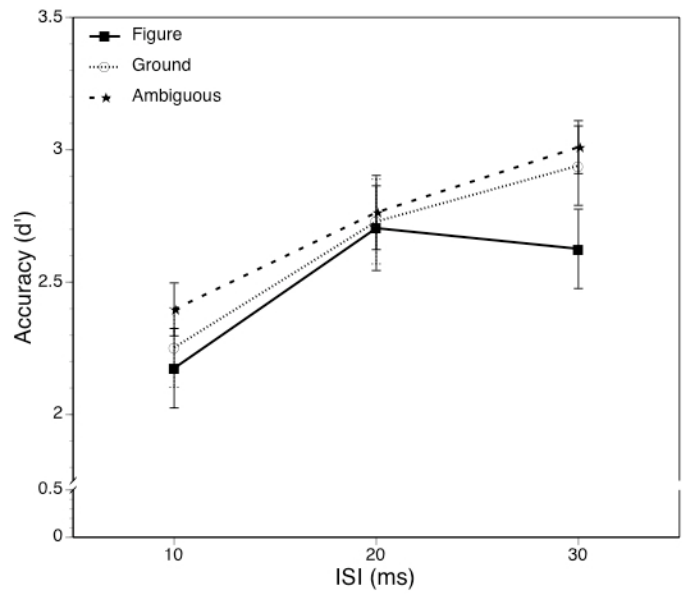

Figure 16. Results from Experiment 8, plotting accuracy (*d*') in reporting the feature (gap on top or bottom) of the flicker target for each display type across ISIs. All error bars indicate the within-subject 95% confidence intervals for the pairwise comparisons of the figure vs. ground trials (for the figure and ground lines) and of the ambiguous vs. figure trials (for the ambiguous line).

CHAPTER V
A TEMPORAL ORDER JUDGMENT MODEL
OF ONSETS AND OFFSETS

The preceding psychophysical studies have clearly demonstrated that temporal processing is influenced by figure-ground assignment. To accurately make temporal order judgments (TOJs) regarding the onset of the targets, the target on the ground needed to lead the target on the figure in order to perceive the events as occurring simultaneously. Lester et al.'s results suggest a perceptual processing advantage such that figures undergo perceptual processing prior to grounds – a prior entry effect.

In contrast, targets removed (i.e., offsetting) within the figure are perceived as disappearing *later* than targets removed from the ground region (Hecht & Vecera, in prep; see Chapter III). To accurately perceive the offset of information, it must be removed *earlier* on the figure than on the ground. This result suggested that figures are afforded extended durations of processing – a temporal extension effect.

Consequently, I demonstrated that flickering targets are more readily discriminated from among static targets when they appear on ground regions, supporting the temporal extension effect (see Chapter III). When the target flickers, extended durations of processing on figures shorten the perceived amount of time between presentations of the same stimulus.

Despite gaining an understanding of the consequences of figure-ground assignment for temporal processing, a mechanistic account for these effects has not been established. Similar effects have been reported in the attention literature (see Chapters II and III for discussion), and researchers have proposed accounts to explain the effects. Unfortunately, these proposals have developed independently of one another; mechanistic accounts of prior entry and temporal extension due to attention have not currently made contact with one another. Although each effect may arise from separate mechanisms, a cohesive mechanistic account would account for both effects within the same architecture. In the current chapter, I present a computational model that captures both the prior entry and temporal extension effects and in doing so illustrates the neural dynamics that might underlie the temporal processing of figures and grounds, providing a mechanistic understanding of the components underlying the behavioral effects.

A Dynamic Neural Field (DNF) Model

Change detection broadly consists of constant monitoring or storing of information that is then compared at a later point to a new set of information. In the experiments that first noted prior entry and temporal extension as consequences of figure-ground assignment (Lester et al., 2009; see also Chapters II-III), observers determined the temporal order in which two stimuli onset (or offset) within the display. To properly order these temporal events, the state of the visual scene must be compared from one instant to the next, albeit at a very brief timescale. Simply put, information in the visual field is monitored for changes, such as the addition of new visual information (onsets) or the removal of information (offsets). Therefore, the temporal ordering task used in the experiments falls into a broad class of tasks that probe change detection abilities.

Currently, only one computational model provides a thorough account of change detection: a dynamic neural field model of change detection (Johnson, Spencer & Schöner, in press; Johnson, Spencer, Luck & Schöner, 2009). This model emerged from the principles of the Dynamic Field Theory (DFT) of visual-spatial cognition (Simmering, Schutte & Spencer, 2008; Spencer, Perone & Johnson, 2009; Spencer, Simmering, Schutte & Schöner, 2007) and utilizes a neural architecture that captures the dynamics of the visual cortex (Amari, 1977; see also Wilson & Cowan, 1972).

The DFT uses central concepts of dynamic systems theory, which postulates that behavior emerges from time-extended processes in a task- and context-specific fashion. In this perspective, a *soft assembly* of factors, including input from the environment, the current demands placed on the system, and contributions from prior experience, impact the organization of behavior in the moment—typically, no single factor is dominant. Moreover, the DFT seeks to capture the behavior of an organism within an autonomous system that can receive input, process it, and generate its own response.

The concepts of DFT have been implemented using Dynamic Neural Field (DNF) models. At the most basic level, a DNF model consists of an excitatory field of neurons that are reciprocally coupled to a layer of inhibitory interneurons. These neurons are ordered within the field according to a functional topography that arranges the neurons based on their tuning to particular metric dimension (e.g., spatial location, color, etc.). For instance, neurons that respond to similar spatial locations will be close in the neural field, while neurons that respond to very different locations will be far apart in the field.

Within the excitatory field, neurons are locally excitatory, that is, sufficiently activated neurons in the field drive up their own activation (self-excitation) and the activation of their neighbors. The interaction between the excitatory and inhibitory layers creates a form of lateral or "surround" inhibition. Specifically, excitatory neurons stimulate inhibitory interneurons, which then project broad inhibition back to the excitatory layer. Note that only neurons that are sufficiently activated (e.g., above 0 activation) participate in these interactions. The locally-excitatory and laterally-inhibitory interactions in a field can give rise to a peak of activation—a stabilized state at the level of the neural population. Peaks in DNF models serve as the basic unit of representation.

Spencer and colleagues (e.g., Simmering, Schutte & Spencer, 2008; Spencer, Perone & Johnson, 2009; Spencer, Simmering, Schutte & Schöner, 2007) have primarily focused on two types of peak states. Peaks are either *self-stabilizing*, where the peak loses activation and 'dies out' when input is removed, or *self-sustaining*, where activation is maintained after input has been removed but can be de-stabilized through competition with other peaks or via stochastic forces (i.e., noise). Self-stabilized peaks have typically been used to serve the function of perceptual encoding, while self-sustaining peaks have served as the basis for visuo-spatial working memory. One of the unique features of the DNF change detection model is that it effectively integrates these two forms of neural dynamics. This is central to the task of change detection where a new stimulus must be encoded and compared to an existing working memory representation. An overview of this model is discussed below.

A Three-layer DNF Model of Change Detection

The change detection model is a three-layer DNF model (Johnson et al., in press; Johnson et al., 2009; see Figure 17). The perceptual field (PF(u)) is an excitatory neural layer that is reciprocally coupled to an inhibitory layer (Inhib(v))). There is also a second excitatory layer—the working memory field (WM(w))—that is reciprocally coupled to Inhib. Each layer is topographically organized, with locally excitatory and laterally inhibitory interactions emerging among the layers (see Amari, 1977). PF receives direct input from the environment. WM also receives input, but only weakly. Finally, PF has a strong feed-forward connection to WM. Note that this layered architecture was inspired by analyses of the cytoarchitecture in visual cortex (Douglas & Martin, 1998).

Because PF receives strong input from the environment, this field can quickly encode stimuli in the task space. PF generally establishes *self-stabilizing* peaks, allowing for the quick detection of items in both the initial stimulus array and the comparison stimulus array in change detection tasks. Note, however, that peaks in this field are not retained when the associated input is removed. By contrast, WM generally establishes *self-sustaining* peaks when stimulated by input from PF. Thus, peaks in WM can be maintained over time even after, for instance, the initial target array is removed.

To illustrate the functionality of this neural architecture, consider Figure 17, which illustrates how the 3-layer architecture detects a change in the canonical one-shot change detection task used in the literature (e.g., Luck & Vogel, 1997). At the start of a trial in this task, an array of three different colored items is presented, passing input to PF along the metric dimension (i.e., hue). These colors are "encoded" by establishing peaks of activation in PF (Figure 17A). These peaks, in turn, project activation to WM and begin building peaks at the corresponding feature dimensions (Figure 17B). Once the input is removed during the delay between comparisons, the self-sustained peaks persist in WM while the peaks in PF die out. During the delay, the self-sustaining peaks in WM pass inhibition to PF via the shared Inhib layer. This creates troughs of activation (i.e., activation levels that are below the resting level) at the feature values associated with the initial stimulus array (see troughs in Figure 17C).

When the test items are presented, input is again provided to PF, which raises activation at the corresponding hue values. Now, however, the troughs of inhibition prevent peaks from being re-established unless there is sufficient input at a new feature value (i.e., a changed value). For instance, in the case where the display has not changed, the input provided to PF at the time of comparison is suppressed by sustained activation in WM (see Figure 17C). As a result, the activation in WM is maintained which is the basis for a 'same' decision in the model. If a change is present in the array (Figure 17D), however, a peak forms in PF (see Figure 17D). This peak is the basis for a 'different' decision. Note that the model actively generates a decision on each trial in a response system. This system consists of two, bi-stable decision nodes (i.e., 'same' and 'different') that are self-excitatory and mutually inhibitory. The 'different' node receives the summed activation within PF, while the 'same' node receives the summed activation within WM (see Johnson et al., 2009). Once activation in either node crosses threshold (0), a response is generated and activation of the other node is suppressed.

A Temporal Order Judgment (TOJ) DNF Model

As mentioned above, discriminating the order of events over time can be considered one example within the broad category of change detection phenomena.

Therefore, the concepts used in creating an account of change detection can also be applied to onset and offset discriminations. Using the change detection model as a foundation, I demonstrate below that sensitivity to a change in the onset of information can be accomplished by monitoring activation dynamics within PF. To detect a change in the offset of information, however, the interaction between PF and WM is essential.

Model Architecture

In the current model, the three-layer architecture of the change detection model was maintained, as were the parameters governing interaction among the layers (see Johnson et al., in press, and Johnson et al., 2009, for the change detection model's equations). The current model used twelve free parameters that were either changed from or added to the change detection model: resting levels of the PF, Inhib, and WM layers, noise parameters, input strengths, and response parameters. These parameters, along with the remaining parameters retained from the change detection model are reported in Tables 2 and 3.

