

Bullet trains and steam engines: Exogenous attention zips but endogenous attention chugs along

Ramakrishna Chakravarthi

Université de Toulouse, CerCo, UPS, France, &
CNRS, UMR 5549, Faculté de Médecine de Rangueil,
Toulouse, France



Rufin VanRullen

Université de Toulouse, CerCo, UPS, France, &
CNRS, UMR 5549, Faculté de Médecine de Rangueil,
Toulouse, France



Analyzing a scene requires shifting attention from object to object. Although several studies have attempted to determine the speed of these attentional shifts, there are large discrepancies in their estimates. Here, we adapt a method pioneered by T. A. Carlson, H. Hogendoorn, and F. A. J. Verstraten (2006) that directly measures pure attentional shift times. We also test if attentional shifts can be handled in parallel by the independent resources available in the two cortical hemispheres. We present 10 “clocks,” with single revolving hands, in a ring around fixation. Observers are asked to report the hand position on one of the clocks at the onset of a transient cue. The delay between the reported time and the veridical time at cue onset can be used to infer processing and attentional shift times. With this setup, we use a novel subtraction method that utilizes different combinations of exogenous and endogenous cues to determine shift times for both types of attention. In one experiment, subjects shift attention to an exogenously cued clock (baseline condition) in one block, and in other blocks, subjects perform one further endogenous shift to a nearby clock (test condition). In another experiment, attention is endogenously cued to one clock (baseline condition), and on other trials, an exogenous cue further shifts attention to a nearby clock (test condition). Subtracting report delays in the baseline condition from those obtained in the test condition allows us to isolate genuine attentional shift times. In agreement with previous studies, our results reveal that endogenous attention is much slower than exogenous attention (endogenous: 250 ms; exogenous: 100 ms). Surprisingly, the dependence of shift time on distance is minimal for exogenous attention, whereas it is steep for endogenous attention. In the final experiment, we find that endogenous shifts are faster across hemifields than within a hemifield suggesting that the two hemispheres can simultaneously process at least parts of these shifts.

Keywords: attention, exogenous, endogenous, shift, latency, hemifield, bilateral advantage

Citation: Chakravarthi, R., & VanRullen, R. (2011). Bullet trains and steam engines: Exogenous attention zips but endogenous attention chugs along. *Journal of Vision*, 11(4):12, 1–12, <http://www.journalofvision.org/content/11/4/12>, doi:10.1167/11.4.12.

Introduction

We make 3–4 eye movements per second while viewing a scene. The visual system gathers information whenever it fixates. Visual attention, which allows preferential processing of a subset of the input, is generally linked to these eye movements (for example, see Findlay, 2009). However, attention need not be linked to eye movements. Even when the eyes remain fixated on any given point, attention can shift to different parts of the visual field (Posner, 1980). In fact, this might be a preferred strategy in several visual tasks, where attentional shifts precede eye movements (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Sheliga, Riggio, & Rizzolatti, 1994). Such covert shifts of attention can be induced either endogenously or exogenously.

Endogenous and exogenous attention have been shown to have different properties (Egeth & Yantis, 1997; Eriksen & Hoffman, 1972; Jonides, 1981; Nakayama &

Mackeben, 1989; Posner, 1980; Triesman & Gelade, 1980). Endogenous attention can be voluntarily deployed to various spatial locations and objects and is slow but sustained, whereas exogenous attention is captured automatically by salient external stimuli and is fast but transient.

Several studies, using different methodologies, have attempted to determine the time required to shift attention from one location to another. These methods generally fall into one of three categories. *Attentional orienting* involves cueing a spatial location followed by the presentation of a target at that location (e.g., Posner, 1980). The observer performs a task on that target. Manipulating the stimulus onset asynchrony (SOA) between the cue and the target results in a set of performance data from which attentional shift time can be inferred. Schulman, Remington, and McLean (1979) used such a method and determined that endogenous attention took about 150 ms to reach a point 8 deg in the periphery. Eriksen and Collins (1969) estimated a shift time of 200 ms for endogenous attention. Müller and Rabbitt (1989) found shift times in the range

of 275–400 ms. They also estimated a shift time of 175 ms for exogenous attention. Tsai (1983) found a shift time ranging between 80 and 150 ms for exogenous attention. Similarly, Egly and Homa (1991) found a range between 50 and 150 ms. Nakayama and Mackeben (1989) found that the efficiency of exogenous attention peaks around 100 ms after cue onset.

Attentional gating requires the observer to monitor an RSVP stream. On detecting a specified target in the stream, the observer is asked to immediately move her attention to a different RSVP stream and report the first item she can identify in the second stream. By determining the position of the first reported item in the second stream relative to the target position in the other, attentional shift times can be estimated (e.g., Reeves & Sperling, 1986). With this method, Reeves and Sperling (1986) and Sperling and Weichselgartner (1995) estimated that endogenous shifts take around 300–500 ms. When they used a luminance change as a cue instead of detecting a target letter as a cue for shifting attention, they found shift times around 100 ms or less (Weichselgartner & Sperling, 1987). Thus, exogenous shifts were found to be far faster than endogenous ones.

Certain types of *visual search* require shifting attention from one location to another. By manipulating the pattern of search, shift times can be determined. For example, Horowitz, Wolfe, Alvarez, Cohen, and Kuzmova (2009) presented letters in a circle around fixation. The letter identities changed on each frame. The observers were asked to systematically move their attention clockwise. A target letter was presented such that the observers would identify it only if they were attending to the right place at the right time. By manipulating the presentation duration of each frame, attentional shift times can be estimated. They found that it took voluntary attention about 150–300 ms per shift and their data suggested that exogenous attentional shifts are rapid, on the order of less than 100 ms and probably close to 50 ms. Similarly, Horowitz, Holcombe, Wolfe, Arsenio, and DiMase (2004) found shift times of 300–500 ms for endogenous attention. However, there is evidence that the specific temporal layout of the stimulus used affects the rate of attentional shifts in such setups (Benjamins, Hooge, van der Smadt, & Verstraten, 2007).

In summary, these studies provide various estimates of attentional shift times ranging from 150 to 500 ms for endogenous attention and 50 to 175 ms for exogenous attention. A common difficulty encountered by all these methods is the requirement to process the target identity. This target processing time is invariably incorporated into the estimated attentional shift times. Further, in some methods such as attentional orienting and gating, the cue processing time is also incorporated. Here, we develop a *subtraction* method that allows us to separate out the cue and target processing times and enables us to estimate pure attentional shift times. This method builds on that pioneered by Carlson, Hogendoorn, and Verstraten

(2006), which controlled for many variables that usually plague earlier methods. They presented several “clocks” on an isoecentric ring. Each clock had an independently revolving clock hand. During each trial, one of the clocks was cued either endogenously or exogenously. The observers reported the “time” on the cued clock at cue onset. The difference between the reported and the veridical “time,” called *latency*, was taken as the duration that attention took to reach that clock. They estimated that endogenous attention took 250 ms to reach the target clock and exogenous attention took about 150 ms. This method minimizes the confounds of the previous studies by asking observers to do a simple orientation discrimination task instead of a letter identification task. However, it still has some of the same drawbacks as the older studies. The estimates include not only the attentional shift times but also the cue and target processing time, even if minimal, and might also incorporate any biases inherent in the task such as the flash lag effect (Nijhawan, 1994; Patel et al., 2000) or any compensatory mechanism that might try to correct for the motion of the hand.

