

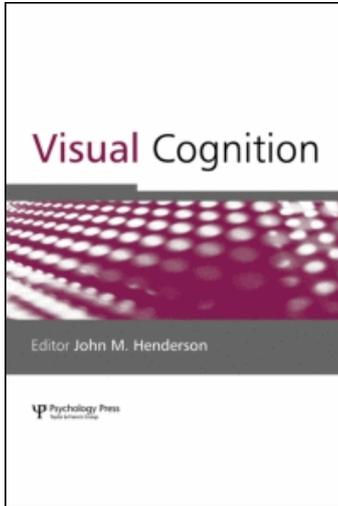
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Top-down control in time and space: Evidence from saccadic latencies and trajectories

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Visual distractors disrupt the production of saccadic eye movements temporally, by increasing saccade latency, and spatially, by biasing the trajectory of the movement. The present research investigated the extent to which top-down control can be exerted over these two forms of oculomotor capture. In two experiments, people were instructed to make target directed saccades in the presence of distractors, and temporal and spatial capture were assessed simultaneously by measuring saccade latency and saccade trajectory curvature, respectively. In Experiment 1, an attentional control set manipulation was employed, resulting in the elimination of temporal capture, but only an attenuation of spatial capture. In Experiment 2, foreknowledge of the target location caused an attenuation of temporal capture but an enhancement of spatial capture. These results suggest that, whereas temporal capture is contingent on top-down control, the spatial component of capture is stimulus-driven.

Keywords: Attention; Capture; Control; Saccade; Curvature.

One of the enduring issues in visual cognition is determining the interplay of bottom-up and top-down processes in the allocation of spatial attention. There are clearly instances when attention is reflexively captured by events in the peripheral visual field, in particular the appearance of new objects and changes in luminance (e.g., Jonides, 1981; Jonides & Yantis, 1988; Theeuwes, 1991a, 1992, 1994; Yantis & Johnston, 1990; Yantis & Jonides, 1984). There are, however, also circumstances in which events that can reflexively capture attention do not. When in a highly focused attentional state, onsets external to the focus of attention do not cause capture (Theeuwes, 1991b; Yantis & Jonides, 1990). In addition, research pioneered by Folk and Remington (e.g., Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994) has

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shown that people involuntarily adopt “attentional control sets” (ACSs) that prevent capture by stimuli unless the stimuli possess task relevant properties. Thus, both the focusing of attention and ACSs provide forms of top-down control that prevent covert attentional capture. In contrast, however, examinations of such control with overt shifts of attention, where the location of gaze is changed by a saccadic eye movement, have revealed that control over the oculomotor system may be less effective (Irwin, Colcombe, Kramer, & Hahn, 2000; Ludwig & Gilchrist, 2002b, 2003a, 2003b; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Wu & Remington, 2003). In particular, visual stimuli may alter programming within the oculomotor system in a purely bottom-up manner that cannot be mediated through top-down control (i.e., generate oculomotor capture). The goal of the present study was to further understand the effectiveness of top-down control in preventing oculomotor capture, in particular by examining both the temporal and spatial consequences of capture on the saccadic eye movement system.

We begin with the form of control offered by ACSs. As described by the contingent involuntary orienting hypothesis (Folk et al., 1992), top-down control can be exerted to prevent irrelevant visual stimuli from capturing covert attention. Namely, when an observer searches for a visual target that is defined by visual features, such as a red object, the observer will adopt an ACS that contains the colour red, and other-coloured stimuli will be prevented from capturing attention. Experiment 1 was designed to assess the effects of ACSs on oculomotor capture.

In order to investigate the effectiveness of ACSs, whether for covert attentional capture (hence forth referred to as simply attentional capture) or oculomotor capture, there are two often overlooked methodological criteria that must be met. The first criterion involves the manipulation used to establish participants’ attentional sets. Typical attentional set paradigms require participants to locate and discriminate a target stimulus; thus, the set is induced by manipulating the properties that define the appearance of the target. For example, Bacon and Egeth (1994) demonstrated that if a target is identified as being a feature singleton (e.g., a colour singleton or an onset singleton) then participants will adopt a singleton search mode, and any singleton will capture attention. If, however, the target can only be identified by a specific feature (e.g., the colour red) then participants will adopt a feature search mode, and only stimuli possessing that feature will capture attention. The second criterion that must be met involves controlling the number of objects that are presented to subjects on each display. The effectiveness of attentional sets is typically assessed by observing whether or not task irrelevant distractors affect reaction time (RT). As demonstrated by Folk and Remington (1998), however, if the presentation of an irrelevant distractor increases the number of visible objects, despite not affecting

spatial attention, the distractor may slow RT due to the filtering cost of the additional object (Hillstrom & Yantis, 1994; Treisman, Kahneman, & Burkell, 1983; Yantis & Hillstrom, 1994). Therefore, in assessing the effectiveness of ACSs, it is important to test the sets against the specific search mode that participants have adopted and to carefully control the number of presented objects. When these two criteria are taken into account, it has been repeatedly demonstrated that the capture of attention, as measured by manual RT, is contingent on ACSs (e.g., Folk, Leber, & Egeth, 2002; Folk & Remington, 1998, 1999; Gibson & Kelsey, 1998; for a review, see Burnham, 2007).¹

More recently, these manual RT studies have been modified to assess the extent to which attentional sets provide control over oculomotor capture. By increasing the difficulty of the target discrimination, these studies required participants to move their eyes to the target before the discrimination could be made. Under such conditions, rather than look directly towards the target, participants frequently looked first towards salient distractors, such as onset singletons and luminance singletons (Irwin et al., 2000; Theeuwes et al., 1998, 1999). It has since been argued that this capture may have resulted from participants adopting a singleton search mode rather than the expected feature search mode (Ludwig & Gilchrist, 2002b, 2003a; Wu & Remington, 2003). When participants were induced to adopt a feature search mode, both Ludwig and Gilchrist, and Wu and Remington, observed a partial reduction in the proportion of initial saccades that were directed towards distractors not matching participants' attentional sets. By measuring the spatial accuracy of saccades, these results showed that irrelevant distractors cause a form of oculomotor capture where the eyes are drawn to the location of distractors. Further, in contrast to the temporal disruptions observed in manual RT tasks, this spatial capture may only be attenuated by ACSs, and not eliminated.