All inputs were projected strongly into PF and weakly into WM at the same strength used by Johnson et al. (20%). Given that the TOJ task differs from one-shot change detection, the inputs to the model were modified accordingly. In particular, several sources of input were provided to the model throughout each trial: Segmentation (Seg), Task, and Target. Seg represents the segmentation of the two regions present in the display (figure and ground, separated figure and ground, or ambiguous). Input from Seg represents the established figure-ground assignment (i.e., the outcome of the process) and could be considered the output from the 'figure' layer from Vecera and O'Reilly's computational model of interactive figure-ground assignment (see Vecera & O'Reilly, 1998, 2000 for details regarding the model). In the TOJ DNF model, Seg either has asymmetric activation (i.e., activation at one location, -30°, and not at the other, 30°), or symmetric activation with strong input (ambiguous trials) or without input (separated regions). The Task input highlighted the relevant target locations. Because these locations were fixed, this input was constant at both -30° and 30°. Finally, the Target input grew and/or receded in time to reflect the onset and offset movements of the target. For onsets, input to PF grew in strength across 110 ms, and then its strength died out across an additional 110 ms. For offsets, input to PF started strong to reflect the initial presentation of the target, and its strength receded across 110 ms in accordance with the disappearance of the targets.

Another notable difference between the change detection model and the current model is that the noise parameters were increased and noise was added to the Target inputs, reflecting a change in the system's susceptibility to noise in a perceptually demanding temporal order judgment tasks (see Tables 2 and 3). Also, noise was added to the resting level of the neural fields. This type of noise plays a critical role in de-stabilizing peaks in WM, which was an important component of the model's ability to detect offsets.

In addition to the noise added to the resting level of the neural fields, the global resting levels were modified from the change detection model for completing the onset and offset TOJs. Generally the PF and WM resting levels were lowered relative to the change detection while the Inhib resting level was raised, requiring stronger inputs projected into the PF and WM to build a peak of activation and weaker input to Inhib to establish peaks and project activation back into PF and WM. More specifically, the resting levels of PF differed between the onset and offset judgments, with the latter being higher than the former. For onsets, the lower threshold allowed for greater selectivity in the neural field. In contrast, offset judgments relied on a higher threshold that helped establish excitation in PF once the peaks in WM destabilized (see the example of modeling offsets below for discussion).

One final change in the TOJ DNF model was the addition of a new response field. In the change detection model, the system generated a same or different judgment on each trial (Johnson et al., in press; Johnson et al., 2009). By contrast, in the TOJ task, the model must provide a localized response to indicate which target onset (or offset) first. Thus, I added a response field that was reciprocally coupled to PF but was selective in its response; that is, a left or right location was selected based on the time-dependent input received from PF. This decision mechanism was realized by the equation:

$$\tau \dot{r}(x,t) = -r(x,t) + h_r + q_h\xi(t) + \int c_{r\_excite}(x - x')\Lambda_{r\_excite}(r(x',t))dx'$$
$$-\int c_{r\_inhib}(x - x')\Lambda_{r\_inhib}(r(x',t))dx' + \int c_{ru}(x - x')\Lambda_{ru}(u(x',t))dx'$$
$$+ T_r(x,t) + q\int c_n(x - x')\xi(x',t)dx' \qquad (1.1)$$

where $\dot{r}(x,t)$ is the rate of change of the activation level for each neuron across the spatial dimension, x, as a function of time, t. The first factor that contributes to the rate of change of activation in the response layer is the current activation in the field, $-r(x,t)$. This component is negative so that activation changes in the direction of the resting level, h_r. Next, activation is influenced by noise in the resting level as well as by local excitation and lateral inhibition. The next term in the equation is input from PF(u). Finally, the response layer receives activation from the target input as well as spatially correlated noise (for details, see Johnson et al., 2009).

The final modification to the change detection model was the addition of coupling between the response layer and PF. In particular, the response layer fed back onto PF according to the modified equation (1) taken from Johnson et al. (2009):

$$\tau \dot{u}(x,t) = -u(x,t) + h_u + \ldots \int c_{ur}(x - x')\Lambda_{ur}(r(x',t))dx' \qquad (2.1)$$

Modeling Onsets: An Example

An example of an onset simulation is presented in Figure 18. At the start of the trial, the TOJ DNF model was provided 50 ms to relax into a stable state. As task-relevant information (e.g., figure-ground display) is presented, these events are input to the three-layer model for 500 ms (see Figure 18). In particular, Seg and Task inputs projected activation to the PF and WM fields, building activation at the corresponding spatial location of the two regions (e.g., figure and ground). As shown in Figure 18B, the activation of the peak building at the location of the figure left) was stronger than at the ground location (right). Note, however, that these inputs were relatively weak; thus, activation in PF remained below threshold.

After 550 ms, the target events were introduced to the model via the Target input. The target inputs were presented at varying stimulus onset asynchronies (SOAs: 26, 50, 100 and 150 ms). As the first target began to onset, the strength of the input at this location (left) began increasing to its full strength over the course of 110 ms. Upon reaching full strength, the Target input began decreasing in strength over an additional 110 ms. After the designated SOA, the second target location received the same growth and recession of activation from the Target input field.

As can be seen in the figure, the convergence of the Target, Seg, and Task inputs built a peak of activation in PF (i.e., activation > 0). Once a peak pierced threshold in PF, activation began projecting more strongly into the response field at the location of this peak (left in Figure 18C). As a consequence of the peak in PF, activation at the left location in the response field raises above threshold generating a ‘left’ response. Because the figure was on the left, the model has generated a decision that the ‘figure’ target led the ‘ground’ target.

Modeling Offsets: An Example

As above, the model began by relaxing into its stable state for the first 50 ms. Next, in addition to input from the Seg and Target input fields, an initial boost of input was provided from the Task input field (see Figure 19). This initial boost in activation generated a large peak of activation in PF, capturing identification processes for the task relevant information. Because the targets were presented at the beginning of the trial, this information built peaks in WM, with the peak at the ‘figure’ location (left) growing to a greater strength due to the stronger input at this location. Note that the initial boost of activation from Task was removed after 200 ms, reflecting the completion of the identification process.

The sustained activation of peaks in WM decreased activation in PF until it fell below threshold due to activation from the shared Inhib layer. Target input then began to diminish at the target locations at varying stimulus offset asynchronies (SOAs: 26, 50, 100 and 150 ms), starting 550 ms after the beginning of the trial. As the first target began to offset, the strength of the input at this location (left) began decreasing from its full strength over the course of 110 ms. After the designated SOA, the second target location proceeded with the same recession of activation from the Target input field.

Upon removing the Target input, peaks in WM begin to decrease in activation (i.e., destabilize). Once the WM peaks are no longer above threshold, PF can then build a peak of activation in response to the continued Seg and Task inputs. Thus, the destabilization of the WM peaks was critical in generating activation in PF that can project into the response layer in order to generate a response from the system. As portrayed in the figure, the peak pierced threshold in PF at the figure's location (left in Figure 19D). Consequently, activation at that location in the response field rose above threshold, generating a 'left' response that indicated the 'figure' target was perceived as offsetting first.

Model Simulations

Simulations were conducted in MATLAB 7.2 (Mathworks, Inc., http://www.mathworks.com). Each time step within the simulator was equivalent to 1.33 ms. The conditions were separated by task (onset or offset TOJs) and display type (figure-ground, ambiguous, separated). Within each task and display type, there were 500 trials at 4 different SOAs (26, 50, 100, 150 ms). Each SOA occurred twice for each display condition to simulate figure-first and ground-first trials. Therefore, each batch of simulations had a total of 24,000 trials. Simulations were five batches of runs.

Results

Raw data from the simulations are plotted in Figure 20, with the left panels displaying the average performance of the simulations and the right panels displaying the empirical data collected in Experiments 1, 3, 5, and 7 (see Chapters II and III). Visual comparison of the onset and offset data suggests a substantial overlap between the simulation and the empirical data. In both tasks the figure-ground functions show approximately the same direction and amount of shift. Additionally, the model replicated the differences between slopes of the functions for all conditions, demonstrating its ability to capture the behavioral effects.

To quantify the fit of the model to the behavioral data, I calculated the root mean squared error (RMSE) between the simulations relative to Experiments 1, 3, 5 and 7. For all five batches of the simulation, the RMSE was calculated for each condition and then averaged to determine the overall fit of the simulated to the behavioral data (see Table 4). Thus, I compared a total of 96 means (and an additional 6 means determined by curve fits, see below) between the model, with 12 free parameters, and the empirical data. The average RMSE across each of the five simulations was 0.0447 (range: 0.0423-0.0491). The model provided an excellent fit to the behavioral data.

After determining the best fit of the model, the logistic curve for each simulation was calculated (see Figure 20). These logistic curves were then used to calculate two performance measures for TOJs. First, I calculated the point of subjective simultaneity (PSS; i.e., 50% 'ground first' responses), which is the primary measure of the prior entry and temporal extension effects within a TOJ paradigm. Second, I used the best-fitting curves to calculate the just noticeable difference (JND), which is half of the difference between the SOA values required to produce 75% and 25% 'ground first' responses. The

JND provides an estimate of the slope of the function as it is monotonically related to the function. See Tables 5-6 for a summary of each run of the simulation's PSS and JND as well as the behavioral averages for these values.

Onsets and Prior Entry

The PSS for onsets was 15.9 ms for figure-ground trials, -1.0 ms for separated region trials, and -3.3 ms for ambiguous trials (see Table 5). These values are a close approximation to the average behavioral data for all three trial types (10.1, -0.5, and -2.7 ms, respectively). The positive PSS for figure-ground trials indicates that the point at which the stimuli would be perceived as simultaneous requires the ground target to lead, similar to the behavioral data. No shift was observed in the ambiguous and separated region trials, as evidenced by the near-zero PSSs. Therefore, the model obtained a prior entry effect for figure-ground trials.

Upon calculating the JNDs, the model yielded estimates of 62.3 ms for figure-ground trials, 48.2 ms for separated regions, and 73.1 ms for ambiguous. Again, these data are similar to the findings in the behavioral data (see Table 5). Interestingly, the model was able to predict the shallower slope for the ambiguous trials, relative to both figure-ground and separated region trials.

Offsets and Temporal Extension

Analysis of the PSS for offsets indicated a PSS of -10.6 ms for figure-ground trials, compared to -10.1 ms in the behavioral data (see Table 6). In contrast, the separated region and ambiguous trials yielded a PSS of -2.7 ms and -1.1 ms, respectively, mirroring the behavioral data (1.8 ms and -1.3 ms, respectively). The negative PSS for figure-ground trials suggests the model requires the figure target to *lead* the ground target in order to accurately order the offset events, as did the participants in the behavioral experiments (i.e., a temporal extension effect). Again, the near-zero PSS for separated regions and ambiguous trials replicates the effects observed in the data.