The aim of this study is to develop a new subtraction method that controls for these confounds. A second goal is to explore the dependence of shift times on distance. Previous research is divided as to this question. Some studies have reported that attention takes the same amount of time to move to different locations irrespective of distance (Kwak, Dagenbach, & Egeth, 1991; Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995), while others have reported that shift times depend on distance (Egly & Homa, 1991; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Schulman et al., 1979; Tsai, 1983). This discrepancy might arise because of the confounds that might be incorporated while measuring shift times. If we are able to control for variables unrelated to attentional shifts, it would be possible to address this question directly.

A third aim of this study is to determine if the computations required for shifting attention can be carried out in parallel by the two cortical hemispheres. It has been suggested that the two hemispheres have independent attentional resources (Alvarez & Cavanagh, 2005; Delvenne, 2005; Sereno & Kosslyn, 1991). If so, the two hemispheres could share the processing burden needed to shift attention from one hemifield to another but not when the shift is within a hemifield. We might, therefore, predict that shifts across hemifields should be faster than those within a hemifield.

Experiment 1: Determining attentional shift times

How can we control or eliminate the confounding variables in determining shift times? Here is how our

subtraction method works. Our setup is the same as that of Carlson et al. (2006). We present 10 clocks in the periphery, each with independently revolving hands. In order to study endogenous attention shifts, we first cue a clock *exogenously*. We obtain latencies for this cued clock in the same manner as Carlson et al. (2006). This latency includes the cue processing time, the exogenous shift time, target clock, and hand orientation processing times. It may also include any consequences of flash lag or other compensatory mechanisms. Then, in a separate block, we again cue a clock *exogenously* but ask the observer to voluntarily move her attention to a different clock at cue onset and report the time on this clock upon arrival. Here, we have the same cue processing time, exogenous shift time, effects of flash lag and other compensatory mechanisms, and target and orientation processing times, as earlier. However, in addition, we have the endogenous shift (from the *exogenously* cued clock to the new clock position) time as well. To estimate the pure attentional shift time, we merely subtract the latency of the former block from the latency of the latter.

Similarly, we obtain exogenous shift times by a different combination of endogenous and exogenous cueing. We first present an *endogenous* precue. The observer now knows which clock to monitor. We then present an exogenous cue on that clock on the majority of the (valid) trials and ask the observer to report the hand position at this cue onset. We obtain latencies for such trials. On other trials, a different clock is *exogenously* cued. Attention has to *exogenously* move from the precued location to this clock. The latency obtained on these trials incorporates all the components of the validly cued trials, but in addition, it also contains the exogenous shift times. Subtracting the former from the latter provides us with pure exogenous shift times.

Thus, our method takes the general form of (a) localizing position X and reporting latencies at X on one set of trials, (b) localizing position X, moving attention from position X to position Y, and reporting latencies at Y on a different set of trials, and finally (c) subtracting latencies obtained in (a) from those obtained in (b) to compute pure attentional shift times. We make the reasonable assumption that (a) and (b) differ only in the attentional shift from X to Y. However, one might argue against this assumption. For example, both steps (a) and (b) involve localizing position X, but the time required for this localization might be sensitive to whether a further operation is required. In other words, the time to localize X might be different in steps (a) and (b), in which case our subtraction method is imperfect. Nevertheless, a linear sequence wherein the same process is utilized in both steps seems to be the simplest and most parsimonious assumption. Further, we point out that, even if there are non-linear processes involved in attentional shifts, the utilization of a subtraction step certainly produces better estimates than not utilizing one. Another advantage with our method is that shift times for endogenous and exogenous attention

can be measured to various distances from the cued clock. Moreover, any effect of distance on shift times, as measured by our method, should be invulnerable to the potential influence of non-linear processes, as any non-linearity is likely to be present and similar for shifts to all distances.

However, there are also limitations to our method. Hazlett and Woldorff (2004) described two stages of attentional shifts: planning and subsequent execution. Our method cannot separate out the two stages. Using their vocabulary, what we call *attentional shift* is, in fact, the sum total of planning and execution stages. Our method provides estimates for the entire shift but not for the component parts. Nevertheless, we can derive some predictions from their proposal. They argued that the planning but not the execution stage is distance dependent. The planning stage requires computing the coordinates of the final position. This includes calculating how far (in our setup, how many clocks away) the final location is from the current location. We can suppose that for exogenous attentional shifts, the cue location itself can serve as a marker, which enables fast computation of the final coordinates. This predicts that exogenous shifts will not be distance dependent. On the other hand, in the absence of any external markers, a laborious computation of the final coordinates might be required for endogenous attentional shifts, predicting that they are distance dependent.

Methods

Observers

Nine observers (including the authors), aged 23–37, with normal or corrected-to-normal vision took part in this experiment.

Stimuli

Stimuli were generated using MATLAB with the Psychtoolbox extensions (Brainard, 1997; Pelli, 1997) running on an Apple Mac Pro computer and presented on a 23-inch LCD monitor with a resolution of 1920 × 1080 pixels and a frame rate of 60 Hz. The display was placed 57 cm from the observer, whose head was stabilized with chin and forehead rests.

Procedure

We tested shift times for endogenous and exogenous attention in separate sub-experiments (**Experiment 1A** = endogenous; **Experiment 1B** = exogenous). We used a different combination of exogenous and endogenous

