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Attentional modulation of the gap effect

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Abstract

The gap effect refers to a reduction in the latency of saccades to peripherally appearing targets when the fixation point disappears a short time before target appearance. The effect has been attributed to a number of potential mechanisms that function to assist in the maintenance of fixation. One such mechanism, attention, has been the focus of some disagreement in the literature regarding the gap effect. In the present study, we had subjects attend to a portion of a complex fixation stimulus. On some trials the attended portion was removed prior to onset of a saccade target whereas on other trials an unattended portion was removed. Subjects were faster to initiate saccades when the attended portion was removed, thus establishing a role of attention in the gap effect. The results have important implications for our understanding of eye movements and the gap effect.

Keywords: Gap effect; Saccades; Attention; Disengagement

1. Introduction

Our ability to successfully acquire visual information from the environment critically depends on the planning and production of saccadic eye movements. This is because the fovea, which contains the high density of cone cells that code high spatial frequencies and color, only subtends about two degrees of the human visual field. Thus, we need to constantly reposition the fovea across the visual field, and the mechanism by which we do so is through fast, ballistic eye movements called saccades. It is estimated that approximately three saccades are produced every second that we are awake (Cassavaugh, Kramer, & Peterson, 2004), a figure that attests to the significant role played by saccades in our daily lives.

Given the importance of saccades in the acquisition of visual information across the visual field, it is not surprising that saccades have the shortest reaction times (RTs) and highest velocities of any overt movements. Nor is it surprising that a considerable amount of research has been conducted regarding the factors that influence saccadic RTs. Perhaps the most significant factor in reducing RTs, in terms of both the magnitude and robustness of the reduction, occurs in a phenomenon known as the "gap effect." In a typical gap effect study, participants are asked to fixate on a centrally located fixation point and then make a saccade, as quickly as possible, to a suddenly appearing peripheral target. When the fixation point remains present throughout the entire trial (termed an overlap trial because the fixation point overlaps in time with the target), mean RTs are often in the 200–250 ms range. However, when the fixation point is removed from view just before the appearance of the target (termed a gap trial because of the temporal gap between the offset of the fixation point and the onset of the target), much faster mean RTs are observed (typically between 150–180 ms, Saslow, 1967; Fischer & Ramsperger, 1984; Bekkering, Pratt, & Abrams, 1996). Thus, the gap effect refers to the RT advantage of removing the fixation point before the onset of a target.

Although the gap effect has been examined in many studies since the first report by Saslow in 1967, the exact

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nature of the mechanism underlying the reduction in saccadic RTs remains a point of contention. One possibility is that the gap effect is due to attentional disengagement that is facilitated by removal of the fixation point (e.g., Fischer & Breitmeyer, 1987; Fischer & Weber, 1993). This account stems in part from several findings that have shown that attention movements precede saccades (e.g., Shepherd, Findlay, & Hockey, 1986; Hoffman & Subramanium, 1995), and that to shift attention from a fixated object to a peripheral target, attention must first be disengaged from the fixation point, then shifted to the periphery, then re-engaged on the target. It is assumed that by turning off the fixation point prior to the onset of the target, attention is already in a disengaged state when the target appears, and thus RTs are reduced. According to this explanation, the gap effect is caused primarily by relatively high-level cortical mechanisms involved in the guidance of attention.

Some indirect evidence in support of this explanation comes from a study by Abrams and Dobkin (1994). They studied the magnitude of the gap effect on two types of trials: (1) trials on which latencies would be expected to be slowed by inhibition of return (an inhibitory attentional phenomenon; Posner & Cohen, 1984), and (2) trials on which saccades would be unaffected by inhibition of return. They found that the gap effect was smaller in the presence of inhibition of return (similar results have recently been reported by Guimaraes-Silva, Gawryszewski, Portugal, & Klausner-de-Oliveira, 2004). Given the presumed attentional locus of inhibition of return, the interaction suggests that the gap effect may also be influenced, at least in part, by attentional processes.

An alternative explanation for the gap effect has also been suggested. According to the alternative, the gap effect is due instead to lower-level, subcortical mechanisms—the offset of the fixation point produces disinhibition in the superior colliculus (SC; e.g., Reuter-Lorenz, Hughes, & Fendrich, 1991). This fixation offset account derives from neurophysiological evidence of the manner in which the SC is involved in generating saccades (e.g., Everling, Paré, Dorris, & Munoz, 1998; Munoz, Dorris, Paré, & Everling, 2000). In particular, the SC is known to contain "fixation cells" and "movement cells." During fixation on an object, the fixation cells are active and they inhibit the movement cells. However, when a fixated object disappears, activity in fixation cells decreases and the movement cells consequently become disinhibited—permitting saccades to be initiated more quickly. A number of studies in addition to those noted earlier have yielded results consistent with this explanation (e.g., Muonz & Wurtz, 1992).