The JNDs also fell close to the behavioral data (see Table 6). Figure-ground trials (29.3 ms), separated regions (29.8 ms), and ambiguous trials (30.7 ms) were identical. Likewise, the behavioral data had not differed between these display types (36.4 ms, 42.6 ms, and 39.6 ms, respectively). This suggests that the slopes of the functions were equivalent, as was sensitivity to the offset events across display types, though there was a greater range and generally higher SOAs in the empirical results.

Denser SOA Sampling

An additional set of simulations (5 batches) was conducted with a denser sampling of SOAs (13, 26, 39, 50, 65, 80, 100, 125, and 150 ms) to provide a closer estimate of the PSS and JND statistics. The best-fitting logistic curve fits are dependent upon the data samples; adding data points increases the precision of the curve fit due to a decreased influence of potential outliers. Although the behavioral experiments require sparse sampling of SOA due to time and other constraints (e.g., fatigue), the model is able to sample across many SOAs. Thus, these batches of runs should show less variation in the estimates of the PSS and JND, which are both calculated on the best-fitting curve, resulting in better fits with the PSS and JND values obtained in the behavioral experiments.

Figure 21 illustrates the curve fits for these simulations, and Tables 7 and 8 contain the PSS and JND values for all batches of the simulations. For onsets, the average PSS was now 14.1 ms for figure-ground trials, -0.5 ms for separated regions, and -1.9 ms for ambiguous trials. These estimates are less variable among batches of the simulation, and they are closer estimates of the behavioral data. The JNDs for figure-ground (44.7 ms), separated regions (47.2 ms) and ambiguous (70.0 ms) trials show a similar trend: the estimates are more stable and better approximate the data.

The same reduction in variance of estimates was found in the case of offsets. The PSS values were now -10.3 ms, -0.4 ms, and -0.7 ms for figure-ground, separated regions, and ambiguous trials, respectively. These estimates are all within 2.5 ms of the behavioral data. Once again, the JNDs did not vary across trials; figure-ground (29.8 ms), separated regions (31.7 ms) and ambiguous (30.1 ms) trials did not demonstrate differences in the slopes of the function.

Discussion of the TOJ DNF Model

Using real-time simulations, this model was able to capture the prior entry and temporal extension effects. These simulations are critical because they show the neural fields changing over time, responding to the particular input at any given instance. Furthermore, this model provides insight into the mechanism creating these effects and can be generalized beyond the figure-ground results to account for the results found in the attention literature.

Interestingly, the model not only captured the shifts in temporal perception as a result of figure-ground assignment, but it also was able to produce the differences in sensitivity (i.e., slope differences) in the onset judgments while retaining the lack of differences in the offset judgments. The operation of the model and its ability to simulate the behavioral data provide insights into the temporal effects of FG assignment. By designing and testing the model, I revealed parameters that played a critical role in shifting the PSS and creating slope differences for onsets but not offsets. Even more, the model accomplished this with the change detection DNF model's framework and parameters; the TOJ DNF model had only twelve free parameters, providing a powerful extension of Johnson and colleagues' model (Johnson et al., in press; Johnson et al., 2009) to a different change detection paradigm (i.e., TOJs).

One critical component for completing TOJs for onset events is the structure of the segmentation input. When conducting initial tests of the parameters, the input coming from Seg impacted the amount of shift of the PSS. Specifically, shifts in the PSS only occurred when asymmetric input was provided to the model. The ambiguous and separated trials did not produce systematic shifts in the PSS. Therefore, one critical assumption of the TOJ DNF model presented here is that figure-ground assignment is treated as an asymmetric input.

For figure-ground trials, the PSS shifts away from zero due to increased errors in judgments at the shortest SOA – a consequence of the asymmetric activation projected from Seg. For onsets, this is the positive (ground-first) SOA, and for offsets it is the negative (figure-first) SOA. In the case of onsets shown in Figure 22, Seg's input is strong enough to keep the activation at the figure location slightly higher than the ground. As the first target input (i.e., at the ground location) is presented, activation at that location begins to rise. Still in order to make an accurate judgment, the ground's peak must overcome the difference in activation between the figure and ground before the figure target onsets. On a higher proportion of trials than when the figure's target leads, 26 ms is not a sufficient amount of time for the ground activation to recover, surpass the figure's activation and begin projecting activation to the response field, so the incorrect response is generated (i.e., 'figure') relative to the comparable SOA (i.e., figure-first: 26 ms).

Similarly, the shift in offset PSS is directly impacted by Seg's asymmetric projection. Again, raised levels of input for the figure location increases its peak activation in PF, which consequently builds a stronger peak in WM. Therefore, the 'disadvantaged' ground is, in the case of offsets, actually at an advantage by having less activation. As portrayed in Figure 23, less activation at the ground's location allows the peak in WM to return to sub-threshold levels of activation (i.e., destabilize) sooner than the figure. At the shortest figure-first SOA (26 ms), the higher amount of activation at the figure's location is not always able to diminish rapidly enough to release inhibition on PF, allowing a peak to be built in PF in response to the Task input. Instead, the ground peak destabilizes earlier in response to the offset of the corresponding target at its location, causing the incorrect response (i.e., 'ground') to be generated.

Clearly the asymmentric input from Seg played a critical role in producing the shift in the psychophysical functions, supporting previous figure-ground research suggesting that neural activation differs between figures and grounds. For example, Vecera and O'Reilly generated and tested a model to explain the increased salience of foreground figures relative to ground regions (see Vecera & O'Reilly, 1998, 2000; also see Kienker, Sejnowski, Hinton, & Schumacher, 1986; Sejnowski & Hinton, 1987; but see Peterson, 1999, and Peterson & Skow, 2008 for an alternative account). Their interactive model contained neural representations of both figures and grounds. They predicted that figures have an enhanced neural activation compared to grounds. Vecera and O'Reilly's simulations provided strong support for their hypothesis, as opposed to other descriptive models that were used to generate behavioral predictions that were tested in additional experiments (see Peterson, 1999, and Peterson & Skow, 2008). Supporting Vecera and O'Reilly's conclusions, neurophysiological studies have demonstrated that perceiving figures results in increased neuronal firing relative to perceiving grounds. For example, V1 and V2 neurons in macaques increased in firing when their receptive fields were located on the figure (e.g., Lamme, 1995; Marcus & Van Essen, 2002; Qiu, Sugihara & von der Heydt, 2007). Therefore, it is reasonable to assume that the Seg input is asymmetrical between figures and grounds and can be a critical factor in generating consequences of figure-ground assignment (e.g., prior entry and temporal extension effects).

The second critical component that emerged from the TOJ DNF model was the strength of the input from Seg. The separated regions displays were assumed to lack segmentation input because these displays should be interpreted as two distinct objects. Thus, by not sharing a contour, there is no competition between the regions for figural assignment. In contrast, there is some competition in the figure-ground displays, but the majority of the competition can be resolved early in the trial, prior to the onset or offset events, and remains consistent throughout the trial.

In the case of an ambiguous display, strong input was provided at both locations. I conjecture this was necessary due to constant competition between these regions for figural assignment. The displays presented in the behavioral experiments contained an abrupt transition between regions along a straight, shared contour (see Figure 1 in Chapter II). The regions appeared to accidentally align, which may have increased confusion in how to perceptually organize the display. The behavior of the model suggests that the increased input raises activation closer to threshold, making the system more susceptible to noise, which then could push either location's activation over threshold in PF (onsets) to generate a response, thereby reducing the accuracy of the TOJ.

Supporting this interpretation, Vecera, Vogel and Woodman (2002) presented data in which ambiguous trials demonstrated a reaction time benefit over figure-ground displays. Observers viewed two-region displays whose shared contour was aligned horizontally (figure-ground trials) or vertically (ambiguous trials). They demonstrated that the horizontal alignment (i.e., one region in the upper visual field and one in the lower) produced a reaction time benefit for lower regions (i.e., figure) over the upper regions in a memory matching task in which participants chose which of two regions was present in the previous two-region display. Interestingly, trials in which memory for ambiguous trials was probed yielded faster reaction times and higher accuracy than the figure-ground trials. They concluded this benefit for ambiguous displays may result from fewer constraints placed on the ambiguous displays, allowing them to be processed more quickly than figure-ground displays (see also Driver & Baylis, 1996). My TOJ DNF model agrees with Vecera et al.'s (2002) discussion and suggests that fewer constraints may increase activation associated with processing these ambiguous regions, which can also speed response generation relative to figure-ground trials. Further confirmation of this hypothesis can be provided by conducting a series of analyses examining the reaction times produced by the model and comparing them between figure-ground and ambiguous trials. As found behaviorally, the model should be faster to generate a response for the ambiguous trials than for the figure-ground trials in the case of onset detections.

Interestingly, the strength of the Seg input did not impact the JND for ambiguous trials in the offset task: all conditions yielded the same slopes. This result highlights the difference between the onset and offset tasks. For onsets, the performance of the system is highly dependent upon, and sensitive to, the input. Slight variations in the input strength can shift the slope of the function. In contrast, offsets are not as strongly impacted by the strength of the input. Because offset judgments rely on the WM peaks falling back below threshold, and not in establishing the initial peaks in PF, the strength of the input is not as critical in determining the slope of the function. Sensitivity to noise remains the same, unlike onsets, and differences between conditions instead rely on the interaction and inhibition between the two locations.

The strength of the input also interacted with the symmetry of input to influence the figure-ground PSS. Providing asymmetric input shifted the PSS, and the strength of the asymmetric input determined the size of the PSS: stronger inputs yielded larger shifts in the PSS (i.e., higher estimates of the SOA at 50% ‘ground first’ responses). One prediction that can then be tested is to manipulate the strength of the input at either location (e.g., manipulate saliency of the figure). As the saliency of the figure increases, the PSS should continue to become larger, meaning that more time would be required between the figure and ground events to accurately order them.

