

Mechanisms of Moving the Mind's Eye: Planning and Execution of Spatial Shifts of Attention

Chad J. Hazlett and Marty G. Woldorff

Abstract

■ The usefulness of attentional orienting, both in the real world and in the laboratory, depends not only on the ability to attend to objects or other inputs but also on the ability to shift attention between them. Although understanding the basic characteristics of these shifts is a critical step toward understanding the brain mechanisms that produce them, the literature remains unresolved on a very basic and potentially revealing characteristic of these shifts—namely, whether attention takes longer to shift a farther distance across the

visual field. We addressed this question using a series of behavioral tasks involving the voluntary orienting of attention to locations in the visual field. The findings support a model in which attentional shifts include separate “planning” and “execution” stages and in which only the planning stage requires more time for shifts of a greater distance. These results offer resolution to the longstanding debate concerning the effect of attentional shift distance on shift time and provide insight into the fundamental mechanisms of attentional shifting. ■

INTRODUCTION

The flexibility of our attentional systems depends not only the ability to attend to specific sources of information, but also the ability to shift attention between those sources. Understanding the basic characteristics and properties of these shifts is critical for understanding the mechanisms by which they are produced. However, attempts to determine one of the fundamental properties of these shifts have resulted in apparently contradictory findings in the literature. Specifically, studies attempting to determine whether it takes longer to shift covert visual attention a farther distance across the visual field have generated intransigently inconsistent results (for reviews, see Egeth & Yantis, 1997; Yantis, 1988; Eriksen & Murphy, 1987). That is, some studies have reported that shift time is independent of distance (Sperling & Weichselgartner, 1995; Kwak, Dagenbach, & Egeth, 1991; Sagi & Julesz, 1985; Remington & Pierce, 1984), while others have reported that shift time increases with distance (Egly & Homa, 1991; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Tsal, 1983; Schulman, Remington, & McLean, 1979). Here, we report a series of studies investigating the hypothesis that shifts of covert attention occur in at least two stages—a “planning” stage, and an “execution” stage—with only the former requiring more time for further shift distances. The results further our understanding of attentional shift mechanisms, while also appearing to be useful in understanding a variety of the contradictory results reported in previous studies.

Studies on the effect of attentional shift distance on shift duration typically have taken precautions to avoid several types of confounds. Covert shifts of attention are used, so that the kinetics of eye movements do not affect the time taken to relocate attention. It has also been critical in these studies to determine that any effect of shift distance is not due to differential target eccentricity between the near- and far-shift conditions. However, even studies that have controlled for target eccentricity have produced contradictory findings. For example, Sperling and Weichselgartner (1995) had an approach that allowed them to rule out any effects of eccentricity, and they found that there was no difference in the time required to shift to a farther distance relative to a shorter distance. On the other hand, various other studies that have also controlled for eccentricity did detect a distance effect. Egly and Homa (1991), for example, controlled target eccentricity across near and far shifts of attention by presenting all targets and cues at positions of equal eccentricity and still found that shifts of a greater distance took longer to complete than shorter ones.

We hypothesized that a key reason for these continued differences among findings might be that studies have differed as to whether subjects had sufficient information to “preplan” their shifts of attention. For example, in Sperling and Weichselgartner’s (1995) work, in which shift time was not affected by distance, subjects knew the location to which they would have to move their attention before being cued to do so. In contrast, Egly and Homa’s (1991) subjects did not know where they would need to move their attention on the critical trials until they were cued to move by the appearance of the targets

Duke University

themselves at unexpected locations, and in this case, a distance effect was observed. This difference in the possibility of preplanning the shift could impact whether a distance effect is observed in the measured reaction time (RTs). Specifically, if there are separable phases of planning and execution in covert attentional shifting, and in some studies the planning phase was included in the measured RTs, but in other studies it was not, then differential sensitivity of these phases to shift distance would affect whether a distance effect was observed. In particular, if the planning stage was dependent on distance (and the execution stage was not), then only studies in which subjects could not “preplan” shifts of attention would include a distance effect in the observed RTs.¹

To directly address this hypothesis, we performed a series of experiments investigating the effects of shift distance on the time it takes to perform covert attentional shifts, but we included conditions in which subjects either could or could not preplan the relevant attentional shifts. This allowed us to investigate not only whether there is a distance effect in covert attentional shifting but whether it could be clearly associated with a separable planning stage.