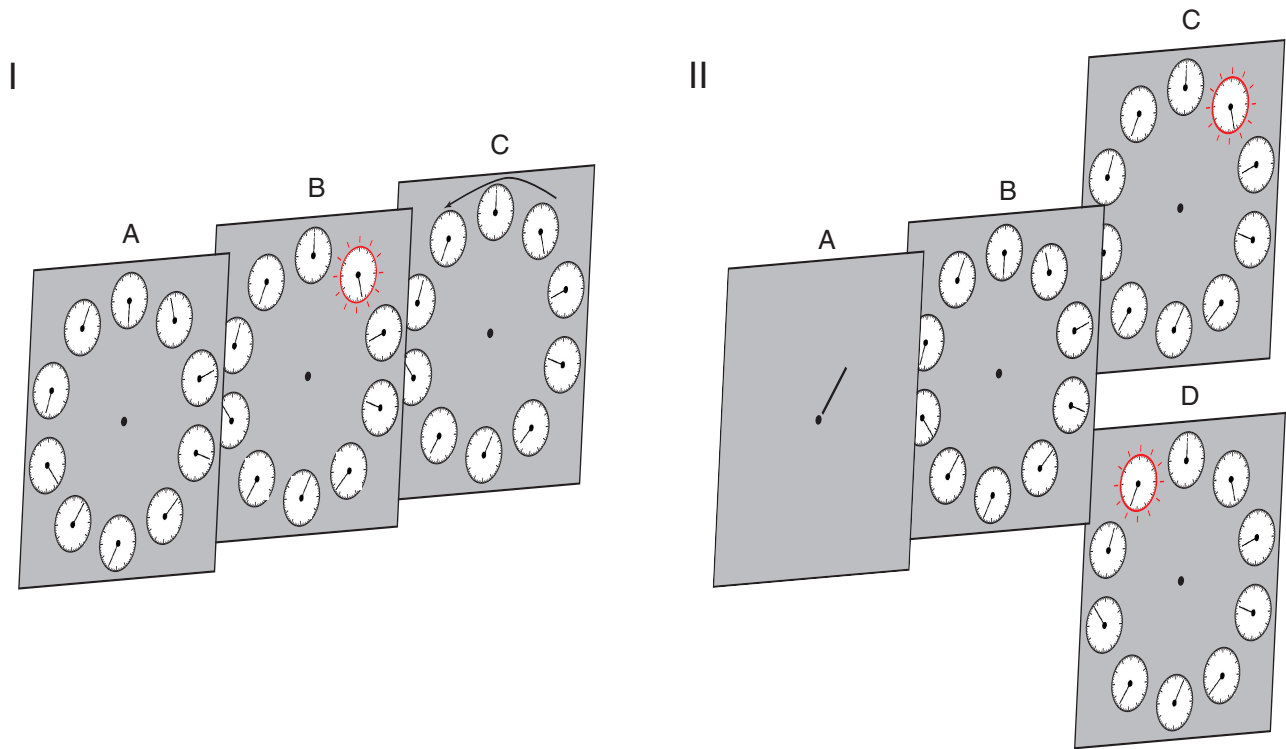


Figure 1. Measuring attentional shift times. (I) Endogenous attention shift time (Experiment 1A). (A) The trial begins with the presentation of 10 clocks with revolving hands. (B) One of the clocks is then exogenously cued by changing that clock's rim color to red, at a random moment between 0.75 and 1.5 s after trial onset. In one block, the subject reports the time perceived at cue onset. (C) In the remaining blocks, the observer is asked to move her attention endogenously to a clock a prespecified number of steps from this cued clock (shown here by an arrow to a clock two steps away in the counterclockwise direction). The observer reports the earliest hand position noticed in this endogenously attended clock. A subtraction between report latencies measured in these two kinds of blocks reveals the duration of the endogenous attention shift. (II) Exogenous attention shift time (Experiment 1B). (A) A precue is presented 300 ms before trial onset. (B) The observer is asked to maintain attention on the precued clock. (C) In half the trials, this precued clock is then exogenously cued. (D) In the other half, clocks at different distances from the precued clock are cued. The observer reports the hand position on these exogenously cued clocks. A subtraction between report latencies measured in these two kinds of trials (C and D) reveals the duration of the exogenous attentional shift.

cueing to determine shift times for the two kinds of attention (as explained previously and illustrated in Figure 1).

The stimulus consisted of 10 “clocks” presented in a circle with a radius of 10 deg around fixation. The radius of each clock was 2 deg. The center-to-center distance between two adjacent clocks was 6.18 deg. Each clock had a single hand, with a length of 1.5 deg, that revolved around the center of the clock at the rate of 0.5 Hz. The clock had the traditional 12 major ticks, one at each of the “hour” locations, and 48 minor ticks, one at each of the remaining “minute” locations, comprising a total of 60 ticks (Figure 1, Panel I). It took 33.33 ms for the clock hand to move from one tick to the next. All the markings on the clocks, including their rims, were black (luminance of 3.6 cd/m²) and were presented on a white background (luminance of 295.4 cd/m²). The initial locations of the hands in all the clocks on each trial were randomly determined. On each trial, the hands revolved for 2 s reaching the initial position at the end of that trial.

We used two kinds of cues—endogenous and exogenous. The endogenous cue was a bar with a length of 4 deg pointed toward the relevant clock with one end 0.5 deg from the fixation square. Clocks were exogenously cued by turning their rim from black to red. The cues each lasted for 100 ms.

Experiment 1A

We tested endogenous attention as follows. There were 7 blocks of 40 trials each in Experiment 1A. Ten clocks with independently revolving hands were presented in the periphery. Each trial lasted 2 s, during which the hands completed one revolution. One of the clocks was exogenously cued for 100 ms between 0.75 and 1.5 s after trial onset. The cued clock and the time of cueing were randomly picked on each trial. The hand would veridically be at some tick location at cue onset (t_v). In the baseline block, the observer's task was to report the perceived hand position at the onset of the exogenous cue.

A clock was presented in the fovea at the end of each trial, and the observer could adjust the hand location on this clock, using arrow keys, to report their perceived hand location (t_r). The difference in the reported hand position and the veridical hand position multiplied by the time it takes for the hand to move between adjacent ticks ($T_{\text{tick}} = 33.33$ ms) gives us the latency for that trial. This is the *baseline* latency:

$$\text{Latency} = (t_r - t_v)T_{\text{tick}}. \quad (1)$$

The next trial started once the response was confirmed by a key press. The inter-trial interval was 1 s. The observer had the option to discard a trial if she was not sure about her response or had failed to observe the cue. We excluded the discarded trials from analysis. However, each discarded trial was immediately replaced with a new trial with similar parameters and its position was randomized among the remaining trials, thus ensuring that all observers were presented with the same number of trials across all conditions. We later excluded trials from analysis whose latencies were beyond 2.5 standard deviations of the mean latency for that block. Overall, about 2% of trials were discarded by this method. So far, the procedure is similar to the one adopted by Carlson et al. (2006).

In other blocks, we used the same setup but with one change. Observers were asked to fixate in the center as earlier. An exogenous cue was presented on one of the clocks. However, instead of reporting the hand position in this cued clock, the observers had to voluntarily move their attention, at cue onset, to a different clock whose position was defined relative to the exogenously cued clock. The clock they had to move to depended on the instructions given at the start of that block. For example, in one block, they had to move their attention one clock from the cued clock in the clockwise direction, in another, two clocks counterclockwise. The observers had to report the earliest hand position they noticed in this clock. Another advantage of using this method is that this ensures that we know the location of the attention's initial location before the endogenous shift. In the case of Carlson et al.'s method, the observers were asked to fixate and make an endogenous shift to a cued clock. It is unclear if the initial position of the observer's attention was at fixation. Attention could have been spread out or at an unspecified location. In the current method, the location of the clock to which endogenous attention has to shift to depends crucially on the exogenously cued clock's location, and hence, the observers had to attend to the exogenously cued clock before shifting their attention.