The interaction between these two components (i.e., asymmetric input and strength of input) also offers an explanation for other aspects of the empirical data. Individual curve-fits from the prior entry and the temporal extension experiments (see Experiments 1, 3, 5, and 7) showed noticeable variation in both the PSS and the JND for both figure-ground and ambiguous trials upon visual inspection. While a majority of the participants had the corresponding rightward (Experiment 1) or leftward (Experiment 5) shift in PSS or the lacking shift (Experiments 3 and 7) in addition to the larger JND (i.e., shallower slope) for the ambiguous trials in only figure-ground onset trials (Experiment 1), many other participants deviated from these patterns. One account for these differing individuals is that their perception of the display is changed relative to those fitting the trends. Figure-ground assignment, while often similar across individuals, is still a heuristic used by the visual system. The cues that are used to complete figure-ground assignment (e.g., convexity) are not used consistently across individuals. Individuals whose PSS did not noticeably shift, for example, may have established a weaker representation of the convex region as figure, while those with opposite shifts likely established a reverse assignment (i.e., concave region as figure), on a greater proportion of trials. Similarly, the perception of the ambiguous trials can differ across participants, changing the strength of the input in accordance with changes in constraints implemented when processing the display.

The individual differences may also be highlighted in the empirical data because of the sparse sampling of SOA. This methodological point is critical when considering individual differences in JND, though it also impacts the calculation of PSS. By obtaining a smaller sampling across SOA, fewer points are used to fit the logistic functions to each individual's data. As a result, the curve-fits are more likely to be impacted by outliers. Denser sampling across SOA in the model supports this conjecture: the five batches of runs of the denser sampling simulation provided closer estimates of the PSS and JND to one another than did the five batches of the simulation using the SOAs tested empirically (see Table 4 and compare Tables 5 to 7 and Tables 6 to 8). Therefore, the individual data likely includes the impact of differences in curve-fits on the JND and PSS; denser sampling may better estimate each individual's psychophysical function and reduce variation between individuals. The model supports this prediction; however, due to constraints (e.g., time) this prediction may only be tested using psychophysically trained participants, though other concerns (e.g., fatigue) remain.

Further, other manipulations (e.g., allocation of spatial attention to one location) may also be provided, in lieu of Seg, to the change detection mechanism to produce these same consequences for temporal processing. Figure-ground assignment and attention do affect temporal processing in similar ways: both processes result in prior entry and temporal extension effects (see Chapters II and III for a discussion). Therefore, I surmise that these processes may utilize the same mechanism in order to influence temporal processing in the same, structured fashion. By extension, current theories regarding spatial attention's impact on temporal processing may provide further insight into the nature of the mechanism portrayed in the TOJ DNF model. The current model suggests that raised activation (i.e., asymmetric input) for figures relative to grounds puts activation closer to detection threshold in the case of onsets, but can also extend the duration of processing for these regions as well.

Similar accounts were proposed within the attention literature, but unfortunately they are separate mechanisms: one to account for prior entry and one to account for temporal extension. Schneider and Bavelier (2003) found that the prior entry effect can be attributed to both an acceleration of processing and to a sensory facilitation, whereby perceptual processing is accelerated (e.g., neurally enhanced) independently of attention. Their proposal suggested that the neurons responding to attended regions increased in activation, enhancing their representation. This enhancement then allowed for faster detection of targets appearing at that location. This general account aligns with the characteristics evident in the TOJ DNF model, which also predicts an increase in activation in response to the source of the asymmetric, or biased, input (i.e., figure-ground assignment), but Schneider and Bavelier did not examine the hypothesis beyond their mathematical model.

However, a more structured theory has been proposed to account for the temporal extension effect. In examining the impact of attention on both spatial and temporal processing, Yeshurun and Levy (2003) considered two alternatives: spatial and temporal resolution may be independent, separable processes (e.g., Lehky, 1985; Wilson, 1980) or that they interact (e.g., Carrasco, 1990; Drum, 1984), yielding a tradeoff between the two (e.g., Wilson, 1980; Wilson & Bergen, 1979) where foveated locations are provided higher spatial resolution compared to high temporal resolution afforded in the periphery. Using a gap detection task to assess spatial resolution and a two-flicker fusion threshold paradigm (e.g., Levine, 2000) to assess temporal resolution, Yeshurun and Levy found behavioral support for a tradeoff between the two processes. After finding that attended locations had high spatial and low temporal resolution, they outlined a neurophysiological hypothesis that accounted for these behavioral effects.

Yeshurun and Levy's (2003) hypothesis considered the aforementioned processing differences between foveated and peripheral locations, and drew parallels between them and the characteristics associated with the parvocellular (P) and magnocellular (M) pathways in visual processing. Parvocellular neurons have smaller receptive fields (e.g., Schiller & Logothetis, 1990; Shapley & Perry, 1986) and extended response durations (e.g., Merigan & Maunsell, 1993; Schiller & Logothetis, 1990), contrasting the properties of M neurons. Moreover, these characteristics align with the differences found between foveated and peripheral locations (e.g., Allen & Hess, 1992). Therefore, enhancing one domain (spatial or temporal resolution) should result in a decrease to the other domain, creating a tradeoff between the two. By Yeshurun and Levy's account, attention increases the activation of P neurons. In turn, this activation then projects inhibition to the M neurons resulting in higher spatial acuity but poorer temporal resolution at the location of attention.

Yeshurun (2004) later supported this neurophysiological hypothesis in a series of behavioral experiments examining temporal resolution using a two-flicker fusion threshold paradigm. Critically, these studies were designed to inhibit the M neurons prior to activation of the P neurons. In doing so, the P neurons, when activated via attention, would not be able to inhibit the M neurons. Yeshurun inhibited the M pathway by presenting either colored stimuli in isoluminant pairs (e.g., blue paired with yellow) or a diffuse red light. Magnocellular neurons are both colorblind (e.g., Merigan & Maunsell, 1993; Schiller & Logothetis, 1990) and are suppressed by diffuse red light falling on the surround of their receptive fields (e.g., Livingstone & Hubel, 1984; Van Essen, 1985). If the inhibition of M by P neurons while processing information at an attended location is critical in degrading temporal resolution, then, Yeshurun argued, eliminating this inhibitory process should improve temporal resolution at attended regions.

Yeshurun (2004) found decrements in temporal resolution under normal circumstances, but found attenuated decrements when the flicker stimuli were isoluminant and found no differences in resolution between attended and unattended locations when a diffuse red background was used. These results supported the neurophysiological hypothesis that P-M inhibition processes impact temporal discrimination by decreasing temporal resolution. Furthermore, Yeshurun's results also offer an additional explanation for the observation that P neurons are active for longer durations and have a slower rate of decay relative to M neurons (e.g., Merigan & Maunsell, 1993; Schiller & Logothetis, 1990).

Therefore, Yeshurun and Levy's (2003; see also Yeshurun, 2004) neurophysiological hypothesis addresses the physical mechanism that can give rise to the temporal extension effect (i.e., extended processing for attended locations or figures). Figure-ground assignment has a similar impact on temporal resolution, such that figures are processed similarly to attended locations. Specifically, the temporal resolution is degraded at these locations (see Chapter IV). Yeshurun and Levy's account is reminiscent of one proposed by Weisstein, Maguire and Brannan (1992). Weisstein et al. proposed that regions processed by the P pathway are recognized as figures, suggesting that attention and figure-ground may be utilizing similar mechanisms. Because figure-ground has been shown to impact temporal processing in similar ways as attention, potentially resulting in similar neurophysiological behaviors, I speculate that temporal processing decrements from figure-ground assignment and from attention are generated from use of the same mechanism, as demonstrated above by the TOJ DNF model, and that the source of this mechanism may relate to the P and M pathways.

Still, it is important to note that there is no direct evidence for the P-M inhibition hypothesis. Indirect behavioral evidence has been provided (e.g., Yeshurun, 2004) to support the hypothesis, but currently no studies have examined activation patterns in these pathways during completion of TOJ tasks to study the role and interaction of the P and M pathways. As Schiller (1996; see also Schiller & Logothetis, 1990) noted, the separation of these pathways is less distinct in later visual processing (e.g., V4). Without directly studying the neurophysiological functioning in these tasks, it is uncertain if an appropriate theory should distinguish between the P and M pathways. In contrast, the current TOJ DNF model provides a detailed depiction of the neural dynamics (i.e., patterns of activation and their interaction) that can produce the prior entry and temporal extension effects. Moreover, this model accounts for both effects whereas the P-M inhibition hypothesis has only addressed the temporal extension effect.

To conclude, I presented a TOJ DNF model that demonstrated the plausible dynamics of a single architecture that can account for differences in onset and offset temporal judgments. Ordering the onset (or offset) of events requires change detection, so the change detection model (Johnson et al., in press; Johnson et al., 2009) was extended, and slightly modified, in order to account for the results and gain an understanding of the factors involved in producing these consequences of figure-ground assignment (and spatial attention). In successfully modeling the prior entry and temporal extension effects, the current TOJ DNF model demonstrates the capability of the change detection model by extending its architecture to account for a wide variety of tasks.