RESULTS

Experiment 1A: Distance Dependency

To test these predictions, we performed a series of cued attentional orienting experiments using a form of the Posner cueing paradigm (Posner, Snyder, & Davidson, 1980) that involved multiple shifts of attention in each trial. Experiment 1A and its control experiments (1B and 1C) were designed to determine the distance dependency of RTs under conditions in which planning and execution of attentional shifts both needed to occur during the RT period.

The stimulus display was configured as shown in Figure 1A. Figure 1B illustrates the attentional paths formed by the far (orange arrows) and near (yellow arrows) covert movements of attention during Experiment 1A. The stimulus sequence that directed subjects to execute shifts along these paths is shown in Figure 1C. Subjects maintained fixation at the center box at all times during the experiment, and the boxes on the perimeter were equally distant from fixation. At the beginning of each trial, a first cue presented at fixation instructed subjects to covertly shift attention to one of the two upper boxes. At a second point in time (1500 msec later), a second cue presented at this cued upper box position then instructed subjects to make a second shift of covert attention to either the bottom (“far”) or lateral (“near”) box on the same side. After shifting their attention, subjects performed a discrimination of the letters “A” versus “H” at the cued position. Note that for any “first cue” to the left or right, the “second cue” could instruct subjects to make a “near” move (to lateral boxes) or a

“far” move (to bottom boxes) (see Figure 1B). In addition, at the time of the second cue (at the covertly attended left or right upper box), stimuli were presented at all the boxes simultaneously to preclude any exogenous drawing of attention by an isolated stimulus. Lastly, to ensure that subjects maintained their central eye fixation, electro-oculographic (EOG) recordings were employed to monitor eye position.

The chief result from Experiment 1A was that on average, far trials (756 msec) required 70 msec longer than near trials (686 msec) to complete (far minus near = 70 msec, $SE = 13$ msec, $t = 5.1$, $p = .0004$) (Figure 3A). Because all critical aspects of near and far trials, including eccentricity, were equivalent except for the path-length difference traveled by attention, this result indicates that when planning must occur during the RT window, it takes longer to move attention a farther distance. The EOG recordings indicated that subjects made little eye movement on these trials ($<0.85^\circ$; see blue trace on Figure 4).

Experiment 1B: Control for Target Position

Experiment 1A provided evidence for a distance effect on attentional shifting. Because near and far target positions (lateral and bottom boxes, respectively) were equally eccentric from fixation, it would be expected that subjects perceived them with similar acuity, and thus, targets in the far boxes would not be any more difficult to process than targets in the near boxes—that is, these targets would not have generated any RT difference based solely on their position. However, because near trials always utilized the “lateral” boxes and far trials always utilized the “bottom” boxes, a control experiment was performed to empirically verify that the results in Experiment 1A were truly due to path-length difference and not to target position per se.

Subjects from Experiment 1A also participated in this control experiment during the same session. Identical target positions as those in Experiment 1A were used, but without attentional path-length differences. To achieve this, subjects were cued from the center position to covertly move their attention directly to one of the four target boxes (lateral and bottom boxes), where they performed the same A/H discrimination as in Experiment 1A.

Under these conditions, no significant difference was observed between the RTs to the bottom targets compared to RTs to the lateral targets ($p = .147$) (Figure 3B), confirming that the effect in Experiment 1A was due to path-length differences, not to the target positions themselves.

Experiment 1C: Control for Possible Eye Movement

An additional control study (Experiment 1C) was performed to ensure that eye movements had not contam-