We obtained latencies for these trials as before. This is the *clock* latency. As mentioned earlier, on different blocks, the observers were instructed to move their attention to clocks one, two, or five steps (diagonally opposite clock) away from the cued clock. For each clock

distance, both clockwise and counterclockwise directions were tested in separate blocks. The latencies in the two directions were averaged together. The order of all blocks (including baseline) was randomized.

To obtain attentional shift times, we subtracted baseline latency from clock latency (for each clock distance). Since both latencies contain the same components except for the endogenous shift time, we can estimate pure endogenous shift times by this method. Note that this subtraction procedure is applied to each observer individually (not on the means of all observers' data), thus ensuring that we control for all extraneous processes, other than the attentional shift, for each observer separately.

Experiment 1B

We used a similar stimulus setup and protocol for estimating exogenous attentional shift times, except that the sequence of cues was different. There were 6 blocks with 42 trials per block in [Experiment 1B](#). On each trial, the location of one clock was endogenously precued using a central pointer line. The observers were instructed to attend to the clock at that location. The precue, lasting 100 ms, was presented 300 ms prior to the presentation of the clocks. While monitoring this clock, the observers were asked to report the perceived hand position at cue onset on the clock that would be exogenously cued during the trial. In half the trials in that block (21 trials per block, a total of 126 trials over the entire session), the exogenous cue was simply presented on the precued clock. We obtained the *baseline* latency from these trials. This latency is comprised of cue processing and hand position decoding times. In the other half, the exogenous cue was presented on a different clock, 1, 2, or 5 clocks away, from the precued clock, in either direction (clockwise and counterclockwise). The observers would have been attending the clock at the precued location, and at cue onset, their attention would be drawn to the exogenously cued clock. One might argue that with 50% cue validity, observers would not necessarily be attending to the cued location but might have spread their attention over several clocks. However, the location of the subsequent exogenous cue is still unpredictable when it is not presented on the precued clock itself (it can be presented 1, 2, or 5 clocks from the precued location in either direction). Thus, it would remain that the best strategy would be to maintain attention on the precued location. Further, there is evidence that monitoring clocks at even two locations is costly (Hogendoorn, Carlson, VanRullen, & Verstraten, 2010), which would render it inefficient for observers to monitor many clocks at once. Finally, the instructions were explicit that they must attend the precued location on each trial, as most trials would probe that clock subsequently.

We obtained *clock* latencies for each of the clock positions. These latencies contain the exogenous shift time in addition to cue and hand position processing times.

To determine exogenous shift times, we subtracted baseline latency from each of the clock latencies.

As in [Experiment 1A](#), the observer had the option to discard a trial if she was not sure about her response or had failed to observe the cue. The trial, however, was replaced with a new trial with similar parameters and its position was randomized among the remaining trials. We excluded from analysis trials whose latencies were beyond 2.5 standard deviations of the mean latency for that condition. Less than 3% of all trials were discarded by these methods.

Results

In [Experiment 1A](#), we first obtained *baseline* latencies for an exogenous cue. Then, we obtained *clock* latencies for this exogenous cue plus an endogenous shift. To obtain endogenous shift times, we subtract the former from the latter. The mean \pm SEM exogenous or *baseline* latency was 137 ± 21 ms, similar to the estimates obtained by Carlson et al. (2006). This estimate includes cue and hand position processing time, effects of compensatory mechanisms and flash lag in addition to the exogenous shift. The *clock* latencies for clocks at different distances from the exogenously cued clock are depicted as circles in [Figure 2](#) (Panel I). Subtracting the *baseline* latency from each of the *clock* latencies, we obtained the endogenous shift times indicated by circles in [Figure 2](#) (Panel III).

Similarly, the *baseline* latency in [Experiment 1B](#) or a precued clock was 90 ± 24 ms. Subtracting this latency from each of the latencies of exogenously cued clocks at various distances away from this precued clock ([Figure 2](#), Panel II) provides exogenous attentional shift times, indicated by squares in [Figure 2](#) (Panel III).

Exogenous attention appears to be fast (shift time = around 100 ms). It changes with distance [$F(2,16) = 9.45$, $p = 0.002$; linear contrast: $F(1,8) = 12.88$, $p = 0.007$]. We are agnostic about the actual route taken by attention. It may have taken the shortest route (a straight line connecting the two clocks) or a curved path. Since we are unclear about the route, and hence the actual distance covered, it is not possible to compute the speed of movement (e.g., in deg/s). However, we can provide an estimate of the dependence on distance by computing the time required per step. Exogenous shift times do not change much with distance (slope = 6.45 ms/step). That is, it takes nearly the same amount of time for exogenous attention to shift to any clock from a precued location. Endogenous attention, on the other hand, is slow and shift times depend on the distance to the final location [$F(2,16) = 8$, $p = 0.004$]. It takes 249 ± 13 ms to move from a previously cued clock to the next nearest clock (clock 1) and 341 ± 20 ms to go two positions away (clock 2). The shift times for these two locations are significantly different [$t(8) = 5.1$, $p = 0.0017$]. If we consider the shift times to clocks 1 and 2 (we ignore, for now, the shift time to clock 5 for reasons provided below), it takes endogenous attention 92 ms/step, which is much steeper (30 times higher) than the speed of exogenous attention. In any case,