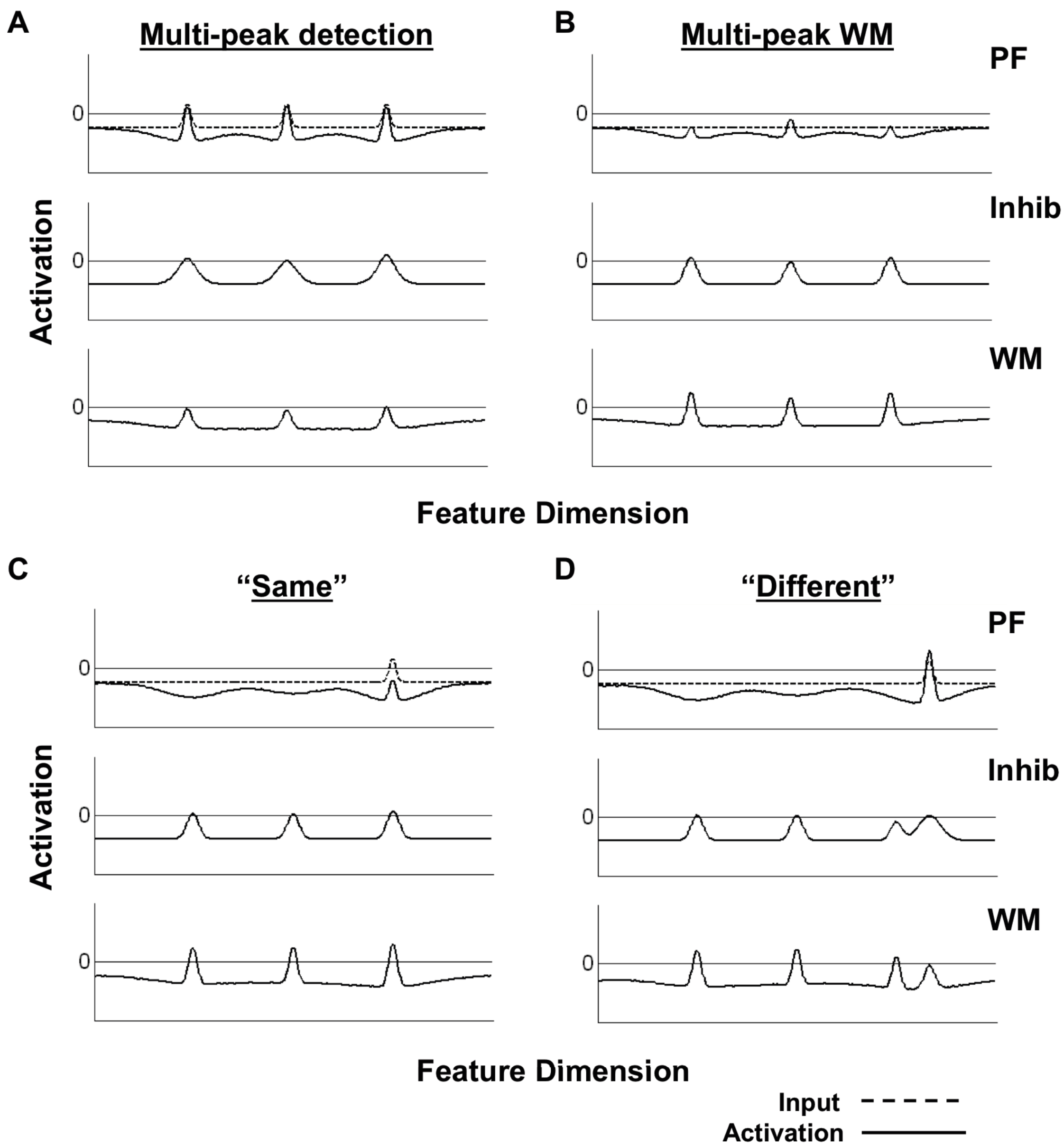

Figure 17. Simulations of the three-layer model in response to multiple simultaneous inputs. (A) and (B) show the detection of the inputs by PF, and their consolidation and maintenance in WM, respectively. The simulations in (C) and (D) show the generation of "same" and "different" responses in the multi-item case. Figure used with permission and taken from Johnson, J. S. (2008). A dynamic neural field model of visual working memory and change detection. *The University of Iowa: Ph.D. Dissertation*.

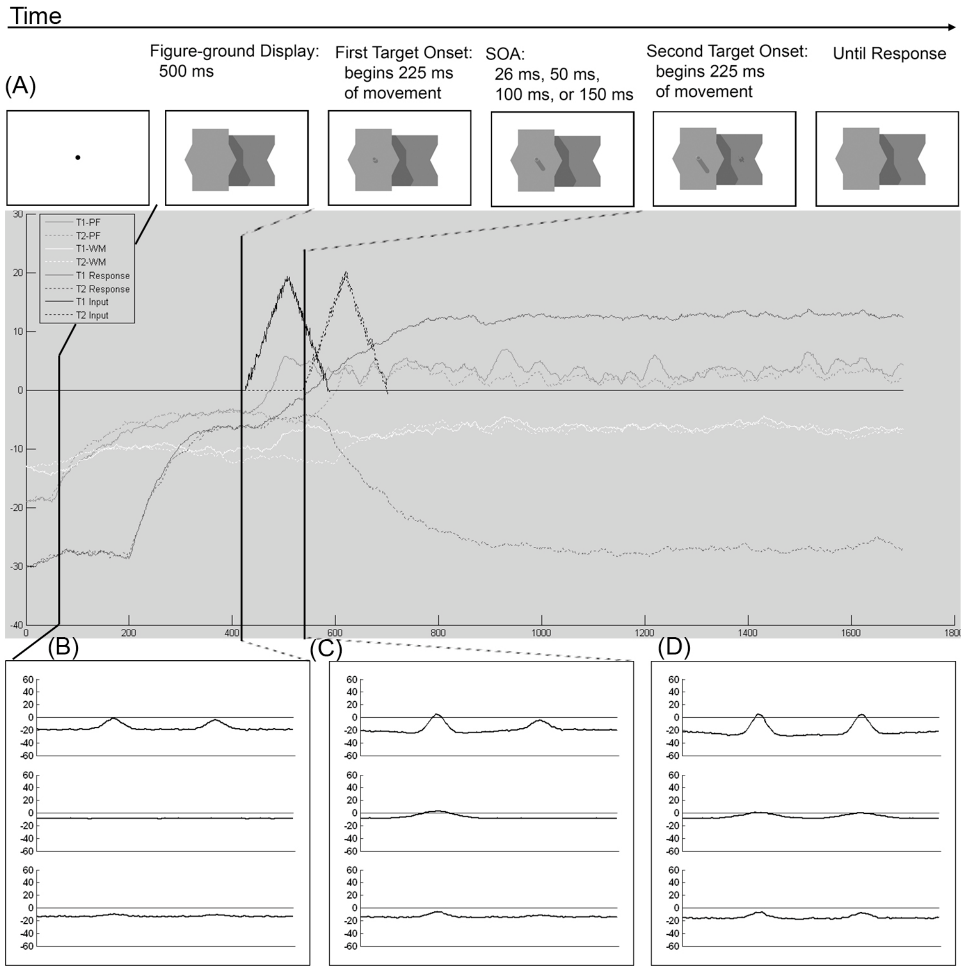

Figure 18. Depiction of a single onset trial presented to the model during the simulations and the three-layer model's activation over time. (A) The progression of trial events over time as presented to the participants and the corresponding activation in the model appears in the grey panel below. Activation is plotted along the y-axis, with time plotted on the x-axis. Starting at the top of the y-axis, the first black lines crossing the y-axis at 0 indicate the Target input over time. Going down the y-axis, the next pair of lines indicate activation in the WM field for T1 (figure) and for T2 (ground). The next pair of lines indicate activation in PF for T1 and T2, and the final dark grey lines indicating activation in the response field. For all lines, the solid lines indicate activation in response to T1 and the dotted lines are activation levels in response to T2. (B) Activation at the end of the presentation of the figure-ground display prior to the targets' appearances. (C) Activation in PF is higher for the figure location (left) at the end of the initial presentation of the figure target and the SOA (150 ms). (D) Activation levels after the onset of T2.

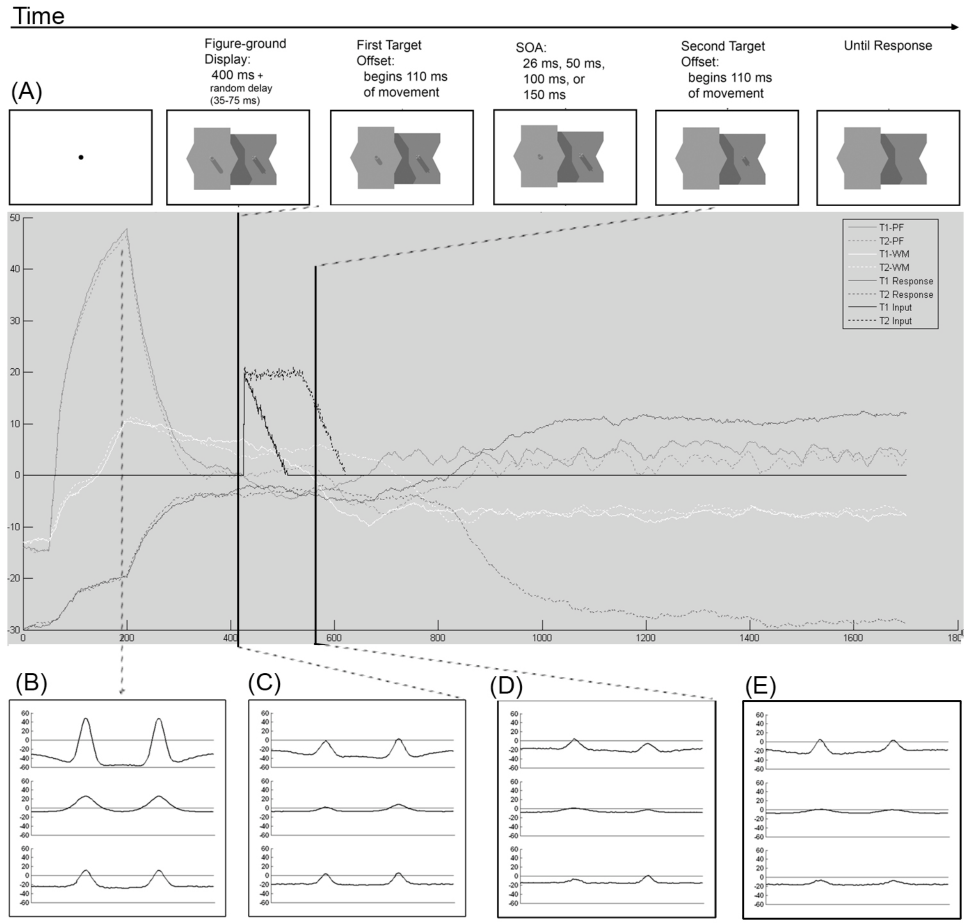

Figure 19. Depiction of a single offset trial presented to the model during the simulations and the three-layer model's activation over time. (A) The progression of trial events over time as presented to the participants and the corresponding activation in the model appears in the grey panel below. Activation is plotted along the y-axis, with time plotted on the x-axis. Starting at the top of the y-axis, the first black lines crossing the y-axis at 0 indicate the Target input over time. Going down the y-axis, the next pair of lines indicate activation in the WM field for T1 (figure) and for T2 (ground). The next pair of lines indicate activation in PF for T1 and T2, and the final dark grey lines indicating activation in the response field. For all lines, the solid lines indicate activation in response to T1 and the dotted lines are activation levels in response to T2. (B) Activation in the three-layer model at the end of the initial boost with the figure-ground display. (C) Activation at the end of the presentation of the figure-ground display prior to the targets' disappearances. (D) Activation in PF is higher for the figure location (left) at the end of the initial offset of the figure target and the SOA (150 ms). Note that activation in WM is below threshold for the left (figure) location. (E) Activation levels after the offset of T2. Now both peaks in WM are below threshold.