The change in the effectiveness of the control of attention between manual RT tasks and oculomotor accuracy tasks is interesting because the tasks differ along two dimensions, making it unclear to which the change should be attributed. The change may indicate that the oculomotor system is less sensitive to control than the manual motor system. Alternatively, it may indicate that the spatial accuracy of responses is less sensitive to control than the timing of responses. Without measuring the spatial accuracy and temporal profile of saccades simultaneously, a full characterization of the sensitivity of oculomotor capture to top-down control cannot be made.

¹ It is unclear, however, whether this contingency reflects an attentional filter (Chen & Mordkoff, 2007; Folk & Remington, 2006; Remington, Folk, & McLean, 2001) or rapid disengagement (Arnott & Pratt, 2002; Theeuwes, Atchley, & Kramer, 2000).

Although saccadic reaction times (SRTs) were recorded in the previous oculomotor capture tasks, it is difficult to evaluate these SRTs with regard to ACSs. In particular, because these tasks measured the spatial accuracy of the direction of saccades, this measure could only be compared between conditions if participants did not perform at ceiling levels of accuracy. Therefore, tasks were employed that caused participants to make a large proportion of erroneously directed saccades. As a result, participants may have altered the temporal profile of their responses to focus on accurate performance rather than speed (e.g., Prinzmetal, McCool, & Park, 2005), and, as the number of errors varied between conditions, SRTs may have been differentially affected by speed-accuracy tradeoffs across conditions. As well, the distribution of SRTs across conditions may have been further biased by the production of distractor directed saccades, as saccades that are initiated quickly are more likely to be directed towards the distractor than saccades with longer SRTs (Godijn & Theeuwes, 2002; Van Zoest, Donk, & Theeuwes, 2004). For these reasons it is difficult to evaluate any limitations of ACSs using these recorded SRTs, and, therefore, further investigation is required to fully reveal the effectiveness of top-down control on oculomotor capture.

In order to simultaneously evaluate top-down control over the temporal and spatial oculomotor disruptions caused by distractors, a measure of spatial accuracy is needed that does not depend on the production of erroneous saccades. Such a measure is offered by saccadic trajectory curvature. Even when a saccade correctly lands on a target, the presence of a salient distractor causes a predictable spatial bias in the trajectory of the saccade. Namely, depending on the conditions surrounding the production of the saccade, its trajectory will either curve towards (e.g., McSorley, Haggard, & Walker, 2006; Van der Stigchel & Theeuwes, 2005; Walker, McSorley, & Haggard, 2006) or away (e.g., Doyle & Walker, 2001; Sheliga, Riggio, Craighero, & Rizzolatti, 1995; Sheliga, Riggio, & Rizzolatti, 1994; Van der Stigchel & Theeuwes, 2006) from the distractor. While a precise account of saccadic curvature is still being developed, a useful framework for interpreting this behaviour has been proposed. When a saccade is initiated shortly after the onset of a distractor, in particular when the distractor is presented in close spatial proximity to the target, a motor programme is reflexively generated to move the eyes to the location of the distractor, which is averaged together with the target-directed programme resulting in an initial deviation towards the distractor. If, however, the saccade is initiated well after the onset of the distractor, then there is sufficient time to inhibit the distractor-directed programme, resulting in an initial deviation away from the distractor location (for a review, see Van der Stigchel, Meeter, & Theeuwes, 2007). Indeed, this time course of saccadic trajectory curvature has been demonstrated (McSorley et al., 2006). Trajectory curvature

provides a measure of the spatial disruption in saccades caused by salient distractors. As this measure does not rely on the production of erroneously directed saccades, we used this measure in the present study, along with the measure of SRT, to evaluate the effectiveness of top-down control over the temporal and spatial aspects of oculomotor capture simultaneously.

It is worth noting that the interpretation of saccadic trajectory curvature as resulting from stimulus-driven oculomotor capture may, at first glance, seem discordant with past observations of these deviations. Although recent studies have demonstrated that there is a strong stimulus-driven component to trajectory deviations (Van der Stigchel & Theeuwes, 2006), curvature can also be generated as a by-product of top-down cognitive processes. For example, saccadic trajectories curve away from locations that are attended volitionally (Sheliga et al., 1994, 1995) and from spatial regions that are encoded in working memory (Theeuwes, Olivers, & Chizk, 2005). Further, although curvature towards a visual stimulus can intuitively be seen as resulting from the capture of the eyes by the stimulus, it is less clear that curvature away from a stimulus also results from this capture. Indeed, trajectory deviations away from a stimulus are often attributed to a top-down inhibitory process (Godijn & Theeuwes, 2002; McSorley et al., 2006; Sheliga et al., 1994; Tipper, Howard, & Jackson, 1997; Van der Stigchel, Meeter, & Theeuwes, 2006, 2007), although at least some component of this inhibition must be reactive to stimulus signals (Van der Stigchel & Theeuwes, 2006; this issue is addressed further in the General Discussion section). Nevertheless, if a visual stimulus that is task irrelevant alters when, or to where, a saccade is made, we interpret this effect as temporal or spatial oculomotor capture, respectively. That is to say, such a stimulus has caused oculomotor capture because top-down control could not prevent it from altering programming within the oculomotor system. Therefore, under this definition of oculomotor capture, if an irrelevant visual stimulus causes a bias in saccadic trajectories, whether the curvature is towards or away from the stimulus, we interpret this effect as a demonstration of spatial oculomotor capture.

One prior study has evaluated the extent to which ACSs provide control over saccadic trajectory curvature. In this study, Ludwig and Gilchrist (2003b) had subjects make a saccade to whichever of two targets, appearing above and below fixation, matched a prespecified colour, thus inducing participants to enter the feature search mode and establish an ACS for the target colour. On some trials, prior to the onset of the target, a distractor appeared to the left or right of fixation. As with previous oculomotor capture studies, by measuring curvature Ludwig and Gilchrist observed a large amount of spatial capture that was partially attenuated by the ACS manipulation. Although the authors recorded both trajectory curvature and SRTs, their study was not designed to examine reaction time. In particular,

the presentation of distractors in their study resulted in the appearance of new objects, which may have affected SRT due to filtering costs (Folk & Remington, 1998). As well, distractors were presented prior to the target and, therefore, could be used as a warning signal that the targets were about to appear, in turn speeding SRTs on trials with distractors relative to trials with no distractors (Taylor, Kingstone, & Klein, 1998). Indeed, under some conditions, Ludwig and Gilchrist recorded faster SRTs on distractor than no-distractor trials. For these reasons, the effect of ACSs on temporal oculomotor capture could not be evaluated.