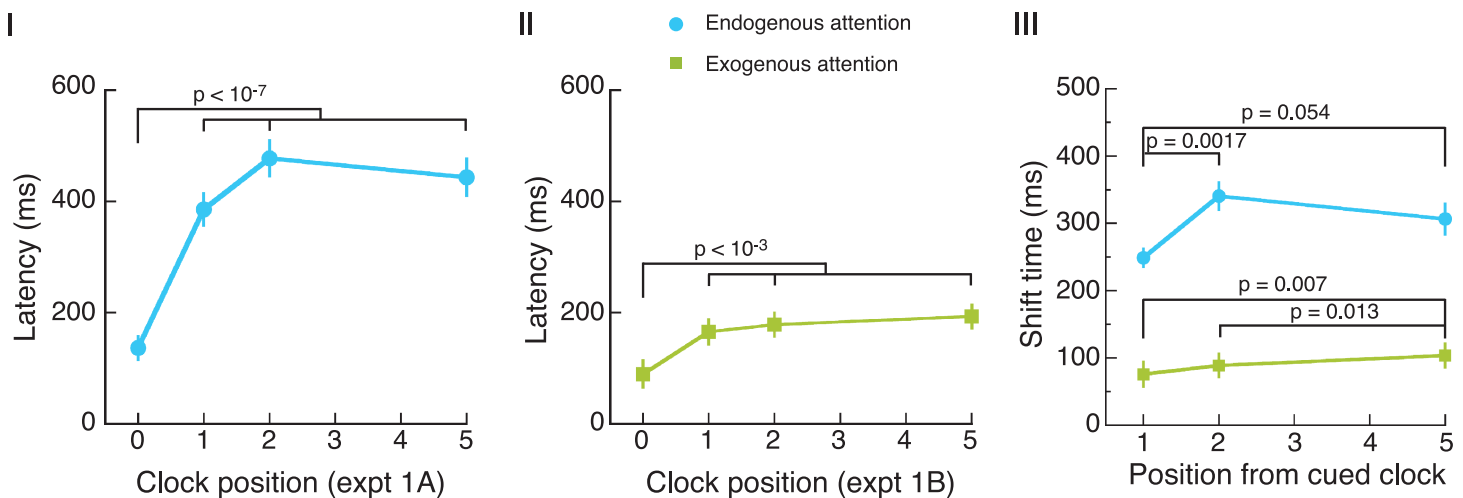


Figure 2. Attentional shift times. (I) Latencies in [Experiment 1A](#) for the baseline condition (exogenous cue) and for a further endogenous shift to a clock one, two, or five steps away. (II) Latencies in [Experiment 1B](#) for the baseline condition (endogenous cue) and for a further exogenous shift to a clock one, two, or five steps away. (III) A plot of shift times obtained by the subtraction procedure. The *baseline* latencies are subtracted from *clock* latencies for each clock distance in both experiments. Exogenous shift times (squares) are around 100 ms, with a small change as a function of distance. Endogenous shift times (circles) are higher, around 250 ms for a clock 1 step away and 350 ms for a clock 2 steps away: the shift time depends on distance. However, the time required to move to a clock 5 steps away is not more than that to move 2 steps away. This seemingly contradictory result is explored in [Experiment 2](#). Error bars are 1 SEM. All significant differences are indicated with p values.

it is clear that the further the attended location, the longer it takes for endogenous attention to move.

The time required for endogenous attention to move to a clock that is diametrically opposite the cued clock (clock 5) is only 313 ± 20 ms. Even assuming that attention takes the shortest route, this estimate seems to violate our claim that shift times depend on distance. At this point, we must note that the difference in shift times between clock 2 and clock 5 was not significant ($t(8) = 1.42$; $p = 0.19$). Attention does not take longer to travel 5 clocks away compared to traveling 2 clocks away. How can this be reconciled with the finding that shift times increase with distance from clock 1 to clock 2?

Clock 5 is always in the opposite hemifield relative to the exogenously cued clock. It has been suggested that independent attentional resources subserve the two hemifields (Alvarez & Cavanagh, 2005; Cavanagh & Alvarez, 2005). Perhaps some of the shifting process is independently handled when attention has to be shifted to the other hemifield, reducing the time required for the shift. This might be why we do not see any increase in shift times with distance between 2 and 5 steps. We test this possibility in [Experiment 2](#).

Experiment 2: Hemifield effects

Endogenous attention is slow and dependent on distance. However, we also saw in [Experiment 1](#) that the shift time to a clock diametrically opposite the exogenously cued clock was the same as that for a clock 2 steps away, seemingly contradicting the conclusion that shift times depend on the distance to be traveled. As mentioned earlier, this might be because some part of the shift for the diametrically opposite clock was handled by a potentially independent attentional resource available to the other hemisphere (Alvarez & Cavanagh, 2005). We directly tested this possibility in [Experiment 2](#).

Observers and stimuli

Six of the observers that took part in [Experiment 1](#) participated in [Experiment 2A](#). The same six observers and one additional observer ($n = 7$), who had also participated in [Experiment 1](#), took part in [Experiment 2B](#). The stimuli used were the same as in [Experiment 1](#).

Procedure

Experiment 2A

We asked observers to move their attention to a clock two positions away from an exogenously cued clock. This clock (reported clock) could be either in the same hemifield as the cued clock or in the opposite hemifield. The distance from the cued clock to the reported clock is

the same in both conditions, the only difference being the hemifield location of the reported clocks. If some aspect of shifting attention to the opposite hemifield is independently processed, then the shift time for the clock in the opposite hemifield should be less than that for the clock in the same hemifield.

The procedure was the same as for determining endogenous attention shift times in [Experiment 1A](#), with the following changes. There were three blocks and three conditions: *baseline*, *same hemifield*, and *opposite hemifield*. In one block, we obtained baseline latencies, where the observer had to report the hand position in the exogenously cued clock. In the other experimental blocks, the observer was asked to endogenously move her attention to a clock two positions from the exogenously cued clock and report the earliest hand position observed in that clock. Of the two blocks, the observer shifted attention in the clockwise direction in one block and in the counterclockwise direction in the other. The same and opposite hemifield conditions were intermixed in these two blocks. The order of blocks was randomized across observers.

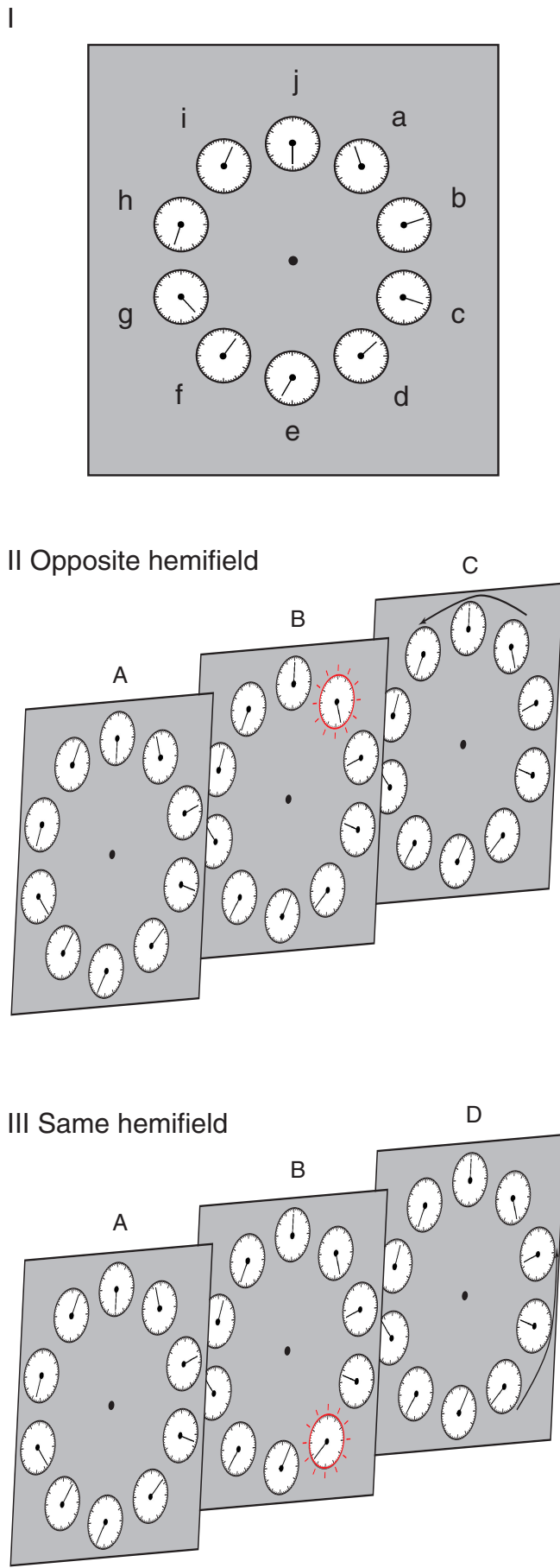
Only the clocks straddling the vertical midline were exogenously cued (clocks a, d, f, and i in [Figure 3](#), Panel I). In the blocks where the observer had to move attention to a clock two positions away, the final clock would be in the opposite hemifield on some trials and in the same hemifield on others. For example, if clock a is cued, the observer reports from clock c (same hemifield) in the clockwise block and from clock i (opposite hemifield) in the counterclockwise block. Similarly, within a counterclockwise block, observers move attention from clock a to i (opposite hemifield) and from clock d to b (same hemifield). In one third of trials in each block (15 of 45 trials), clocks in other positions were also cued (clocks b, c, g, and h). This would ensure that the observer did not develop strategies such as selectively attending to the locations of interest to us, which might act as a confounding factor. However, we did not include data from these trials in our analysis.