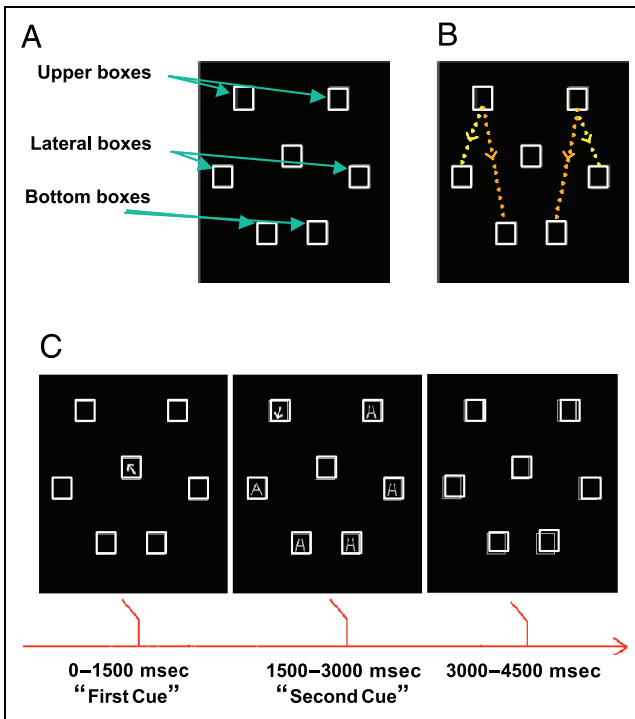


Figure 1. Stimulus layout and sequence. (A) Stimulus layout and labels used throughout text. (B) Layout showing the near (yellow) and far (orange) paths of covert attentional shifts in Experiment 1A. (C) Stimulus sequence for Experiment 1A.

inated the data. Although the observed amount of eye movement in Experiment 1A was small ($<0.85^\circ$ on average), a handful of eye movements scattered throughout the data could have potentially distorted

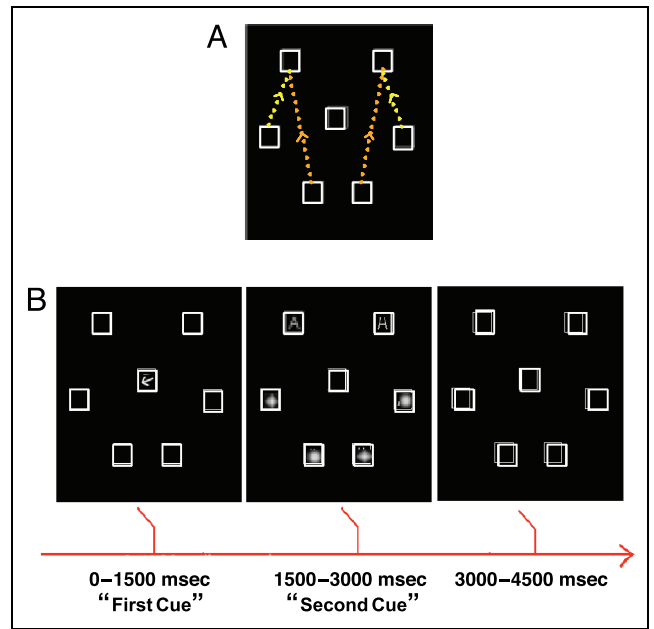


Figure 2. (A) Attentional shift paths for near (yellow) and far (orange) shifts in Experiment 2A. (B) Stimulus sequence for Experiment 2A.

the observed distance effect in the averaged RTs, if such eye movements would take substantially longer for far shifts than for near shifts.

To test this possibility, subjects that were run in Experiment 1A and the associated position control experiment (1B) described above also participated in an eye-movement control experiment (1C) during the same session. This was identical with Experiment 1A in terms