In the present research we employed a paradigm similar to that of Ludwig and Gilchrist (2003a), but modified to specifically evaluate the effectiveness of top-down control over the spatial and temporal aspects of oculomotor capture. In Experiment 1, control was tested using an ACS manipulation. In order to properly evaluate the effect of ACSs on SRT, the paradigm was modified such that distractors appeared on placeholders and were presented concurrently with an auditory warning tone that occurred on both distractor and no-distractor trials. Thus, the presentation of a distractor did not increase the number of visible objects, nor did it provide any additional warning of upcoming targets. In Experiment 2, control was tested by providing participants with advance knowledge of the target location. Together, these two experiments can reveal any limits on ACSs and the focusing of attention in providing top-down control over temporal and spatial oculomotor capture.

EXPERIMENT 1

Method

Subjects. Subjects were 11 undergraduate students enrolled in an introductory psychology course at the University of Toronto and one author (NA). One participant was excluded from the analyses due to a high percentage of error trials (18%). As compensation for their participation, the undergraduates received extra credit towards their final course grade. All subjects reported having normal, or corrected to normal, vision.

Apparatus. Eye movements were recorded by monitoring retinal position and corneal reflectance using a camera-based eye tracker (SR Research Eyelink II) with a temporal resolution of 250 Hz and a spatial resolution of 0.2° of visual angle. Gaze position was established using a nine-point calibration and validation. Eye-position data were recorded from whichever eye was tracked most accurately, as determined by the validation procedure. The beginning and end of saccadic eye movements were determined using a

30°/s threshold with the additional criteria that the eye exceeded an acceleration of 8000°/s/s during the movement. Experimental displays were presented on a 48 cm flat CRT at a refresh rate of 100 Hz and a resolution of 1024 × 768 pixels. A chinrest was used to fix participants' heads 60 cm from the monitor.

Procedure. Each participant was randomly assigned to search for either a red target or a green target throughout the experimental session, which consisted of eyetracker setup, followed by one block of 10 practice trials and seven blocks of 50 experimental trials. During eyetracker setup, a calibration was performed and validated repeatedly until a minimum average accuracy of 0.5° was attained. Between blocks the experimenter could elect to perform a recalibration; otherwise subjects rested until they were ready to continue. Each trial began with the presentation of a central fixation stimulus (a grey disc subtending 0.3° of visual angle) on a black background. The trial commenced once subjects moved their gaze to within 1.5° of the disc, at which point four placeholders (grey rectangles 0.6° in width and height) appeared 6° to the left of, right of, above, and below the fixation stimulus (see Figure 1). Subjects were required to hold their fixation on the grey disc for 442 ms. If they were unable to do so, a 200 Hz error tone sounded, a blank screen was presented for 400 ms, and then the trial was restarted. If subjects failed to maintain fixation more than three times on any given trial a drift correction or, if deemed necessary by the experimenter, a recalibration was performed. Once fixation had been maintained successfully, a 1000 Hz warning tone was sounded for 100 ms to alert the subjects that the targets were about to appear. On some trials, a single distractor was presented concurrently with the onset of the tone. The distractor was randomly determined to appear in the placeholder to the left or right of fixation and to be red, green, or not present. Seventy-two milliseconds after the onset of the warning tone, the fixation point offset and two potential targets were displayed in the placeholders located above and below fixation. One target was randomly determined to be displayed as red and the other as green, and subjects were required to initiate a saccade that would land within 3° of the target that matched the colour they had been assigned to search for. If an error was made, a 200 Hz error tone was sounded. Between trials, a blank screen was presented for 750 ms.

The simultaneous presentation of two potential targets, from which the true target could only be discriminated by colour, created the attentional set manipulation. Namely, as each participant's assigned colour provided the only target defining feature, contingent attentional capture should have been established for that colour. The effect of this attentional set manipulation on eye movements was evaluated by comparing saccades for the three different distractor types: None (no distractor presented), nonmatching (distractor

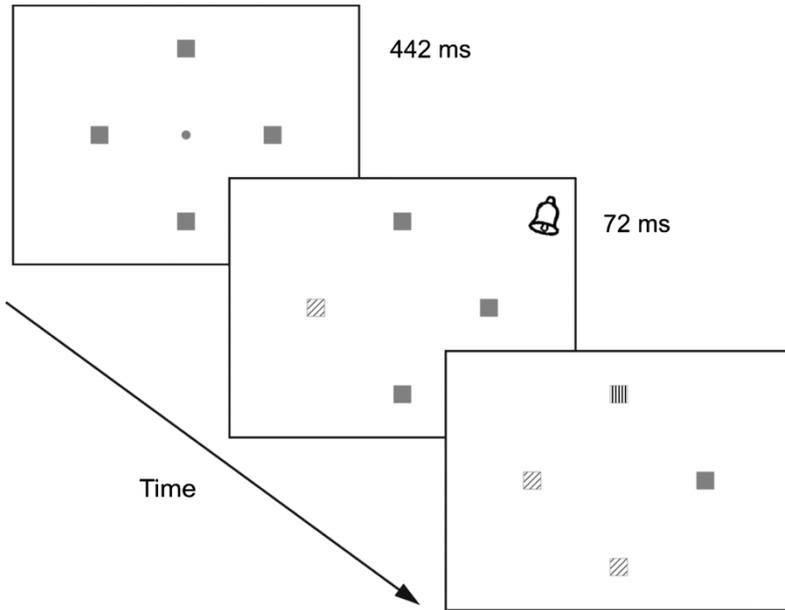


Figure 1. Sequence of events in Experiment 1 for a nonmatching distractor trial with a green (vertical stripes) target. Participants' maintained fixation on the central grey disc until the targets appeared above and below fixation. An alerting tone was sounded prior to the onset of the targets. On this distractor trial, a red (diagonal stripes) distractor is presented to the left of fixation concurrently with the alerting tone. The correct response is to reorient the eyes to the upper target. Stimuli were presented on a black background during the experiment.

different colour from target), and matching (distractor same colour as target).