Experiment 2B

[Experiment 2B](#) was exactly the same as [Experiment 2A](#) except that observers were asked to move their attention 3 steps away from the exogenously cued clock (instead of 2 steps as in [Experiment 2A](#)). Thus, the same hemifield shifts were from locations a, d, f, and i to locations d, a, i, and f, respectively. The shifts in the opposite hemifield condition were from locations a, d, f, and i to h, g, c, and b, respectively.

Results

The top plot in [Figure 4](#) shows the results from [Experiment 2A](#). Endogenous shifts were faster across the



midline (340 ± 25 ms) than within a hemifield (398 ± 12 ms). This significant difference ($t(5) = 4.5$, $p = 0.006$) suggests that independent resources for the two hemifields can process at least some aspects of endogenous attentional shifts in parallel. Moreover, the endogenous shift time obtained in [Experiment 1A](#) is faster than the same hemifield shift time but slower than the opposite hemifield shift time. This indicates that the shift time obtained in [Experiment 1A](#) was likely a composite or average of trials where attention sometimes crossed the midline and sometimes did not.

We tested, using an analogous method (adapting [Experiment 1B](#)), if there was a hemifield effect for exogenous attention as well. We found no effect of hemifield (same hemifield = 67 ± 18 ms, opposite hemifield = 71 ± 13 ms; $t(5) = 0.5$, $p = 0.64$) suggesting that the independent resources of the two hemispheres do not provide any advantage in shifting attention across the vertical midline.

We observed a bilateral advantage for endogenous attentional shifts. However, there might be a few possible confounds in the testing procedure that might have given rise to these results. First, shifts across hemifields were symmetrical across the vertical midline, whereas shifts within a hemifield were not symmetrical across the horizontal midline. Enhanced neural activity has been observed at locations symmetrical to where a stimulus is presented (Hsieh & Tse, 2010). Further, there is evidence for neurons with bilaterally symmetrical receptive fields (Motter, Steinmetz, Duffy, & Mountcastle, 1987; Pigarev, Nothdurft, & Kastner, 2001; Steinmetz, Motter, Duffy & Mountcastle, 1987). These might have made it easier for stimuli in the opposite hemifield condition to be processed. Second, the final locations in the opposite hemifield condition (a, d, f, and i) were cued more often than those in the same hemifield conditions. Attention might have been preferentially allocated to these locations, despite our attempts to minimize this, leading to faster stimulus processing there. Finally, the shifts in the opposite hemifield condition were close to the vertical

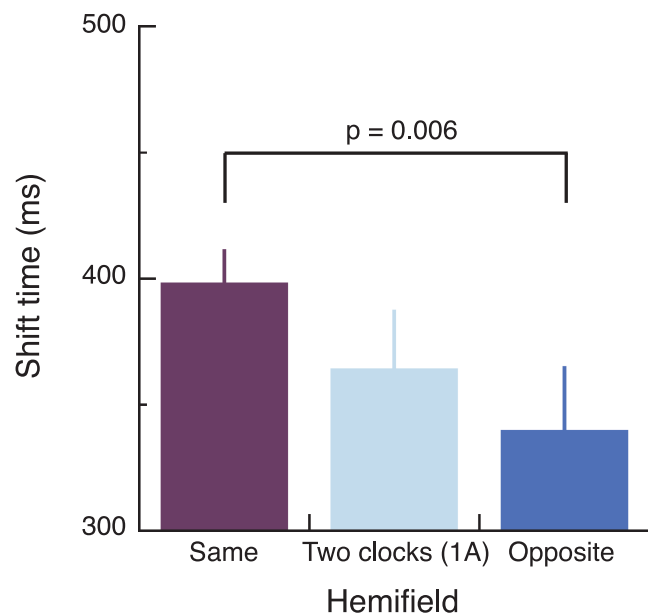
Figure 3. The effect of hemifield on endogenous attentional shifts. (I) This panel shows the positions of the clocks. We test whether shifting endogenous attention to the opposite hemifield is faster than shifting within a hemifield. The procedure is the same as in [Experiment 1A](#), except that the observers are always asked to shift attention to a clock 2 steps away from an exogenously cued clock. In a block where observers are asked to move their attention in the counterclockwise direction, the reported clock is either in the opposite hemifield when clock “a” is exogenously cued (Panel II) or in the same hemifield when clock “d” is cued (Panel III). The same procedure was used in [Experiment 2B](#) except that observers were asked to move their attention 3 steps away. Exogenous shift times were also tested in the same fashion but with the cueing regime used in [Experiment 1B](#).

midline. The space immediately around the vertical midline is represented by bilateral or callosally connected neurons (e.g., Choudhury, Whitteridge, & Wilson, 1965; Hubel & Wiesel, 1967; Tootell, Mendola, Hadjikhani, Liu, & Dale, 1998), which might process both locations efficiently. Each or all of these might have induced faster shifts across hemifields than within a hemifield.