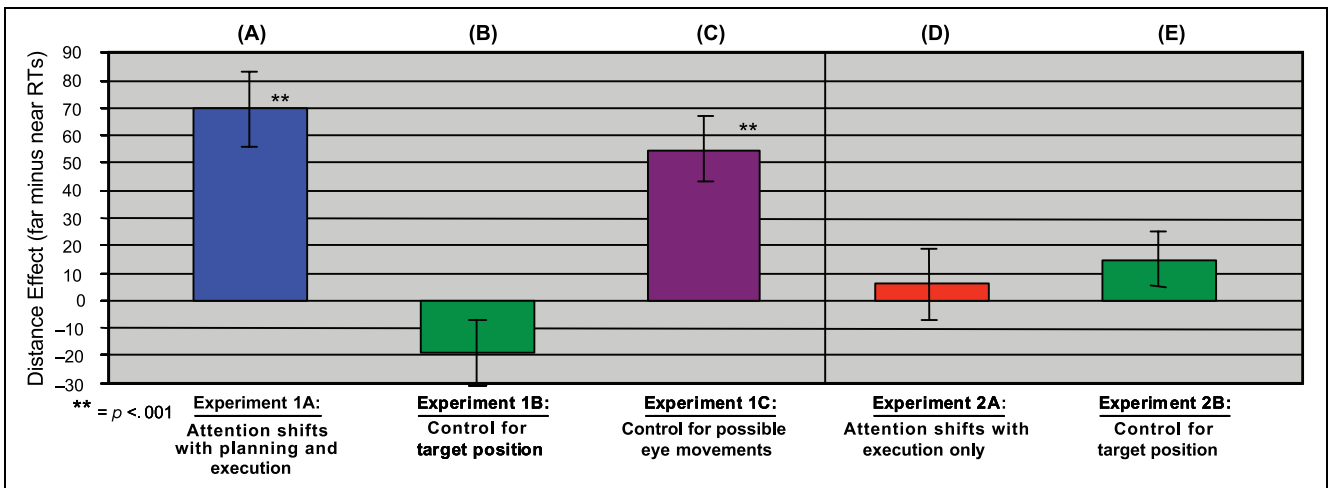


Figure 3. Distance effects (far minus near RTs) under the conditions of the various experiments. From left to right. (A) Experiment 1A: When both planning and execution are included in the RT measure, far shifts take 70 msec longer than near shifts. (B) Experiment 1B: Control for target positions used in Experiment 1A. Notice the null effect of target position alone. (C) Experiment 1C: Control for possible eye movements associated with Experiment 1A. Distance effect during overt attentional shifts in which subjects make full saccades. A distance effect is present, but is not larger than when subjects covertly shift attention in Experiment 1A, ruling out the possibility that occasional eye movements could have caused the effects in 1A. (D) Experiment 2A: Distance effect disappears when RTs measure only execution phase differences between far and near trials. (E) Experiment 2B: Control for target positions as used in 2A. Again, notice the null effect of target position alone for the task in Experiment 2A.

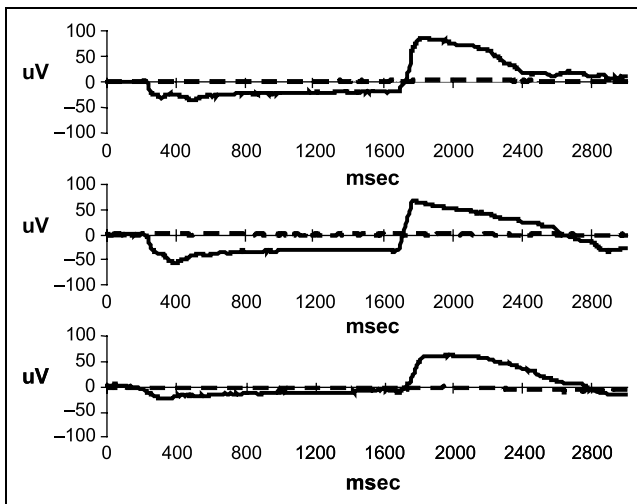


Figure 4. Left vertical EOG recordings for two representative subjects (*top, middle*) and for the grand average across all subjects (*bottom*). In each case, the – traces show the magnitude of deflections recorded from the full eye movements made in Experiment 1B. The almost flat – traces show the corresponding EOG recordings from Experiment 1A, indicating that there was little systematic eye movement in that experiment.

of movement path, instructions, and other features, except that subjects were instructed to make full *overt* saccades each time they moved their attention, rather than to covertly shift their attention. This had two purposes. First, it provided EOG calibration information necessary to obtain an upper estimate of the inadvertent eye movements in Experiment 1A. Second, it provided information as to how full eye movements, had they occurred, would have altered the distance effect observed in Experiment 1A.

In this overt shifting task, we found that RTs during full eye movements were still longer for far than for near shifts (55 msec, $t = 4.71$, $p = .0008$) (Figure 3C); however, this distance effect did not significantly differ from (and tended to be slightly smaller than) the effect for covert shifting ($t = 1.2$, $p = .26$; compare Figure 3C with Figure 3A). In addition, the relative magnitude of the EOG tracings for these full saccades (red trace, Figure 4) indicates how very little the subjects moved their eyes in Experiment 1A when they were only supposed to covertly move their attention (blue trace, Figure 4). Moreover, this experiment argues against the possibility that actual eye movements had such large near–far differences that a few inadvertent eye movements in Experiment 1A could have averaged in and produced the 70-msec average distance effect observed there. That is, if eye movements were the cause of the distance effect, then occasional eye movements in Experiment 1A would have resulted in a distance effect that was only a small fraction of the distance effect observed in Experiment 1C. However, the distance effect, if anything, tended to be slightly larger during the covert orienting experiment (1A) than during the

overt orienting experiment (1C), confirming that eye movements do not play a noticeable role in the covert-attention distance effect.