Measures. Two measures were used to evaluate the effect of attentional sets on saccadic eye movements. First, SRT, the latency between target onset and the initiation of a saccade, was used to measure the temporal effects of distractors. Second, saccadic trajectories were recorded and the magnitude of trajectory curvature was used to measure the spatial effect of a distractor. Curvature was computed using the quadratic method proposed by Ludwig and Gilchrist (2002a). Saccades were rescaled (such that each travelled a common distance) and then mapped onto the best-fitting quadratic polynomial. The quadratic parameter of this polynomial provides an estimate of the maximum deviation of a trajectory away from a straight line in degrees of visual angle. For trials during which a distractor was present, this measurement was then given a sign depending on whether the trajectory curved towards (+) or away (−) from the distractor. Because

saccades do not normally follow a perfectly straight trajectory, rather than compare curvature on distractor trials against zero curvature, a sign was randomly allotted on a trial-by-trial basis to no-distractor trials, and the average curvature on these trials was used as a conservative baseline. The resulting mean curvature should remain zero degrees, but the variance in this condition should now reflect the normal variance seen in the trajectories of eye movements. This assignment was performed before the experimental session began, and reversing the polarity of the assignment had no effect on the pattern of significant results reported below. Together, these two measures allow the spatial and temporal effects of any distractor to be measured simultaneously.

One difficulty in evaluating control over the spatial effects of distractors using trajectory curvature comes from the time course of curvature. It has been shown that as the time between distractor onset and saccade onset decreases, the magnitude of curvature away from the distractor decreases (McSorley et al., 2006). As such, any observed decreases in trajectory curvature may not reflect top-down spatial control, but, instead, may indirectly result from the speeding of SRT due to the elimination of the distractor effect on SRT. That is, if top-down temporal control can prevent distractors from slowing the initiation of a saccade, this decrease in SRT alone could be sufficient to alter the magnitude of curvature. As SRT was measured simultaneously with trajectory curvature, however, it is possible to evaluate whether changes in curvature result from changes in SRT by equating SRT between conditions. For situations where the ACS manipulation caused a decrease in both SRT and curvature, additional comparisons of curvature were made after equating SRT between conditions.

Results

In order to allow subjects to become fully accustomed to the task, and to allow them sufficient time to establish an effective attentional set, the first block of trials was excluded from analysis. The likelihood of erroneous saccades directed to the nontarget colour decreased from 5.6% in the first block to 2.9% in the remaining blocks suggesting that, indeed, subjects were still developing their attentional set during the first block of trials. In addition to the first block of trials, error trials (7.4%) and trials for which SRT was less than 100 ms or greater than 450 ms (0.6%) were excluded from the analyses described next.

A one-way within-subjects analysis of variance (ANOVA) was performed on the SRTs from the three distractor types to evaluate the temporal effects of distractors, revealing a significant difference between distractor types, $F(2, 18) = 9.65$, $MSE = 78.19$, $p = .001$. To characterize this difference, a Fisher's

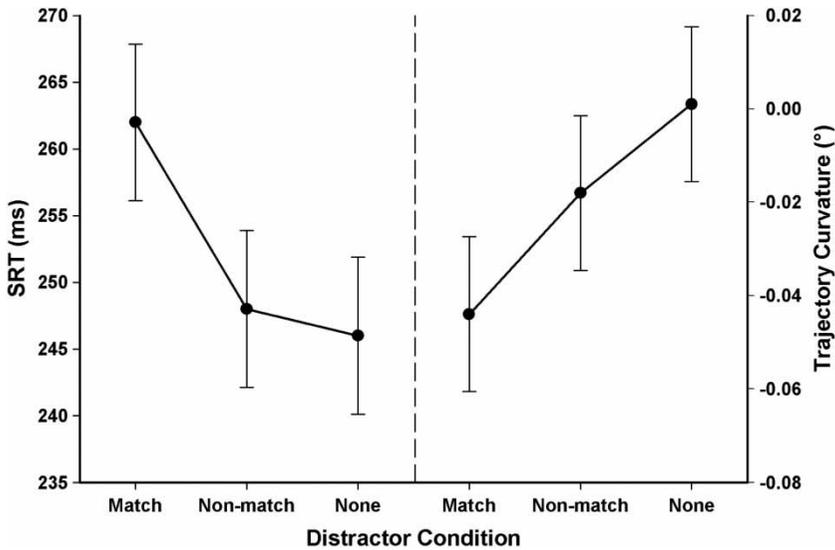


Figure 2. Mean saccadic reaction time (SRT) and trajectory curvature for each distractor type in Experiment 1 ($n=11$). Negative curvatures mean that the trajectory deflected away from the distractor. Participants' attentional control sets prevented nonmatching distractors from slowing reaction time, but not generating trajectory curvature. These results suggest that ACSs can eliminate temporal oculomotor capture, but only attenuate spatial oculomotor capture. Error bars are 95% confidence intervals calculated from Loftus and Masson (1994).

protected least-significant-difference (LSD) analysis was performed on the three groups. As can be seen in the left half of Figure 2, the presence of matching distractors significantly slowed SRTs relative to both nonmatching distractor trials, $t(10) = 2.71$, $p = .022$, and no-distractor trials, $t(10) = 3.53$, $p = .005$, whereas there was no difference in SRT between nonmatching distractor trials and no-distractor trials, $t(10) = 1.01$, $p = .295$. This is the typical attentional set effect found with reaction time measures of manual responses.

To examine the spatial effects of the distractors, a similar one-way within-subjects ANOVA was performed on the trajectory curvature measure, again revealing a significant difference between distractor types, $F(2, 20) = 8.95$, $MSE = 0.001$, $p = .002$.² To characterize this difference, a Fisher's protected LSD analysis was performed on the three groups. As can be seen in the right half of Figure 2, relative to the no-distractor baseline, both matching,

² As required by this measure of trajectory deviation, the mean of the average predicted start and end y-coordinates (see Ludwig & Gilchrist, 2002a) did not differ significantly from zero for either Experiment 1, $t(10) = 0.28$, $p = .789$, or Experiment 2, $t(9) = 1.57$, $p = .150$.

$t(10) = 3.13$, $p = .011$, and nonmatching distractors, $t(10) = 2.38$, $p = .038$, caused significant deflections in saccadic trajectories away from the distractors. This effect, however, was somewhat attenuated for nonmatching distractors relative to matching distractors, $t(10) = 3.08$, $p = .012$.