Despite the strong evidence in favor of the fixation offset account of the gap effect, a few studies have attempted to directly compare the fixation offset and attentional explanations. For example, Kingstone and Klein (1993) found a large gap effect with the offset of a fixated object but a much smaller gap effect when an attended but not fixated object was offset, suggesting a limited role for attention in the gap effect. Importantly, the offset of a non-fixated *un*attended object produced an almost identical reduction in RT as the attended object offset, further supporting the fixation offset account (similar results were reported by Tam & Stelmach, 1993; Taylor, Kingstone, & Klein, 1998). The small benefit of the offset of the non-fixated object (either attended or unattended) was presumed to reflect merely a general warning-signal benefit that could be produced by a range of visual or auditory stimuli, and not a benefit specifically due to offsets of attended or fixated objects (see also Taylor et al., 1998).

Walker, Kentridge, and Findlay (1995) also conducted experiments that serve to directly contrast fixation offset and attentional accounts of the gap effect. In one of their experiments subjects made saccades either to an attended or an unattended stimulus under conditions with and without an advanced fixation offset. The fixation offset produced a gap effect but the size of the effect did not differ as a function of the attentional manipulation—further weakening any claims that attentional disengagement might be involved in the phenomenon.

If the mechanism underlying the gap effect solely involves disinhibition in the SC caused by the offset of a fixation point, the gap effect could be considered a sensory-driven process that should be virtually impervious to higher-order cortical processing. There is, however, evidence that suggests otherwise. Machado and Rafal (2000) used gap and overlap trials with both reflexive and volitional saccades in which the probability of target appearance was manipulated. In their first experiment, using peripheral targets to elicit reflexive saccades, the targets were very likely to occur (80% of trials) in one block while very unlikely to occur (20% of trials) on another block. The probability manipulation had a major impact on the gap effects, with a 49 ms gap effect in the low probability block and a 28 ms gap effect in the high probability block. In a second experiment, an auditory signal indicated the direction in which to make a volitional saccade on the non-peripheral target trials. This experiment showed larger gap effects for (a) reflexive saccades when the peripheral target was unlikely and (b) for volitional saccades when the peripheral target was likely (i.e., the auditory target was unlikely). In both experiments, the reduction in gap effects were due to greater reductions in the target-likely overlap trials than the target-likely gap trials. Machado and Rafal concluded that strategic processes, presumably involving cortical structures such as the frontal eye field (FEF), decreased fixation cell activity in the SC during high probability target blocks, thereby reducing the effect of the fixation offset and producing smaller gap effects.

The finding of a strategic manipulation of the gap effect indicates that the gap effect is not simply a sensory-driven process but can be affected by other processes that interact with the cortical components of the oculomotor system. It is now well known that the oculomotor system overlaps considerably with the visual attention system (e.g., Corbetta, 1998; Thompson, Biscot, & Sato, 2005), to the extent the some researchers have suggested that there is essentially no separation between oculomotor and attentional processes (e.g., Rizzolatti, Riggio, Dascola, & Umilta, 1987; but see Juan, Shorter-Jacobi, & Schall, 2004). Thus, despite the findings of Kingstone and Klein, re-visiting the possibility of an attentional manipulation of the gap effect, in the light of Machado and Rafal (2000), seems prudent. More specifically, we followed the lead of Machado and Rafal and examined an attentional manipulation that was instantiated via the centrally fixated object (i.e., the fixation point). To accomplish this, we used a novel paradigm in which subjects viewed two centrally presented intersecting line segments that differed in color. Each subject was assigned an attended color, with the critical comparison between trials in which only the attended line segments were offset and trials in which only the unattended line segments were offset. If attentional selection does play a role in the gap effect, removing the attended lines should yield a larger gap effect than removing the unattended lines. However, if attentional selection plays no role in the gap effect, no differences between the attended and unattended conditions should be found.

2. Methods

2.1. Subjects

Eighteen Washington University undergraduates ranging in age from 18 to 22 (Mean = 20.07) received course credit for their participation.