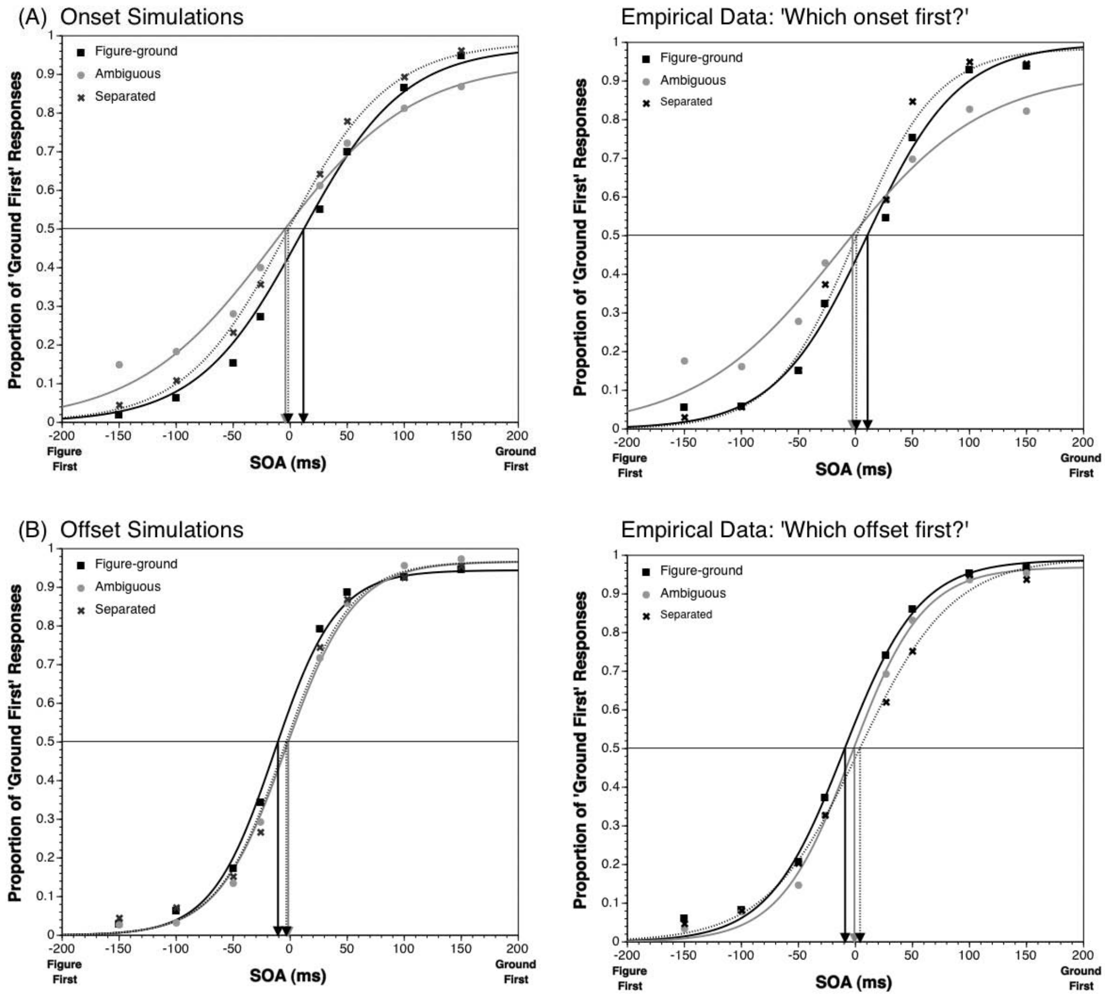

Figure 20. Model simulations (left panels) and empirical experiments (right panels) data for both the (A) onset tasks and the (B) offset tasks.

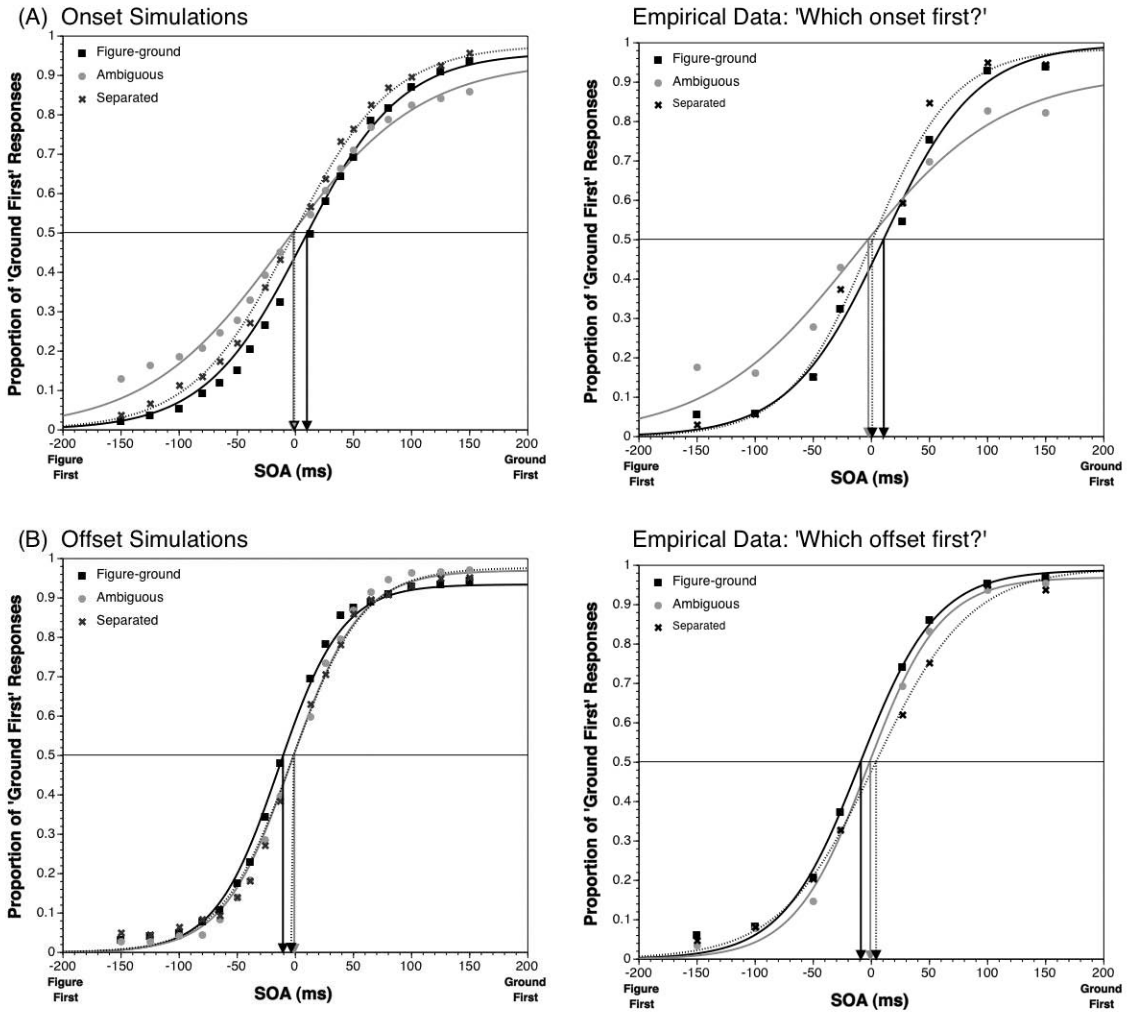

Figure 21. Model simulations (left panels) with a denser sampling across SOAs and empirical experiments (right panels) data for both the (A) onset tasks and the (B) offset tasks.

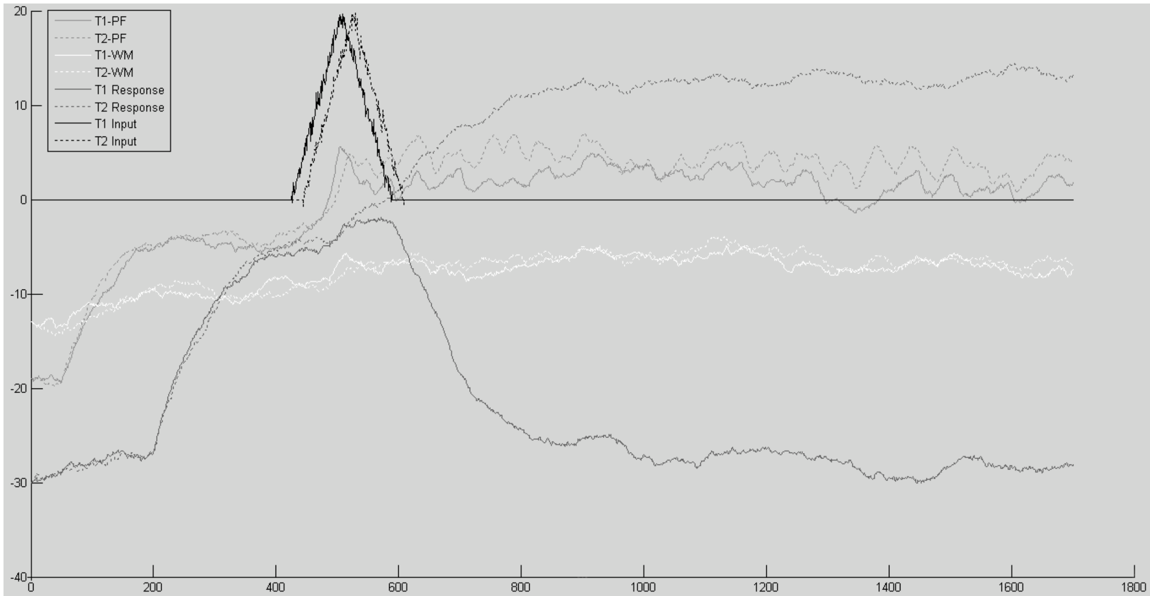

Figure 22. Sample model simulation's activation (y-axis) over time (x-axis) for a figure-ground trial in the onset task where the ground target led by 26 ms. This example demonstrates the model incorrectly responding 'figure'.

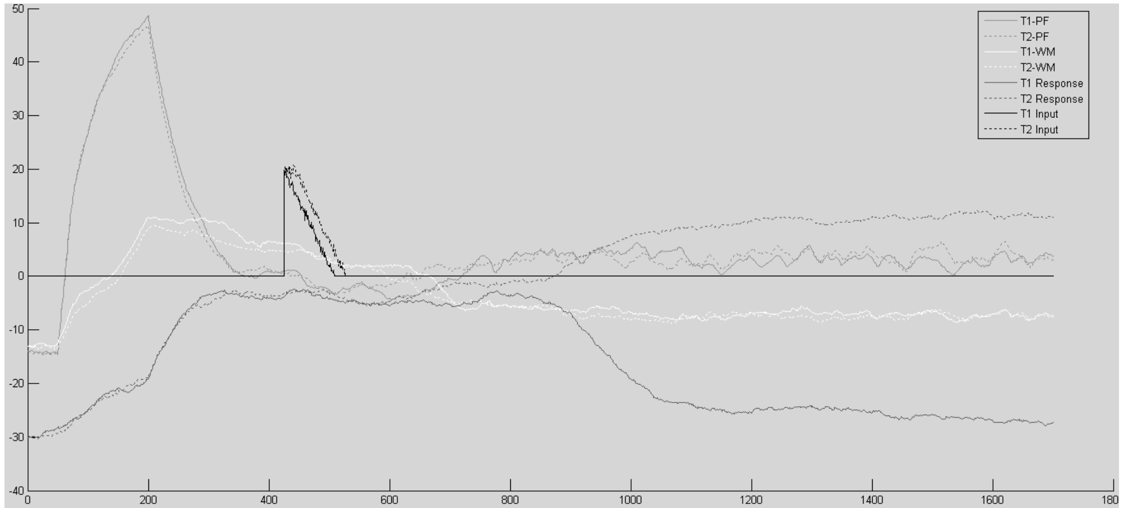

Figure 23. Sample model simulation's activation (y-axis) over time (x-axis) for a figure-ground trial in the onset task where the ground target led by 26 ms. This example demonstrates the model incorrectly responding 'figure'.