The decrease in the magnitude of trajectory curvature from matching to nonmatching distractors would seem to indicate that some control can be exerted over the spatial effects of distractors. This difference, however, might also be explained by the change in SRT between these two conditions. To evaluate if the attenuation of curvature resulted from the change in SRT, SRTs were equated between conditions by removing the fastest 9% of trials from the nonmatching condition and the slowest 9% of trials from the matching condition for each participant. With these trials removed, there was no difference in SRT between matching and nonmatching distractor trials ($M = 0.07$, $SD = 15.38$), $t(10) = 0.02$, $p = .986$; however, there was still a significant difference in curvature ($M = 0.03$, $SD = 0.03$), $t(10) = 3.07$, $p = .012$. The persistence of this difference suggests that the attenuation in curvature cannot be attributed to the change in SRT; rather, this difference suggests that ACSs provide some control over saccadic curvature.

Discussion

The SRT results from Experiment 1 demonstrate that the temporal effect of distractors is eliminated when the distractors do not possess task relevant properties. That is, whereas the salient matching distractors slowed SRT by nearly 20 ms relative to no-distractor trials, this effect was less than 2 ms for irrelevant nonmatching distractors. As such, the SRT results from Experiment 1 suggest that ACSs provide essentially complete control over the temporal effects of distractors on saccades.

In contrast to the SRT results, the curvature results demonstrate the limitations of ACSs. Although the magnitude of curvature away from distractors was reduced, nonmatching distractors still produced significant saccadic trajectory curvature relative to matching distractors; this finding is in line with the results of Ludwig and Gilchrist (2003b). The value of the present experiment comes from the simultaneous evaluation of ACSs on SRT and curvature. As the ACS manipulation eliminated SRT effects, it can be concluded that the persistence of curvature for nonmatching distractors did not result from the failure of the manipulation. As such, the present results demonstrate that temporal oculomotor capture can be completely controlled by ACSs; however, even under conditions where this control is exerted, spatial oculomotor capture will persist.

EXPERIMENT 2

The majority of past research on the top-down control of oculomotor capture has investigated the control offered by ACSs (although see Theeuwes et al., 1998). In contrast, Experiment 2 tested the control offered by advance knowledge of the target location. Informing participants on some trials of the location of the upcoming target should reduce the effects of distractors by allowing participants to both focus attention on the target location (Theeuwes, 1991b; Yantis & Jonides, 1990) and begin to prepare a motor programme to the target (e.g., Dorris & Munoz, 1998, Glimcher & Sparks, 1992). Counter to the effect of this manipulation on attentional capture, measured through manual RT, it is unlikely that this manipulation will completely eliminate the effect of distractors on the oculomotor system. Indeed, investigations of the remote distractor effect (Walker, Deubel, Schneider, & Findlay, 1997) have demonstrated that, even when the target location is known with 100% certainty, the appearance of distractors located distantly from the target will cause a temporal disruption, and the appearance of distractors located in proximity to the target will cause a spatial disruption. Nevertheless, this form of control was evaluated in Experiment 2 in order to determine whether, as with ACSs, the effectiveness of advance target-location knowledge differs for the temporal and spatial aspects of saccade production.

Method

Subjects. Subjects were 10 undergraduate students enrolled in an introductory psychology course at the University of Toronto. One participant was excluded from the analyses due to a high percentage of error trials (30%). As compensation for their participation, participants received extra credit towards their final course grade. All subjects reported having normal, or corrected to normal, vision.

Apparatus and procedure. The apparatus was identical to that used in Experiment 1. The display layouts and stimuli were very similar to those used in Experiment 1, with the exceptions that there were no placeholders and all stimuli were presented in white (see Figure 3). As well, the procedures involved with eyetracking (i.e., eyetracker setup, calibration, validation, and drift correction) as well as the criteria for maintaining fixation and making a saccade to a target, did not change from Experiment 1.

The experimental session began with instructing participants that they would be required to make a saccade to a target, which could appear above or below fixation, as soon as they heard an auditory go signal. Each participant performed one half of the experiment with advance knowledge of

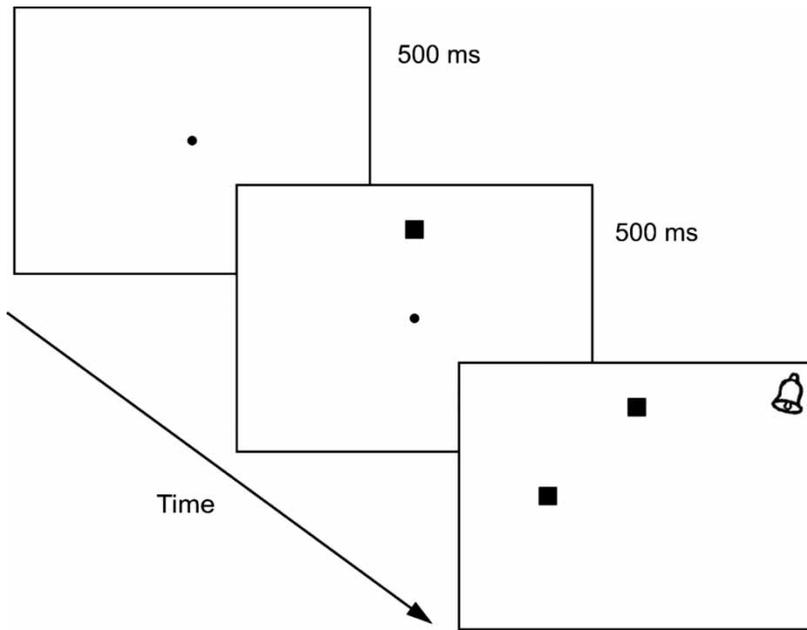


Figure 3. Sequence of events in Experiment 2 for a preview distractor trial. Participants' maintained fixation on the central white disc until an auditory go signal sounded. On preview trials, the target was visually previewed for 500 ms before the onset of the go signal. On no-preview trials, the visual target appeared simultaneously with the onset of the go signal. A distractor was presented on 50% of trials to the left or right of fixation. The correct response is to orient the eyes upwards. All stimuli were presented in white on a black background.