2.2. Procedure

Subjects viewed two intersecting line segments oriented in the shape of an "X" at the center of a display screen. The segments formed the diagonals of a 0.79° square area. A small area (0.13° × 0.13°) where the two segments intersected, at the exact center of the display, remained blank (so the intersection was not actually visible). One line segment was always magenta (the one sloping down from left to right) and the other was always green. Subjects were told to focus their attention to a specified one of the two line segments (designated as either the "purple" or the "green" segment) throughout the experimental session. They were reminded about the designated color at the beginning of each block. Because the segments were quite small subjects fixated both of them. Subjects were given two seconds within which to acquire a stable fixation at the center of the display—eye position was checked to confirm fixation. If fixation was not achieved then the eye movement monitor was recalibrated and the trial was repeated. Two hundred milliseconds after confirming fixation, the designated line segment disappeared for 100 ms, reappeared for 100 ms, disappeared again for 100 ms and finally reappeared. This served to summon attention to the designated line segment. Subjects fixated for an additional 1000 ms after which a 1000 Hz warning tone was presented for 100 ms. This fixed tone interval alerted subjects to the appearance of a target. Coincident with the offset of the warning signal, one of two types of trials was presented: a *saccade trial* or a *keypress trial*. These two types of trials were randomly mixed throughout the session. The saccade trials permitted us to measure the gap effect; the keypress trials were used to confirm that subjects complied with the attention instructions.

2.3. Saccade trials

The sequence of events for a saccade trial is illustrated in Fig. 1. There were five different eye movement conditions. On *full-gap* trials, both line segments were removed 200 ms before the onset of the peripheral target. On *zero-gap* trials, both lines were removed simultaneously with the onset of the target. On *overlap* trials, both line segments remained on the screen for the duration of the trial. There were also two *partial-gap* conditions where, either the attended (*partial-gap attended* condition) or unattended (*partial-gap unattended* condition) line segment was removed 200 ms before the appearance of the target. Targets were equally likely to appear 7° to the left or right of fixation and remained on the screen for 700 ms. On partial-offset trials, one of the two line segments remained on the screen for the duration of the trial. At the end of each trial, the peripheral target was extinguished and replaced by the central fixation stimulus. The intertrial interval was 500 ms.

2.4. Keypress trials

The stimulus events for the keypress trials are illustrated in Fig. 2. Keypress trials began in exactly the same manner as the saccade trials, but no eye movement target was presented. Instead, one of the line segments at fixation either grew or shrank in size 200 ms after the offset of the warning tone (the size change was 22% of the original length). Subjects were told to press the "/" key when a line segment grew in size and the "z" key when a line segment shrank in size. These trials served as a manipulation check to ensure that subjects were paying attention to the designated line segment and were performing the task accurately. Subjects were told that a greater proportion of keypress trials (80%) involved a change in the attended line segment and that they would benefit from focused attention. If this manipulation were effective, then subjects would be faster to detect a change in the attended line segment than in the unattended line segment.

2.5. Design

Each participant performed in a practice block of 10 trials that were not analyzed. There were six test blocks consisting of 80 trials each. Each block included 50 saccade trials (10 trials in each of the five possible gap conditions) and 30 keypress trials. Of the 30 keypress trials, 24 (80%) involved a change in the size of the attended stimulus and 6 (20%) involved a change in the unattended stimulus. Growing and shrinking were equally likely. The target on a saccade trial was equally likely to appear on the left or right. Half of the subjects were instructed to attend to the magenta line segment and the other half to the green line segment throughout the testing session. The 80 trials in each block were presented in random order.

3. Results

3.1. Keypress trials

Mean keypress latencies for the attended and unattended stimuli are illustrated in Fig. 3. There was a main effect of attention, $F(1,17) = 35.244$, $p < .001$. Subjects were faster to detect a change in the attended line segment (524.3 ms) than in the unattended line segment (592.1 ms) indicating that they were complying with the attention instructions. There were no other significant main effects or interactions. Errors were scored if subjects responded with the wrong key, or with a latency less than 100 ms or greater than 800. An analysis of the error trials did not reveal any significant main effects or interactions. The overall percent correct on experimental trials was 96.28%.

3.2. Saccade trials

Mean saccadic latencies for each gap condition are shown in Fig. 4. The latencies were analyzed with a 5 (gap) × 2 (location) repeated measures analysis of variance.