Experiment 2A: Preplanning Effects

Experiment 1A and its companion controls (Experiments 1B and 1C) provided strong evidence for a distance effect on the time taken to complete covert shifts of spatial attention. However, because subjects had to both “plan” and “execute” the movement of attention during the RT period in Experiment 1A, this distance effect may have occurred in either the planning or execution stage, under the hypothesis that such stages exist and occur discretely and at least partially sequentially. In several well-designed studies that did not find a distance effect, particularly in the work by Sperling and Weichselgartner (1995), subjects had foreknowledge of the final target position, perhaps thereby allowing subjects to completely “preplan” attentional shifts before the RT period even began. If the distance effect observed in Experiment 1A occurred entirely during this kind of planning stage, then no distance effect would be expected in cases where planning can be accomplished before the RT period begins. To explicitly investigate this possibility, we performed Experiment 2A, which differed from Experiment 1A specifically in that subjects could now “preplan” the attention shifts.

The same stimulus layout from Experiments 1A–1C was used. This time, however, the first cue (at the center position) cued attention to one of the four lower (lateral and bottom) boxes. At the cued location, 1500 msec after the initial central cue, a difficult go/no-go discrimination instructed subjects when/if they should move attention up to the top box on the attended side. At the top box thus cued, subjects performed the same A/H discrimination used in Experiments 1A–1C (Figure 2). The RT period began with the go/no-go stimulus and continued until subjects completed the trial. As in Experiment 1A, at the time of the second cue that occurred at the covertly attended lower box, stimuli would occur at all the boxes simultaneously to preclude any exogenous drawing of attention by an isolated stimulus.

In this experiment, since the first cue provided the information necessary to predict the final target location (i.e., whether it would be the upper left or the upper right box), subjects would now have the opportunity to preplan the movement of attention. However, because the difficult go/no-go stimulus at the first cued position was titrated to require heavy attentional resources, subjects were not able execute that shift until processing the go/no-go stimulus.

The key result from Experiment 2A was that, with preplanning now possible, shift distance did not affect RTs (far = 861 msec, near = 855 msec, far minus near = 6 msec, $SE = 14$ msec, $t = 0.49$, $p = .93$) (see Figure 3D).

Thus, the execution phase alone does not appear to be dependent on distance.

Experiment 2B: Control for Target Position

As with Experiments 1A–1C, subjects from Experiment 2 also participated in control runs to verify that the target positions used for near and far trials did not differentially affect RTs on those trials. Subjects were again cued from the center directly to each of the four lower/lateral boxes, where they made a button press for “go” stimuli and no button press on “no-go” stimuli. The results of this control verified that the go/no-go discrimination itself took equally long to perform at lateral versus bottom positions ($t = 0.42$, $p = .65$) (see Figure 3E). Thus, target position itself was again not a factor affecting the far versus near RTs in Experiment 2A.

DISCUSSION

The principal result drawn from these data is that the time taken to shift visual spatial attention is dependent on shift distance when subjects plan and execute shifts during the RT period, but this distance dependency disappears when subjects are given the information that enables them to plan the shift of attention ahead of time. These results provide evidence for two distinct stages of covert shifts in visual spatial attention: a planning stage, the duration of which depends on the distance to be shifted, and an execution stage, the duration of which is independent of shift distance.

This dissociation not only explains why we observed a distance effect in Experiment 1A that was eliminated in Experiment 2A, but may additionally be useful as it offers a possible means of resolving some of the otherwise contradictory findings in the literature regarding the distance-dependency of attentional shifts.² For example, studies by Egly and Homa (1991), Rizzolatti et al. (1987), Tsal (1983), and Schulman et al. (1979) involved experiments that appear to have included planning effects in the RT measures. In each of these studies, subjects were cued to one position, but then were given targets at that position as well as at other unexpected positions at varying distances away. Because shifts of attention to those unexpected locations required subjects to plan shifts “on the fly” during the RT period, planning effects would have been included in the RT data for these experiments. As would be predicted by our model, these articles did find a distance effect.