the target location (preview condition) and the other half with no advance knowledge (no-preview condition); the order of the halves was counter-balanced between subjects. Each half consisted of 8 practice trials followed by three blocks of 40 experimental trials. Every trial commenced with the presentation of the fixation stimulus, and participants were required to maintain fixation for 500 ms. On preview trials, the target then appeared as a white square subtending 0.6° in width, indicating the location for the required upcoming saccade. Participants were required to withhold making a saccade to the target for 500 ms, at which point a 1000 Hz auditory go signal sounded for 100 ms. On 50% of trials a distractor was presented simultaneously with the onset of the go signal, randomly to the left or right of fixation; the distractor was identical to the target stimulus (i.e., a white square). No-preview trials were identical to preview trials with the exception that the visual target stimulus appeared at the same time as the auditory go signal and distractor (if there was one), rather than being previewed for 500 ms. Participants were required to make a saccade to the target within

1000 ms of the onset of the go signal, after which the trial ended. If participants moved their eyes from the fixation stimulus prior to the onset of the go signal, or made a saccade to any location other than the target following the onset of the go signal, a 200 Hz error tone sounded for 100 ms and the trial ended. Trials were separated by a blank screen for 600 ms. Thus, this procedure resulted in a 2 (preview status) \times 2 (distractor status) within-subject experimental design. As with Experiment 1, the effect of previewing target location was evaluated through the SRT and trajectory curvature measures.

Results

As with Experiment 1, error trials (9.6%) and trials for which SRT was less than 100 ms or greater than 450 ms (3.4%) were excluded from the analyses. Separate 2 (preview status) \times 2 (distractor status) within-subject ANOVAs were used to evaluate the effectiveness of top-down control on SRT and curvature. As can be seen in Figure 4, the presence of a distractor slowed SRT. The distractor effect, however, was significantly attenuated in the

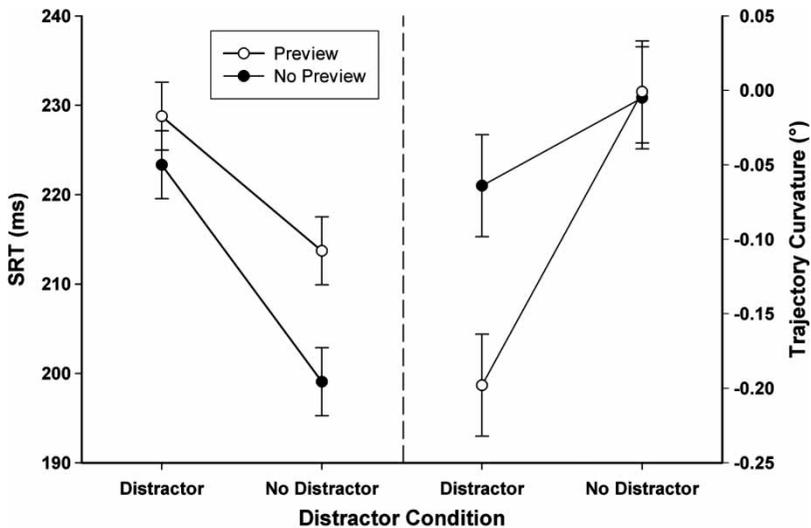


Figure 4. Mean saccadic reaction time (SRT) and trajectory curvature by condition in Experiment 2 ($n = 10$). By offering participants foreknowledge of the target location on preview trials, participants were able to attenuate the slowing of SRTs caused by distractors. In contrast, distractors caused greater trajectory curvature in the preview condition than the no-preview condition. These results suggest that foreknowledge of the target location allows effective control of temporal oculomotor capture, but not spatial oculomotor capture. Error bars are 95% confidence intervals calculated from Loftus and Masson (1994).

preview condition ($M = 24.27$, $SD = 10.02$) relative to the no-preview condition ($M = 15.04$, $SD = 9.43$), as revealed by the two-way interaction between preview status and distractor status on SRT, $F(1, 9) = 7.55$, $MSE = 28.19$, $p = .023$. In contrast to the temporal results, the distractor effect on saccadic trajectory curvature was significantly enhanced in the preview condition ($M = -0.20$, $SD = 0.12$) relative to the no-preview condition ($M = -0.06$, $SD = 0.07$), as revealed by the two-way interaction between preview status and distractor status on curvature, $F(1, 9) = 20.714$, $MSE = 0.002$, $p < .001$. Notably, the magnitude of deviation in the preview condition was very large, nearly three times greater than in any other reported condition. Therefore, giving subjects advance knowledge of the target location caused a reduction in the temporal distractor effect; however, this control resulted in an increased spatial distractor effect.

The increase in curvature in the preview condition is surprising as it suggests that exerting top-down control resulted is more, rather than less, of a spatial distractor effect. This increase in curvature, however, might also be explained by the slowed SRTs on distractor trials in the preview condition. To evaluate if the increase resulted from measuring the spatial distractor effect at a different point in the time course of curvature, SRTs were equated between conditions. This was achieved by removing the fastest 5% of distractor trials from the no-preview condition and the slowest 5% of distractor trials from the preview condition for each participant. With these trials removed there was no difference in SRT between preview and no-preview distractor trials ($M = 0.28$, $SD = 35.82$), $t(9) = 0.02$, $p = .981$; however, there was still a significant difference in curvature ($M = 0.06$, $SD = 0.03$), $t(9) = 6.69$, $p < .001$. The persistence of this difference suggests that the increase in curvature cannot be attributed to the change in SRT; rather, previewing the target location caused distractors to produce a greater amount of saccadic trajectory curvature.

Discussion

In Experiment 2, a reduction in temporal oculomotor capture and an enhancement of spatial oculomotor capture were observed in the preview condition relative to the no-preview condition. That is, when given foreknowledge of the target location, participants were able to exert control over temporal, but not spatial, capture. As with Experiment 1, it can be concluded that temporal oculomotor capture is more sensitive to top-down control than spatial oculomotor capture.