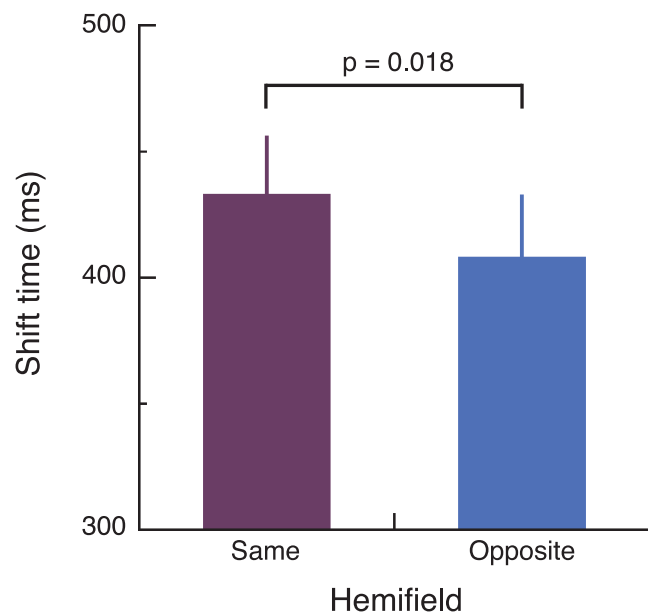
Fortunately, [Experiment 2B](#) does not suffer from these confounds. In this experiment, we asked observers to move their attention 3 steps away from the exogenously

cued clock. It turns out that any advantage afforded by the above-mentioned factors should now favor the same hemifield condition over the opposite hemifield condition. First, the shifts across hemifields were not symmetrical, but those within a hemifield were (with respect to the horizontal midline). Second, the final locations for shifts in the opposite hemifield condition were not the most cued locations, whereas those for the same hemifield shifts were. Finally, the shifts were large enough that midline neurons could no longer process both locations in the opposite hemifield condition. Thus, if these factors were responsible for the bilateral advantage in [Experiment 2A](#), then we should now observe a unilateral (same hemifield) advantage. The bottom plot of [Figure 4](#) displays the results of [Experiment 2B](#). Once again, shifts across hemifields (408 ± 24 ms) are faster than shifts within a hemifield (433 ± 22 ms), confirming the proposal that independent resources are available for processing attentional shifts across hemifields ($t(6) = 3.2$; $p = 0.018$).

Experiment 2A (step 2 clocks away)



Experiment 2B (step 3 clocks away)



Discussion

We used a novel subtraction method to determine shift times for the two kinds of attention unencumbered by confounds such as cue and stimulus processing times. Using this technique, we confirmed that exogenous attention is faster than endogenous attention. Consistent with previous studies, we found that exogenous attention takes about 100 ms to shift to any new location and that endogenous attention takes about 250 ms to shift to a nearby location. Interestingly, we found that exogenous attention shift times are minimally dependent on distance (bullet train like fast travel) whereas endogenous attention shift times depend steeply on distance (traveling laboriously like steam engine-powered trains). We also found evidence for a division of labor for endogenous shifts across the midline. Endogenous shifts across the vertical

Figure 4. Bilateral advantage. The top plot shows results from [Experiment 2A](#). Endogenous attention shifts are slower within the same hemifield (purple bar) than across the midline (blue bar), indicating that some aspects of the shift can be processed in parallel by the two hemispheres. The light turquoise bar in the middle shows the time required to move two clocks away as determined in [Experiment 1A](#). This bar falls squarely in between the current results. The bottom plot depicts results from [Experiment 2B](#), which was the same as [Experiment 2A](#) except that the observers were required to move attention 3 clocks away from the cued clock. This experiment does not suffer from any of the potential confounds (see text) that might have produced the results observed in [Experiment 2A](#). The data once again confirm a bilateral advantage for attentional shifts. Error bars are 1 SEM.

midline were faster than shifts within a hemifield. Such a bilateral advantage was not observed for exogenous shifts.

Carlson et al. (2006) also arrived at similar figures for endogenous and exogenous attentional shift times. This is surprising given our claim that their method, despite being much cleaner than previous attempts, still includes cue and stimulus processing times. The main motivation of using our subtraction method was to get rid of these confounds. So, how could they obtain similar estimates without utilizing a subtraction method? In our opinion, the reason for obtaining similar shift times is fortuitous. Even though they explicitly did not incorporate a subtraction step, they were implicitly utilizing one: in the baseline conditions, their subjects reported a baseline latency of around 0 ms. Hence, even without a subtraction step, their numbers ended up comparable to ours. The reason for their low baseline latency could be because the subjects were unwittingly compensating for the hand movements in the clocks. With our method, we control for this compensation. It does not matter what confounding factors act (or not act) in determining raw latencies; we can eliminate their contribution as long as the contributors are the same in the baseline and main conditions. We have no reason to believe that they are different in the two.

Hazlett and Woldorff (2004) argued that shifting endogenous attention requires two stages: planning and execution. Their findings indicate that the planning stage is distance dependent whereas execution is independent of distance. The current method does not enable us to separate out the two stages and their contributions to shift times, but Hazlett and Woldorff's proposal can help explain several aspects of our results. According to them, planning shifts to locations further away takes more time than to closer locations. Figuring out where to go (e.g., two clocks away in the clockwise direction from *this* exogenously cued clock) is part of this planning. Computing the path and the final location should take longer to a location two clocks away than for one that is one clock away, as we found.

This hypothesis might also explain why exogenous attention is minimally dependent on distance. Exogenous attention requires no or minimal planning as it is entirely driven by external stimuli. The location to be attended is indicated by an external stimulus. In essence, the external world computes the coordinates for displacement. It requires only an execution stage, and hence, the shift can be quick and mostly independent of distance. Further, since exogenous shifts can be considered to be executed without much planning, the independent resources of the two hemispheres would not provide any advantage when shifting across the midline. Correspondingly, we did not observe a bilateral advantage for exogenous shifts.

Hazlett and Woldorff's hypothesis that the planning stage of endogenous attentional shifts has distance-dependent time costs might also explain our hemifield results. We might suppose that the two hemifields are

capable of sharing these costs. When attention has to cross the midline, both hemifields simultaneously and independently participate in planning the shift (Alvarez & Cavanagh, 2005). Thus, the planning stage requires far less time than if the whole path was computed serially by a single attentional source. Hence, shift times do not monotonically increase with distance when the final location is in the opposite hemifield. However, within a hemifield, planning and execution are processed by the same resources. This results in distance dependence of shifts. This seems like a plausible story, yet this hypothesis remains to be tested.

There is a long-standing debate about whether attention, endogenous attention to be specific, travels the intervening space when shifting from one location to another or whether it merely disappears at one location and appears at another (Reeves & Sperling, 1986; Schulman et al., 1979; Sperling & Weichselgartner, 1995; Tsai, 1983). Our findings are agnostic about this debate and are compatible with either account. Both proposals, traveling the intervening space or teleporting from one location to another, are different methods of executing shifts. We have argued above that the planning stage, but not the execution stage, is distance dependent. The difference between the two proposals can be said to lie chiefly at the level of execution and not in planning, where the final coordinates are computed. Hence, both proposals will make identical predictions about distance dependence.

As mentioned earlier, endogenous and exogenous attention are said to have distinct properties (Egeth & Yantis, 1997; Eriksen & Hoffman, 1972; Jonides, 1981; Nakayama & Mackeben, 1989; Posner, 1980; Triesman & Gelade, 1980). The current results point to a further distinction. When an external stimulus captures attention, it takes roughly the same amount of time for attention to arrive at the target location irrespective of the distance to that location. On the other hand, in order to voluntarily shift attention, it takes longer to attend a farther location than a closer one. Further, endogenous shifts can benefit from independent processing of the planning stage by the two cortical hemispheres, which exogenous attention cannot avail. This might suggest distinct neural mechanisms for the two kinds of attention or, if Hazlett and Woldorff (2004) are correct, that exogenous attention uses only a part of the machinery utilized by endogenous attention.