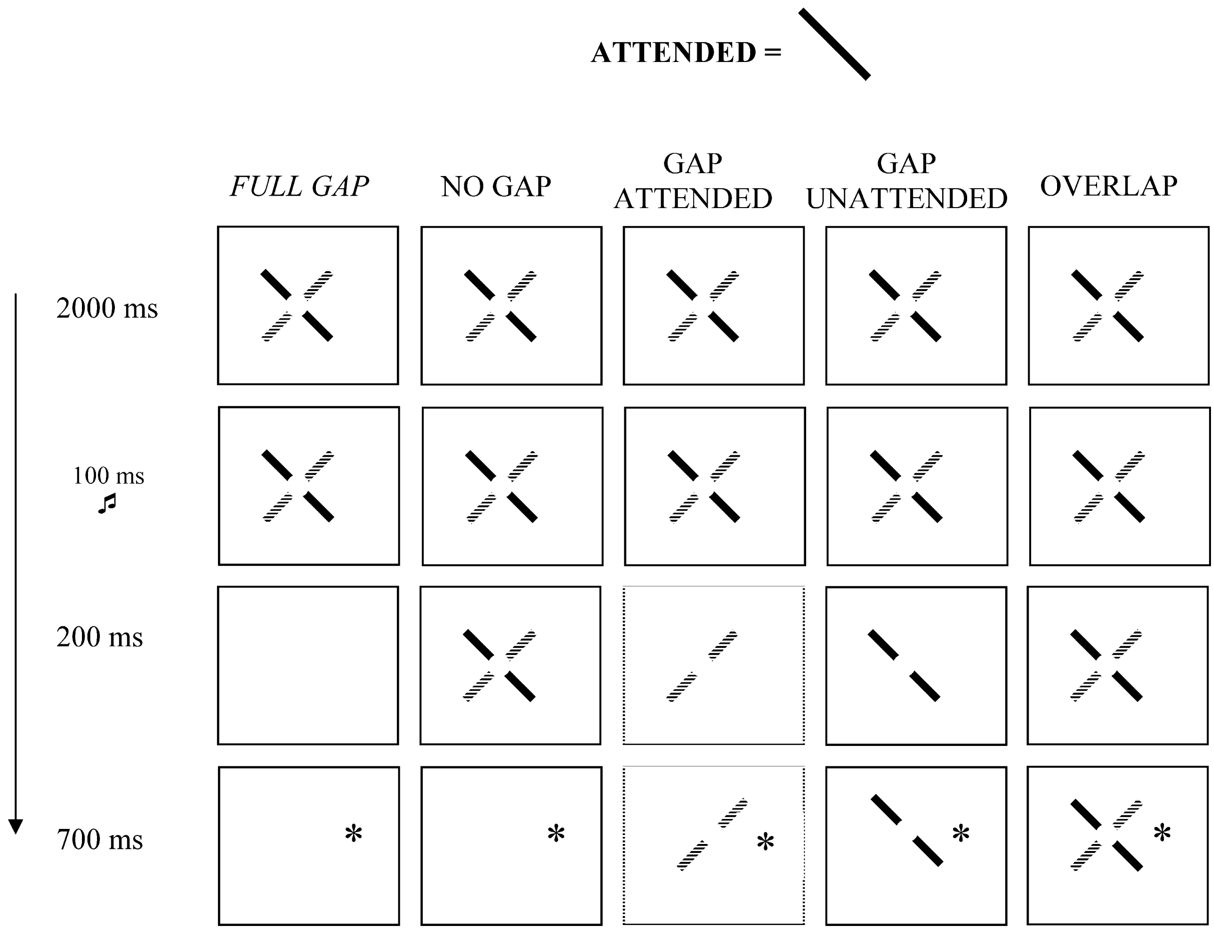

Fig. 1. Stimuli and sequence of events for saccade trials. Each frame shows a substantially enlarged view of the fixation cross in the experiment. The attended line segment is depicted in the figure as a solid bar—in the experiment it was one of two colors. The line segments fit within a 0.79° square area. Asterisks denote the saccade targets, which appeared 7° to the left or right of fixation.