The conclusion that temporal oculomotor capture was controlled through the use of foreknowledge of the target location is consistent with the literature on manual responses. The finding of greater curvature with

advance target-location knowledge, however, was unexpected. Moreover, slowed SRTs were observed in the preview condition relative to the no-preview condition (for both distractor and no-distractor trials), a finding that is opposite to that normally observed with advance target-location knowledge (Dorris & Munoz, 1998). These two results, instead, may be due to differences in the sequence of sensory events between the preview and no-preview conditions. Specifically, because the visual target stimulus was presented simultaneously with the auditory go signal on no-preview trials, the reflexive saccadic programme generated by this luminance transient could have been used to quickly and accurately guide the eyes to the target location. In contrast, on no-preview trials the visual target stimulus appeared well in advance of the auditory go signal and, therefore, the stimulus-generated saccadic programme would likely have dissipated by the time participants made their target directed saccades. Therefore, the sensory signal that could be capitalized on in no-preview trials was not available on preview trials, resulting in slow SRTs and large magnitudes of curvature.

This bottom-up account of the effect on curvature is consistent with models of saccade generation in which the signals for potential saccade targets are integrated through competition (Godijn & Theeuwes, 2002; Trappenberg, Dorris, Munoz, & Klein, 2001). According to these models, the bottom-up and top-down signals associated with potential targets converge on one or more spatially organized saliency maps, and actively compete for target selection. Spatial oculomotor capture occurs when competition from the distractor-related signal has not been resolved at the time of saccade initiation. Based on these models, it has been recently argued that any increase in the strength of target-related signals should reduce, though competition, the spatial disruption caused by distractors (Van Zoest, Van der Stigchel, & Barton, 2008). Accordingly, Van Zoest et al. (2008) have demonstrated that the magnitude of curvature is reduced in a task with strong target representations (i.e., a prosaccade task) relative to tasks with weaker target representations (i.e., an antisaccade task, and a memory-guided saccade task). In line with this argument, curvature was attenuated in the no-preview condition of Experiment 2 because the luminance transient from the presentation of the target resulted in a stronger target representation.

This account of the effect on curvature also clarifies the interpretation of the present results with respect to the effectiveness of top-down control over spatial and temporal oculomotor capture. Namely, changes in spatial capture were consistent with changes in bottom-up control, but not top-down control (i.e., increasing the strength of the target representation though a sensory signal reduced curvature effects but increased SRT effects), and the reverse was true for temporal capture (i.e., target-location

foreknowledge reduced SRT effects, but increased curvature effects). Therefore, whereas top-down control effectively attenuated temporal oculomotor capture by the distractor, it was ineffective at controlling spatial capture.

GENERAL DISCUSSION

It has been repeatedly demonstrated that attentional capture, as measured by manual RT, can be eliminated through top-down control (Folk et al., 1992, 1994; Theeuwes, 1991b; Yantis & Jonides, 1990). When capture is assessed by measuring the spatial accuracy of saccades, however, limits of top-down control have been revealed (Irwin et al., 2000; Ludwig & Gilchrist, 2002b, 2003a; Theeuwes et al., 1998, 1999; Wu & Remington, 2003). To clarify these discrepant results, the present research sought to develop a more complete characterization of oculomotor capture by simultaneously assessing the limits of top-down control on temporal oculomotor capture and spatial oculomotor capture, through SRT and saccadic trajectory curvature, respectively. In Experiment 1 top-down control was assessed using an ACS manipulation, and in Experiment 2 it was assessed by providing accurate foreknowledge of the target location. In both experiments, control over oculomotor capture was more effective when measured through SRT than through curvature. Namely, while ACSs eliminated the effect of distractors on the temporal programming of a saccade, ACSs could not prevent the distractors from altering the spatial programming of the saccade. Similarly, foreknowledge of the target location attenuated temporal distractor effects but actually enhanced spatial distractor effects. Therefore, while top-down processes can be used to prevent temporal oculomotor capture, the same processes have a limited influence on spatial oculomotor capture.

The present measures of SRT and curvature can further be used to clarify prior research on the relationship between attentional capture (measured through manual RT) and oculomotor capture (measured through the frequency of distractor-directed saccades). In particular, in the present study, SRT provides not only a measure of temporal oculomotor capture but also a measure of attentional capture. In the employed paradigms, target-directed saccades could not be produced without first identifying the target and selecting it for action. As such, any distractor-related disruption in spatial attention would have slowed the time to identify and select the target, and, in turn, slowed the production of the saccade. Therefore, the absence of a distractor effect on SRT can be taken as evidence that top-down control eliminated attentional capture.

In addition, in the present study curvature provides a measure of the type of oculomotor capture that has been reported previously. Clearly, the effect of capture is manifested differently in the present study than in past studies.

Whereas capture has previously caused saccades to be biased towards distractors (Irwin et al., 2000; Theeuwes et al., 1998, 1999; Wu & Remington, 2003), in the present study capture caused saccades to be biased away from distractors. Despite this difference, is it likely that both spatial biases are measures of the same form of oculomotor capture; namely, both distractor-directed saccades and saccade-trajectory-curvature away from a distractor are indications that a distractor has generated a stimulus-driven saccadic programme. As has been shown previously, the reflexive saccadic programme generated by a distractor will initially compete with the target-directed programme, causing the saccade to be biased towards the distractor. Once the distractor has been inhibited, however, the saccade will be biased away from the distractor (McSorley et al., 2006; Van der Stigchel & Theeuwes, 2005, 2006). Thus, the difference in the expression of capture is likely due to measurement of the initial reflexive distractor-generated saccadic programme in the aforementioned studies, and measurement of the subsequent inhibition of this programme in the present study.

Although the generation of a reflexive programme and the subsequent inhibition of this programme may reflect distinct processes, there are reasons to believe that observation of curvature away indicates that a prior reflexive programme had been generated. Godijn and Theeuwes (2002) noted that under conditions where saccades are frequently directed to an irrelevant distractor, those saccades that accurately land on the target tend to deviate away from the distractor location. Therefore, curvature away appears to be a typical response to a reflexive distractor-generated saccadic programme. Further, after informing subjects of the location of an upcoming distractor, Van der Stigchel and Theeuwes (2006) observed that trajectory deviations away from that location were greatest when a distractor was actually presented. Thus, at least some component of curvature away is stimulus driven. Finally, Van Zoest et al. (2008) have demonstrated that as the strength of a target-directed saccadic programme decreases, distractors cause greater amounts of curvature away. That is, the greatest amounts of curvature away from a distractor are observed under the conditions where distractor-directed saccades are most likely to occur (Godijn & Theeuwes, 2002). Therefore, the magnitude of curvature away from a distractor may provide a measure of the strength of the distractor-generated saccadic programme. Together, these three studies suggest that curvature provides another indication of oculomotor capture.