Conclusions

We introduce a new subtraction method that can determine accurate shift times of attention, free of confounds such as cue and stimulus processing times. We find that exogenous attention is fast and minimally dependent on distance, whereas endogenous attention is slow and dependent on distance. We also find that shift

times for endogenous attention are faster across hemifields than within a hemifield suggesting that the two cortical hemispheres can work in parallel for completing a shift crossing the vertical midline.

Acknowledgments

We thank Hinze Hogendoorn for his valuable comments on an earlier version of this manuscript. We also thank Todd Horowitz and another, anonymous, reviewer for their helpful comments and suggestions. This research was supported by a EURYI Award Grant to RV.

Commercial relationships: none.

Corresponding author: Ramakrishna Chakravarthi.

Email: rama@cerco.ups-tlse.fr.

Address: CerCo, UMR 5549, Faculte de Medecine de Rangueil, 31000 Toulouse, France.

References

- Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual fields. *Psychological Science*, *16*, 637–643.
- Benjamins, J. S., Hooge, I. T. C., van der Smagt, M. J., & Verstraten, F. A. J. (2007). Disengaging attention sets the temporal limits of attentive tracking. *Vision Research*, *47*, 1055–1059.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.
- Carlson, T. A., Hogendoorn, H., & Verstraten, F. A. J. (2006). The speed of visual attention: What time is it? *Journal of Vision*, *6*(12):6, 1406–1411, <http://www.journalofvision.org/content/6/12/6>, doi:10.1167/6.12.6. [PubMed] [Article]
- Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, *9*, 349–354.
- Choudhury, B. P., Whitteridge, D., & Wilson, M. E. (1965). The function of the callosal connections of the visual cortex. *Quarterly Journal of Experimental Physiology*, *50*, 214–219.
- Delvenne, J. F. (2005). The capacity of visual short-term memory within and between hemifields. *Cognition*, *96*, B79–B88.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition. *Vision Research*, *36*, 1827–1837.
- Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation and time course. *Annual Review of Psychology*, *48*, 269–297.
- Egley, R., & Homa, D. (1991). Reallocation of visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 142–159.
- Eriksen, C. E., & Collins, J. F. (1969). Visual perceptual rate under two conditions of search. *Journal of Experimental Psychology*, *80*, 489–492.
- Eriksen, C. E., & Hoffman, J. E. (1972). Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception & Psychophysics*, *11*, 169–191.
- Findlay, J. M. (2009). Saccadic eye movement programming: Sensory and attentional factors. *Psychological Research*, *73*, 127–135.
- Hazlett, C. Z., & Woldorff, M. J. (2004). Mechanisms of moving the mind's eye: Planning and execution of spatial shifts of attention. *Journal of Cognitive Neuroscience*, *16*, 742–750.
- Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*, 787–795.
- Hogendoorn, H., Carlson, T. A., VanRullen, R., & Verstraten, F. A. J. (2010). Timing divided attention. *Attention, Perception & Psychophysics*, *72*, 2059–2068.
- Horowitz, T. S., Holcombe, A. O., Wolfe, J. M., Arsenio, H. C., & DiMase J. S. (2004). Attentional pursuit is faster than attentional saccade. *Journal of Vision*, *4*(7):6, 585–603, <http://www.journalofvision.org/content/4/7/6>, doi:10.1167/4.7.6. [PubMed] [Article]
- Horowitz, T. S., Wolfe, J. M., Alvarez, G. A., Cohen, M. A., & Kuzmova, Y. I. (2009). The speed of free will. *The Quarterly Journal of Experimental Psychology*, *62*, 2262–2288.
- Hsieh, P.-J., & Tse, P. U. (2010). BOLD signal in both ipsilateral and contralateral retinotopic cortex modulates with perceptual fading. *PLoS ONE*, *5*, e9638.
- Hubel, D. H., & Wiesel, T. N. (1967). Cortical and callosal connections concerned with the vertical meridian of the visual fields in the cat. *Journal of Neurophysiology*, *30*, 1561–1573.
- Jonides, J. (1981). Voluntary versus automatic control over the mind's eye movement. In J. L. A. Baddeley (Ed.), *Attention & performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.
- Kwak, H., Dagenbach, D., & Egeth, H. (1991). Further evidence for a time-independent shift of the focus of attention. *Perception & Psychophysics*, *5*, 473–480.
- Motter, B. C., Steinmetz, M. A., Duffy, C. J., & Mountcastle, V. B. (1987). Functional properties of parietal visual neurons: Mechanisms of directionality along a single axis. *Journal of Neuroscience*, *7*, 154–176.

- Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315–330.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.
- Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, *370*, 256–257.
- Patel, S. S., Ogmen, H., Bedell, H. E., Sampath, V., Eagleman, D. M., & Sejnowski, T. J. (2000). Flash-lag effect: Differential latency, not postdiction. *Science*, *290*, 1051.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.
- Pigarev, I. N., Nothdurft, H.-C., & Kastner, S. (2001). Neurons with large bilateral receptive fields in monkey prelunate gyrus. *Experimental Brain Research*, *136*, 108–113.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.
- Reeves, A., & Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review*, *93*, 180–206.
- Remington, R. W., & Pierce, L. (1984). Moving attention: Evidence for time-invariant shifts of visual selective attention. *Perception & Psychophysics*, *35*, 393–399.
- Rizzolatti, G., Riggio, L., Dascola, I., & Umiltà, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*, 31–40.
- Sagi, D., & Julesz, B. (1985). Fast noninertial shifts of attention. *Spatial Vision*, *2*, 141–149.
- Schulman, G., Remington, R., & McLean, J. (1979). Moving attention through visual space. *Journal of Experimental Psychology*, *5*, 522–526.
- Sereno, A. B., & Kosslyn, S. M. (1991). Discrimination within and between hemifields: A new constraint on theories of attention. *Neuropsychologia*, *29*, 659–675.
- Sheliga, B. M., Riggio, L., & Rizzolatti, G. (1994). Orienting of attention and eye movements. *Experimental Brain Research*, *98*, 507–522.
- Sperling, G., & Weichselgartner, E. (1995). Episodic theory of the dynamics of spatial attention. *Psychological Review*, *102*, 503–532.
- Steinmetz, M. A., Motter, B. C., Duffy, C. J., & Mountcastle, V. B. (1987). Functional properties of parietal visual neurons: Radial organization of directionalities within the visual field. *Journal of Neuroscience*, *7*, 154–176.
- Tootell, R. B. H., Mendola, J. D., Hadjikhani, N. K., Liu, A. K., & Dale, A. M. (1998). Colloquium paper: The representation of the ipsilateral visual field in human cerebral cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *95*, 818–824.
- Triesman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136.
- Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance*, *9*, 523–530.
- Weichselgartner, E., & Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science*, *238*, 778–780.