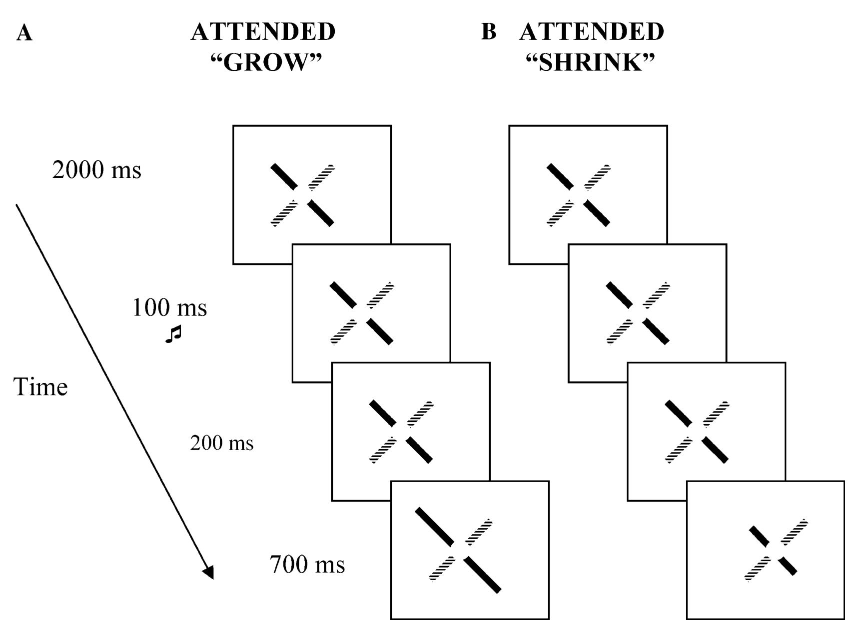

Fig. 2. Trial events and stimulus sequence for a keypress trial for the attended line segment. (A) The attended segment grew in size. (B) The attended segment shrank in size.

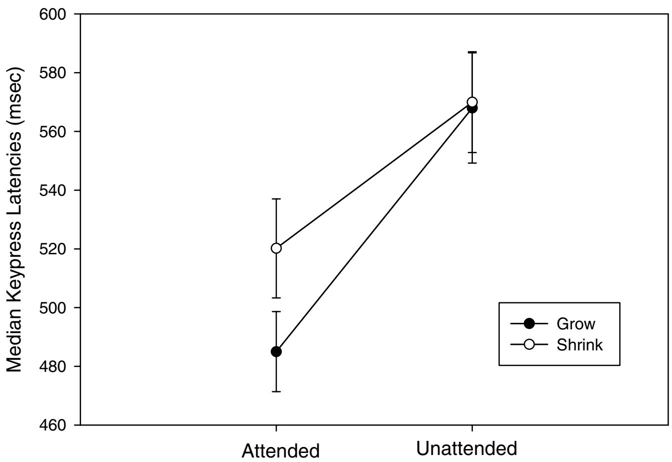

Fig. 3. Mean keypress latencies for the attended and unattended object as a function of the type of change.

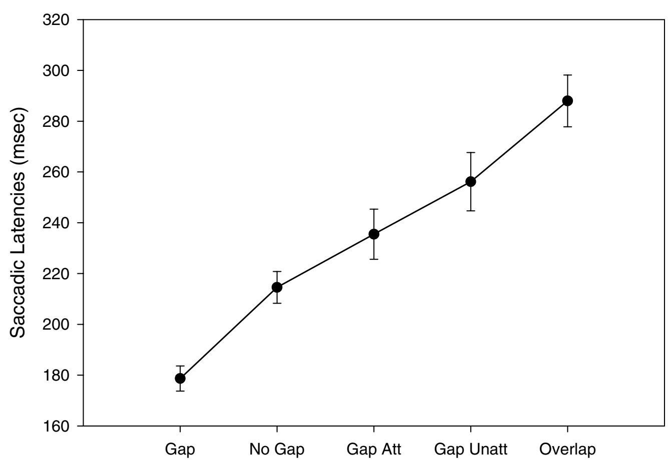

Fig. 4. Mean saccadic latencies for all five conditions of gap.

There was a main effect of gap condition, $F(4,64) = 80.37$, $p < .001$. Overall saccadic latencies were faster on full-offset gap trials (177.4 ms) than on zero-gap trials (214.5 ms), and faster on zero-gap trials relative to overlap trials (288.3 ms). Pairwise comparisons revealed both a reliable gap effect (37.1 ms), $t(17) = 8.505$, $p < .001$, and also a reliable FOE (73.8 ms), $t(17) = 11.942$, $p < .001$.