Thus, the difference between the control of temporal and oculomotor capture observed in the present study clarifies the conclusions drawn from prior observations of oculomotor capture. In the original reports of oculomotor capture, Theeuwes and colleagues (Irwin et al., 2000; Theeuwes et al., 1998, 1999) remarked on the strong relationship between eye movements and attention. In particular, it has been consistently demonstrated

that voluntary saccades affect the deployment of attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986) and voluntary shifts in attention affect the production of saccades (Sheliga et al., 1994, 1995). Further, by recording manual responses concurrently with oculomotor responses, Theeuwes and colleagues observed that distractors caused both distractor-directed saccades and a slowing of manual RTs. Given the coupling between attention and eye movements, and the simultaneous observation of attentional and oculomotor capture, it was concluded that distractors reflexively captured both attention and the eyes. Further, because this capture occurred despite an ACS manipulation, it was argued that this was a case of purely bottom-up attentional capture.

As has been previously argued (Ludwig & Gilchrist, 2002b, 2003a; Wu & Remington, 2003), however, the observed effects on manual RT may have resulted from the search mode adopted by participants. Further, although the link between voluntary attention and saccades is well established, there is only mixed evidence (Schneider & Deubel, 2002) for the same link between attention and the type of reflexive eye movements observed by Theeuwes and colleagues (Irwin et al., 2000; Theeuwes et al., 1998, 1999). To refute the claim that the observed spatial oculomotor capture was an indication of attentional capture, Wu and Remington (2003) demonstrated that when control mode is carefully manipulated, attentional capture is eliminated, but oculomotor capture is not. From this, Wu and Remington concluded that oculomotor capture does not necessitate attentional capture, and, instead, that the oculomotor system is more sensitive to capture than the attentional system.

Because SRT and saccadic trajectory curvature provide measures of attentional capture and oculomotor capture, respectively, our results can be used to clarify the conclusions of Theeuwes and colleagues (Irwin et al., 2000; Theeuwes et al., 1998, 1999) and Wu and Remington (2003). In Experiment 1, distractors that did not match participants' ACSs generated curved saccadic trajectories, but did not slow SRTs. That is, these nonmatching distractors caused oculomotor capture without capturing attention, indicating that oculomotor capture does not necessitate attentional capture. Further, the insensitivity of oculomotor capture to top-down control may not reflect a trait of the oculomotor system, but rather the measure used to assess capture. That is, the results of both Experiment 1 and 2 suggest that the observed limits on control over capture are specific to measures of spatial accuracy and not measures of latency. Therefore, in contrast to the conclusions of Theeuwes and colleagues, and Wu and Remington, the present results suggest that capture by nonmatching distractors is specific to a spatial bias in motor responses that cannot be accounted for by changes in covert visual attention.

If the persistence of capture despite top-down control is inherent in the spatial accuracy of responses and not an exclusive trait of the oculomotor system, then the spatial accuracy of manual movements should also be insensitive to top-down control. This has been demonstrated twice before. The persistence of spatial manual capture was initially demonstrated by Ludwig and Gilchrist (2002b) who had participants move a mouse cursor to a target in the presence of visual distractors that either possessed or did not possess target defining features. Later, Hunt, von Mühlennen, and Kingstone (2007) had participants make directional joystick responses under the same conditions. For both studies, distractors caused spatial errors even when the distractors possessed no target defining features.

It is worth noting that under some conditions where spatial manual capture was observed, both Ludwig and Gilchrist (2002b) and Hunt et al. (2007) also observed a distractor related slowing of manual RT. Specifically, this slowing of RT was observed whenever the presentation of distractors increased the number of items on the display. The slowing of RT for such distractors has been reported previously, and is normally accounted for through nonspatial filtering costs rather than the capture of spatial attention (Becker, 2007; Folk & Remington, 1998). Both Ludwig and Gilchrist, and Hunt et al. used the concomitant effect on spatial accuracy to discount filtering. That is, they argued that the effect on RT could not be from the cost of filtering, as filtering is nonspatial, and a spatial disruption in response accuracy was observed. From this, it was concluded that the effect of distractors on RT, in spite of the ACS manipulation, was an indication of purely bottom-up attentional capture. The results from the present research suggest an alternate interpretation, however. In particular, in Experiment 1 it was observed that spatial oculomotor capture, as measured through the spatial accuracy of responses, does not necessitate the capture of spatial attention, as measured through RT. That is, spatial capture does not provide a measure of an effect on spatial attention. Therefore, it is possible that the effects on RT and spatial accuracy observed by Ludwig and Gilchrist, and Hunt et al., resulted from two separate causes: filtering and spatial manual capture. Alternatively, as was discussed by Ludwig and Gilchrist, and Hunt et al., the effect on RT may have resulted from the intentional slowing of responses in order to adjust for the spatial bias caused by distractors. That is, the effect on RT may have resulted from a speed-accuracy tradeoff. Such a tradeoff was not observed in the present study for spatial oculomotor capture, but such a tradeoff would also not be expected given the main sequence of saccadic eye movements (Becker, 1972; Becker & Fuchs, 1969). Regardless, the observation of concomitant spatial and temporal manual capture by Ludwig and Gilchrist, and Hunt et al., cannot be taken as evidence of purely bottom-up attentional capture, nor can it be used to reject the filtering cost account of the effect on RT.

To summarize, in the present study two distinct forms of capture were observed that are best described in terms of their effects on behaviour. Visual distractors cause temporal capture by slowing saccadic responses, and spatial capture by biasing the trajectory of saccadic eye movements. Through these behavioural effects, it is possible to infer effects on cognition. Certainly, temporal capture provides the classic measure of the capture of visual spatial attention. Spatial capture, on the other hand, may reflect a bias in the spatial programming of motor movements. Such a link between spatial capture and motor programming is consistent with competitive integration models of motor programming (Godijn & Theeuwes, 2002; Tipper, Howard, & Paul, 2001; Trappenberg et al., 2001), although the present research does not address the validity of this link. The results of the present study do suggest, however, that the role of top-down and bottom-up processes differ for these two forms of capture. Whereas temporal capture and, therefore, attentional capture are contingent on top-down control, spatial capture is more resistant to control, possibly reflecting a purely stimulus-driven process.

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