Table 2. Parameter Values Used in Model Simulations

Layer	h_{init}	h_{on}	h_{off}	Self-excitation	Excitatory projections	Inhibitory projections	Scaled Input Strength	τ
u (PF)		-19	-14	$c_{uu} = 3.15$ $\sigma_{uu} = 3$	$c_{ur} = 1.0$ $\sigma_{ur} = 5$	$c_{uv} = 1.85$ $\sigma_{uv} = 24$ $k_{uv} = .05$	$I_u = 1.0$	80
v (Inhib)		-8.5	-8.5		$c_{vu} = 2.0$ $\sigma_{vu} = 10$ $c_{vw} = 1.95$ $\sigma_{vw} = 5$			10
w (WM)		-13	-13	$c_{ww} = 3.15$ $\sigma_{ww} = 3$	$c_{wu} = 1.5$ $\sigma_{wu} = 5$	$c_{wv} = .325$ $\sigma_{wv} = 42$ $k_{wv} = .08$	$I_w = 0.2$	80
r(RESP)	-30	-7	-8	$c_{r\_excite} = 5$ $\sigma_{r\_excite} = 5$	$c_{ru} = 1.0$ $\sigma_{ru} = 5$	$k_{r\_inhib} = 3$	$I_r = 0.2$	80

Table 3. Additional Parameter Values Used in Model Simulations

Strength of spatially correlated noise to fields	$c_{noise} = .1$
Width of spatially correlated noise	$\sigma_{noise} = 0.45$
Strength of noise on resting level (*h*)	$c_{h\_noise} = 3$
Strength of noise on Target input	$c_{input\_noise} = 0.6$
Slope of sigmoid	$\beta = 5.0$
Field size	$n = 151$
Segmentation Inputs	$c_{seg} = 0.6$
	$\sigma_{seg} = 5$
	$c_{seg\_amb} = 3$
	$\sigma_{seg\_amb} = 5$
Target Input	$c_{targ} = 20$
	$\sigma_{targ} = 5$
Task Input	$c_{task} = 15$
	$\sigma_{task} = 5$

Table 4. Root Mean Squared Errors for All Simulations

	Simulations					
Simulation	Run 1	Run 2	Run 3	Run 4	Run 5	*Average*
SOAs Match Empirical Studies	0.0491	0.0423	0.0444	0.0446	0.0430	*0.0447 (0.0027)*
Denser Sampling of SOAs	0.0457	0.0459	0.0430	0.0409	0.0403	*0.0432 (0.0026)*

Note: Parentheses indicate standard deviations.

Table 5. Statistics for Onset Simulations

			Simulations					
Statistic	Trial Type	Behavioral Data	Run 1	Run 2	Run 3	Run 4	Run 5	*Average*
PSS	Figure-ground	10.1	17.9	14.5	13.2	16.4	17.7	*15.9 (2.0)*
	Separated Regions	-0.5	-4.2	-2.1	0.6	1.9	-1.5	*-1.0 (2.4)*
	Ambiguous	-2.7	-0.1	-7.6	-1.4	-4.4	-3.3	*-3.3 (2.9)*
JND	Figure-ground	41.6	66.5	58.9	58.8	62.9	64.1	*62.3 (3.3)*
	Separated Regions	39.8	52.5	47.4	46.6	46.3	48.2	*48.2 (2.5)*
	Ambiguous	82.0	76.9	76.8	70.6	71.5	69.6	*73.1 (3.5)*

Note: Parentheses indicate standard deviations.

Table 6. Statistics for Offset Simulations

Statistic	Trial Type	Behavioral Data	Simulations Run 1	Run 2	Run 3	Run 4	Run 5	*Average*
PSS	Figure-ground	-10.1	-12.4	-9.5	-10.0	-10.5	-10.3	*-10.6 (1.1)*
	Separated Regions	1.8	-5.0	-4.3	-2.2	-1.0	-1.2	*-2.7 (1.8)*
	Ambiguous	-1.3	-3.0	-1.1	2.1	-0.5	-3.0	*-1.1 (2.1)*
JND	Figure-ground	36.4	30.1	30.5	29.4	27.9	28.5	*29.3 (1.1)*
	Separated Regions	42.6	29.9	29.9	30.3	28.4	30.6	*29.8 (0.9)*
	Ambiguous	39.6	30.3	31.2	29.0	31.8	31.2	*30.7 (1.1)*

Note: Parentheses indicate standard deviations.

Table 7. Statistics for Onset Simulations with Denser SOA Sampling

			Simulations					
Statistic	Trial Type	Behavioral Data	Run 1	Run 2	Run 3	Run 4	Run 5	*Average*
PSS	Figure-ground	10.1	15.7	11.8	14.5	13.1	15.1	*14.1 (1.6)*
	Separated Regions	-0.5	-0.7	0.3	-1.6	-0.6	-0.1	*0.5 (0.7)*
	Ambiguous	-2.7	-2.1	-3.2	-2.9	0.9	-2.3	*1.9 (1.7)*
JND	Figure-ground	41.6	43.7	45.9	56.6	43.2	45.0	*44.7 (1.2)*
	Separated Regions	39.8	48.3	47.5	46.5	45.5	48.0	*47.2 (1.2)*
	Ambiguous	82.0	72.2	65.9	68.8	73.5	69.5	*70.0 (3.0)*

Note: Parentheses indicate standard deviations.

Table 8. Statistics for Offset Simulations with Denser SOA Sampling

			Simulations					
Statistic	Trial Type	Behavioral Data	Run 1	Run 2	Run 3	Run 4	Run 5	*Average*
PSS	Figure-ground	-10.1	-9.1	-10.7	-10.1	-9.3	-12.3	*-10.3 (1.3)*
	Separated Regions	1.8	0.0	1.5	1.0	1.2	1.6	*0.4 (1.2)*
	Ambiguous	-1.3	-1.0	-1.1	-1.1	1.4	-1.4	*0.7 (1.1)*
JND	Figure-ground	36.4	29.1	28.1	31.2	29.8	30.7	*29.8 (1.3)*
	Separated Regions	42.6	30.1	32.7	30.1	32.4	32.8	*31.7 (1.4)*
	Ambiguous	39.6	30.9	29.7	29.6	30.4	29.9	*30.1 (0.5)*

Note: Parentheses indicate standard deviations.

CHAPTER VI

GENERAL DISCUSSION

Summary

The goal of this dissertation was to examine the consequences of figure-ground assignment, particularly for temporal processing. As visual scenes are organized, visual features are frequently grouped together in order to alleviate the demands placed on the visual system. In addition these perceptual groups are also ordered such that more relevant regions (i.e., figures) are treated separately from other perceptual groups that are more likely to be irrelevant (i.e., grounds). This is a process known as figure-ground assignment (Palmer & Rock, 1994).

Many studies have examined figure-ground assignment and determined the cues, both bottom-up and top-down, that are used to complete figure-ground assignment (see Introduction for a review), but more recently studies have begun to examine the impact figure-ground assignment has on other behaviors or processes. In particular, several studies have focused on the accuracy and reaction time benefits afforded by designating a region as figure (e.g., Lazareva et al., 2006; Nelson & Palmer, 2007). However, the source of these benefits is not fully understood. Hence, current research is now examining the consequences of figure-ground assignment for other perceptual processes (e.g., Cosman et al., in review; Hecht & Vecera, in prep; Lester et al., 2009).

In Chapter II, I examined one potential source of reaction time benefits: shifts in perceptual processing. Temporal processing is influenced by the allocation of spatial attention (e.g., Schneider & Bavelier, 2003; Shore, Spence & Klein, 2001; Stelmach & Herdman, 1991; Titchener, 1908), such that objects appearing at an attended spatial location are frequently perceived as appearing earlier than those at unattended locations. Because researchers have noted a link between attention and figure-ground assignment (e.g., Vecera et al., 2004), I hypothesized that figural assignment might have a similar impact on temporal processing. Onsets were more readily discriminated on the figure than on the ground, suggesting a perceptual processing advantage such that figures undergo perceptual processing prior to grounds – a prior entry effect.

Due to the parallel between the impact of figure-ground assignment and spatial attention on temporal perception, I explored the duration of processing for figures relative to grounds in Chapter III. In this set of experiments, I predicted that the disappearance of information should be more readily detected on the *ground* region if figure-ground assignment demonstrates similar changes in temporal processing as attention. Spatial attention studies have shown that attending to a region in space can extend perceptual processing durations, making it more difficult to determine when a target is no longer present (e.g., Rolke et al., 2006; Yeshurun & Levy, 2003; Yeshurun 2004). In order to accurately perceive the offset of information, I found that the target must be removed earlier on the figure than on the ground, in accordance with my prediction. These results suggested that attended regions and figures both are afforded extended durations of processing resulting in a temporal extension effect.

In the fourth chapter, I tested a prediction made by the temporal extension effect: extended durations of processing impair temporal resolution. Thus, by having extended processing of figures, temporal resolution should be impaired on figures. In a single experiment, I investigated the ability to discriminate flickering from among static targets when they appear on the figure versus the ground. My results supported the temporal extension effect, finding that when a target flickers, discrimination judgments are more accurate on the ground region than the figure.

Despite presenting behavioral data demonstrating changes in temporal processing as a result of establishing figure-ground assignment (Ch 2-4), I had not explored a mechanistic account for these effects. The empirical work suggests that under some circumstances, figures receive temporal processing advantages (e.g., early and extended perceptual processing), but in other circumstances grounds receive advantages (e.g., higher temporal resolution). Thus, in Chapter V, I assessed the TOJ task commonly used in these studies and determined that it fit into a broad class of change detection tasks. Thus, in order to examine the mechanism behind the prior entry and temporal extension effects and to create a parsimonious explanation of the behavioral results, I examined a dynamic neural network model of change detection (e.g., Johnson et al., in press; Johnson et al., 2009). Using its three-field framework, I presented a TOJ DNF model of the temporal processing of figures and grounds that was later used to computationally model the behavioral data in Chapters II and III and provide some insight as to the dynamics of the system that can produce these effects. Impressively, the TOJ DNF model demonstrated the ability of the change detection model to extend to a range of change detection tasks (e.g., one-shot change detection and TOJs).