A separate 2 (gap) × 2 (location) repeated measures ANOVA was performed for the partial-offset conditions. Subjects were reliably faster when there was a 200 ms gap prior to the offset of the attended line segment (234.3 ms) compared to the unattended line segment (253.7 ms), $F(1,17) = 45.68$, $p < .001$. There was a marginal interaction between the gap condition and location, with the gap manipulation slightly stronger for saccades to the left ($F(1,17) = 4.56$, $p < .05$).

Trials were considered errors if the saccade latency was less than 100 ms or greater than 700 ms, or if the saccade went in the wrong direction. A separate analysis of the error trials revealed no main effects or interactions, $p > .05$. The overall percent correct for the experimental trials was 93.94%.

4. Discussion

The four gap effects found in the present study can be grouped into two sets of two; full-gap effects (full-gap and zero-gap) and partial-gap effects (attended-gap and unattended-gap). In comparing these sets, the full-gap effects were larger than the partial-gap effects. This finding, consistent with Pratt, Bekkering, and Leung (2000), adds support to the notion that fixated objects with larger areas produce larger gap effects, presumably because of greater activity in the fixation cells of the SC in the overlap condition (i.e., greater disinhibition in full-gap and no-gap trials). Within the full-gap-effect set, the finding of a smaller gap effect with zero-gap trials is also consistent with earlier findings (e.g, Wenban-Smith & Findlay, 1991; Tam & Ono, 1994). This is probably due to two reasons; the zero-gap condition provides less of a warning signal and also may not allow the movement cells in the SC to be fully disinhibited when the targets appear. Thus the findings from full-gap and zero-gap conditions fit in well with the existing literature.

As noted earlier, the critical comparison to assess the role of attentional selection in the gap effect is that between the two partial-offset conditions; attended-gap and unattended-gap. Importantly, a difference was found between the two conditions, with attended-gap trials yielding a larger gap effect than unattended-gap trials. Thus, not only is the gap effect sensitive to strategic manipulations (as shown by Machado & Rafal, 2000), it is also susceptible to attentional manipulations. It is important to note that the attentional manipulation was confirmed by the keypress conditions, with faster manual responses to probes on the attended line segments than the unattended segments.

Before continuing it is worth noting one caveat regarding our conclusions. We have shown that attentional selection *can* modulate the gap effect under at least some circumstances, but we have not shown that attention is usually involved in the gap effect. A demonstration of this latter point might be difficult. Nevertheless, it seems clear that the mechanisms that can produce a gap effect are modulated by mechanisms involved in the allocation of attention. This at least rules out a purely low-level account of the gap effect phenomenon.

On the surface, our results seem at odds with results reported by Kingstone and Klein (1993). Those researchers found no benefit for the offset of an attended object compared to an unattended one. However, a key difference exists between our methods and those of Kingstone and Klein (1993): In our study both attended and unattended objects were presented at fixation, whereas in the critical conditions of the Kingstone and Klein (1993) study the attended and unattended objects were presented away from fixation (with the same being true for Walker et al., 1995). This difference is consistent with the notion that important differences may exist between peripheral and foveal attentional mechanisms, such as former being used to resolve spatially overlapping stimuli (i.e., information with the region subtended by the fovea) and the later being used to orient attention to locations in the visual field (LaBerge, 1998). Additionally, our results suggest a role of "object based" attention (Duncan, 1984) in the gap effect. This is because we found that offsets at fixation that were equated in terms of their physical attributes had different effects on saccade latencies depending upon the object to which they belonged (either the attended or the unattended object).

Having found evidence of a role for attentional selection in the gap effect, the question remains; what is the nature of this role? One possibility is that it is attentional disengagement; that removing the attended line segment results in a greater disengagement of attention than removing the unattended line segment, and thus a larger gap effect in the attended-gap condition. Given the results of Kingstone and Klein (1993) as well as Walker et al. (1995), the strict interpretation of this notion seems unlikely, as the removal of any attended object, fixated or not, should produce a larger gap effect. Rather, we suggest that attentional selection modulates the activity of fixation cells in the SC, with attended fixated objects producing greater activity in those cells than unattended fixated objects. Thus, removal of attended lines results in greater disinhibition of the movement cells than does removal of unattended lines. This explanation accounts for why Kingstone and Klein did not find a difference between their non-fixated attended and unattended offset objects, and takes into account the close connection between oculomotor and attentional pathways, as well as the known neurophysiology of the gap effect. Moreover, this study and the earlier work by Machado and Rafal, provide a useful paradigm with which to examine the interaction of other higher-order processes with the oculomotor system.

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