Consequences of Figure-ground Assignment or Spatial Attention?

The results described in Chapters II-IV demonstrate that the consequences of figure-ground assignment on temporal perception parallel those found in the spatial attention research (e.g., Hein et al., 2006; Rolke et al., 2006; Shore & Spence, 2005; Shore et al., 2001; Yeshurun, 2004; Yeshurun & Levy, 2003). This raises the concern of whether the prior-entry-like effect and the temporal extension effect for figures are a corollary of figure-ground processes or simply reflect a shift of spatial attention, in which attention is drawn to figural regions. I argue that the effects observed in Chapters II-IV are consequences of figure-ground assignment and not solely attributable to spatial attention. Instead, there is likely a tightly linked interaction between figure-ground assignment and attention (e.g., Qiu, Sugihara & von der Heydt, 2007; Vecera et al., 2004).

Still, many researchers have argued that attention and figure-ground assignment are completely independent processes (e.g., Baylis & Driver, 1995; Driver & Baylis, 1996; Julesz, 1984; Kimchi & Peterson, 2008; Vecera & Behrmann, 1997). In a recent study, Kimchi and Peterson (2008) attempted to dissociate the effects of attention from those of figure-ground assignment. Their participants completed an attentionally demanding task for a target appearing on a background consisting of multiple regions that can be grouped into figures and grounds in accordance with the convexity cues. Kimchi and Peterson found that participants' performance in the attention task was impaired when the background changed its figural assignment. When probed directly, participants provided inaccurate reports of the background's changes. They were unaware of the changes, though they were able to detect background changes in a second task where they explicitly attended the background. The authors concluded that figure-ground assignment and attention are dissociable processes; when attention was occupied and the figure-ground assignment was irrelevant to the task, participants' reports were still impacted by the figural assignment of the attention target's background. This result is in agreement with other reports that figure-ground assignment occurs preattentively (e.g., Driver, Baylis & Rafal, 1992), as evidenced by intact figure-ground assignment in the face of visual neglect.

Complementing the empirical studies, several neurophysiological studies have demonstrated that neuronal firing in response to the perception of figures is increased relative to firing in response to the perception of ground, even if these regions are outside the focus of attention. For example, Lamme (1995; see also Marcus & Van Essen, 2002) found a 40% increase in the neuronal firing for V1 neurons in macaque monkeys when a figure fell in the receptive field of these neurons compared to when a ground fell in the receptive field. In addition, Qiu et al. (2007) presented macaque monkeys with a figure (i.e., occluder) and ground (i.e., occluded) region. They showed that the firing rates of V2 neurons whose receptive fields were located on the border between the two regions were increased following the assignment of border ownership to the occluding figure (a process analogous to figure-ground assignment), regardless of whether attention was directed to that region or to the occluded ground region. This indicates that attention is not required for border-ownership modulation and seems to imply that figure-ground assignment, as well as subsequent enhancement effects, can occur pre-attentively in non-human primates.

Qiu et al.'s (2007) findings also demonstrate that when attention was directed to the occluding "figure" region there was further enhancement of neuronal responses in the V2 neurons of interest. The authors interpreted this result as providing evidence that the V2 neurons responsible for figure-ground segregation also provide an interface for top-down selection processes. These findings appear to support the assertion that figure-ground assignment produces enhancement effects that precede, but are additive with, attentional enhancement processes. An initial sensory enhancement of figures may serve to bias attention toward particular regions of a visual scene, and subsequently attention may enhance these representations further.

Consistent with this finding, Nelson and Palmer (2007) demonstrated both detection and discrimination benefits for targets appearing in figural regions over those appearing in ground regions, a result they interpreted as being due to attention-related enhancement processes. Specifically, they discussed their results as being due to a preferential allocation of attention to figures following figure-ground assignment, which led to attention-related processing benefits for targets falling within the figure. However, several results suggest that regions assigned figural status need not draw attention to receive processing benefits, suggesting the possibility that the results of Nelson and Palmer (2007) may be due to an interaction between enhancement due to figure-ground assignment and that due to attention (e.g., Cosman et al., in review; Lester et al., 2009; Hecht & Vecera, in prep).

Proposing a strong association between figure-ground assignment and attention does, however, seem contradictory to other behavioral research. Attention and figures typically enjoy sensory and performance benefits, but Weisstein and Wong (1983; see also Weisstein & Wong, 1987, for review) discovered a ground superiority: low spatial frequency targets were detected more readily on the ground rather than the figure. In their task, participants were explicitly holding one region of a face-vase stimulus as figure. It was the *unattended* (i.e., ground) region in which low spatial frequency targets were better detected. This result appears to contradict a close interaction between attention and figure-ground assignment. However, recent attention studies have shown a decrement in performance at the location of attention. Carrasco et al. (2003) have found that textured targets are discriminated faster when they appear in the periphery than when they are presented centrally. Thus, there may be processing *advantages* for items that appear *outside* of the scope of attention, converging with Wong and Weisstein's evidence of a ground superiority.

In regards to the experiments presented in Chapters II-IV, there is evidence to suggest that these results are not simply attention effects. Both Experiment 3 (Chapter II) and Experiment 7 (Chapter III) examined TOJs for separated figure-ground regions. When competition for the regions was removed (i.e., the regions no longer shared the contour), the temporal processing effects were no longer present. Although this is not direct evidence against a purely attentional account of the results, this result does demonstrate that figure-ground assignment is responsible for the effect either by being the sole contributor or by attracting attention to the location of the figure. In the latter case, the temporal processing effects may reflect the use of an attentional mechanism; however, figure-ground assignment would still be the cause of the pull of spatial attention.

Therefore, I suggest that the current studies have demonstrated that figure-ground assignment causes differences in temporal processing. Although the effects may be attributed to the use of an attentional mechanism, I have proposed a model of a mechanism that can be used by both figure-ground assignment and attention to produce these effects. It is difficult to disentangle the effects of attention and figure-ground processes. Some research has indicated that figure-ground assignment and attention can be dissociated (e.g., Kimchi & Peterson, 2008; Vecera & Behrmann, 1997), but further work will be required to fully understand the relationship between these visual processes.

Temporal and Spatial Consequences
of Figure-ground Assignment

Changes in temporal perception are not the only consequences of figure-ground assignment. Other research has demonstrated that figures are perceptually enhanced compared to grounds in tasks requiring fine discriminations (Cosman, Hecht & Vecera, in review). Interestingly, this figural benefit suggests increased spatial resolution for figures, contrary to the current evidence for decreased temporal resolution (see Chapter IV).

Weisstein, Maguire, and Brannan (1992) explored the findings of several experiments examining the role of spatial and temporal perception in the perceptual organization process (e.g., establishing figure-ground assignment). Previous research demonstrated that visual regions containing high spatial frequency or low temporal frequency information were frequently perceived as the figure, with the reverse pairing (i.e., low spatial or high temporal frequency) perceived as the ground (e.g., Klymenko & Weisstein, 1986; Klymenko & Weisstein, 1989a, 1989b; Klymenko, Weisstein, Topolski & Hsieh, 1989). Weisstein et al. (1992) proposed that spatial frequency channels and temporal frequency channels in visual processing interact to produce the tradeoffs between spatial and temporal processing and their subsequent impact on figure-ground assignment. They assumed that spatial frequency channels (a.k.a. sustained channels) are narrowly tuned to spatial frequency information and broadly tuned to temporal frequency, whereas temporal channels are narrowly tuned to temporal frequency information. Weisstein et al. further proposed that these spatial and temporal channels can be associated with the parvocellular (P) and magnocellular (M) pathways in visual processing.

By examining models of each frequency channel (spatial and temporal) independently, Weisstein et al. (1992) determined that neither could account for the high-spatial/low-temporal and low-spatial/high-temporal cues to figure-ground assignment. Each of these singular models failed and was not able to account for all of the existing behavioral data. Instead, the model that was able to account for the preexisting results considered both the spatial and temporal channels. Within this model, competition between the two channels gives rise to behavior. Therefore, they concluded that these spatial and temporal differences can be attributed to how figures and grounds are processed in the brain. Specifically, Weisstein et al. proposed that the interaction between spatial and temporal channels reflects interactive activation (and inhibition) between the P and M pathways, respectively. In other words, they concluded that regions processed by the P pathway are recognized as figures. Parvocellular neurons have high acuity and low temporal resolution, as opposed to M neurons, which have the opposite characteristics; thus, their processing results in the assignment of a ground region.

Attentional studies have also turned to the P and M pathways to explain effects on temporal processing. Yeshurun and Levy's (2003) neurophysiological hypothesis postulated that enhancing one domain (spatial or temporal resolution) should result in a decrease to the other domain, creating a tradeoff between the two. Accordingly, attention increases the activation of P neurons and inhibits M neurons resulting in higher spatial acuity but poorer temporal resolution at the location of attention.

Taken together, these theories and results suggest an interaction between spatial and temporal processes. However, it is not certain if spatial enhancement effects can be observed with temporal benefits (e.g., prior entry) or decrements (e.g., temporal extension). Future research should examine whether the consequences of figure-ground assignment on spatial and temporal processing can be observed simultaneously. Due to the difficulties that may arise when examining the interaction between the consequences behaviorally (e.g., when competing closely with one another, temporal frequency dominates over spatial frequency in determining figure-ground assignment; see Klymenko et al., 1989, for discussion), the TOJ DNF can provide an initial step in examining the interaction between the consequences for each of these domains. The model may indicate the effects on spatial processing via the tuning of the peaks (i.e., width of the peaks) with narrow tuning indicating increased resolution. Once spatial processing is understood with the model, the simultaneous consequences of figure-ground assignment for both spatial and temporal processing can be examined, potentially generating predictions for the conditions under which it may be observed empirically.

Conclusions

The experiments and simulations presented here provide strong evidence that figure-ground assignment influences temporal processing. Over the course of several experiments, I presented not only figural benefits (e.g., prior entry), but also *ground* benefits (e.g., temporal resolution). Additionally, the behavioral results were computationally modeled, offering another perspective to the nature of the effects. I proposed the framework of a dynamic system that can be used by both figure-ground assignment and attention to account for their impacts upon temporal processing. Several directions for future research exist, including studying the distinction between figure-ground assignment and attention, understanding the interaction between spatial and temporal processing, and examining the neurophysiological hypotheses that have been proposed to account for temporal processing effects.

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