In various other studies that did not find a distance effect, there would appear to have been an opportunity for subjects to “preplan” the shifts of attention, as we explicitly designed to be true in our Experiment 2A. This is immediately clear in Sperling and Weichselgartner (1995), as all shifts were made from a static peripheral location (where the cue was embedded in a rapid visual

stream) to a position at fixation, and thus subjects always knew where the final target position would be, although they could not execute the shift until cued. Thus, planning effects would not have been present in the RT data because planning would have been completed before the move cue was ever given.

Two additional studies, those by Kwak et al. (1991) and Sagi and Julesz (1985), also did not find a distance effect. In these studies, subjects were required to make a same/different judgment of two letters presented simultaneously, equidistant from fixation. As noted by Sagi and Julesz (1985), however, in their task “the *locations* of the [two] targets might be detected in parallel, thus enabling fast inertia-free shifts of attention between locations.” This would be consistent with our model in that if targets are detected in parallel, there may be sufficient opportunity to plan the shift to the second target while still processing the first, and thus the distance to the second target would not matter.

In addition to helping to understand the distance effect and perhaps even why past studies may have come to different conclusions about its existence, our results suggest that these two stages underlying attentional shifting—that is, planning and execution—are at least partly serial and separable processes within the context of a single attentional shift. Our findings support a model of planning that may first involve “finding” the coordinates of the next target in some neural representation of (visual) space. These coordinates could then be acted upon or transferred to an executing system that selectively enhances processing at the found coordinates, thereby constituting a shift of attention to that location. In the context of the present study, this dissociation of planning and execution allows that attentional movements can be planned at one point in time but delayed in their execution for an arbitrary length of time, just as movements of the eyes can be planned separately from execution (e.g., Schall, 2001). Thus, additional neural activity beyond that involved with planning/finding the target coordinates seems likely to be necessary to implement (or at the very least, trigger) the actual execution of the attentional shift once planned. This could suggest that planning and execution processes might have at least partly unique neural underpinnings, although additional information, particularly from neuroimaging, will be necessary to further explore this question.

Our findings of a distance effect that is contingent on subject foreknowledge may be akin to those by Cooper and Shepard (1984), who studied the mental rotation of visuospatial objects. In one set of experiments, they found that the time taken to mentally rotate an object is a linear function of the angle by which it is rotated. However, in a separate series of experiments using a sequential matching task, they found that when subjects had preparation time and foreknowledge of the orientation of a target image, the time it took for them to

determine whether it matched an earlier image did not depend on how far they had to rotate the two to match. In that sense, it was a different sort of “preplanning” (one immediately attributable to mental imagery) that eliminated the rotational “distance” effect in that study. Although this is not strictly analogous to the attentional “preplanning” in our study, the parallel nature of these results may suggest a connection between the underlying processes studied in both that work and our own.

Additionally, our finding that it is the planning stage that takes longer for shifts of a greater distance may also be useful in proposing a theoretical mechanism underlying the planning of attentional shifts and the neural representations that produce them. Although it is not yet clear why shifts of a longer distance take longer to plan, one possible explanation is that planning may involve the stepwise progression of activity in adjacent neural populations that represent adjacent parts of the visual field. That is, in some topographically organized neural representation, a search must make its way from a starting position, through the intermediate zones, until it reaches the target position. As the planning of larger shifts would require neural activity to cascade through more of these adjacent regions, planning would take longer to complete for larger shifts. Whereas at this point such a model is best viewed as a working hypothesis, similar theories positing that neural planning or control of limb movements is based on the association between adjacent stages-of-movement/parts-of-space have been hypothesized at least since the time of James (1890), and perhaps have an imagery-related rotational analog in the findings of Cooper and Shepard (1984). It also remains to be determined whether this distance dependency in the time taken for neural activity to arrive at target locations in a topographically arranged map is a generalizable feature of such maps, which appear to be ubiquitous in the brain.

Although the dissociation of planning and execution has not yet been well studied in covert orienting, a similar dissociation is more commonly considered in saccade research. The brainstem saccade generating network, for example, is thought to require two conjoint inputs: one signaling the direction and amplitude of an upcoming movement and another signaling the initiation of that movement (e.g., see Schall, 2001), which corresponds roughly to the output from a planning system and an execution system, respectively. Given the hypothesis that the planning of eye movements is closely related to the shifting of attention (e.g., Gitelman, Parrish, Labar, & Mesulam, 2000; Nobre, Gitelman, Dias, & Mesulam, 2000; Corbetta, 1998; Sheliga, Riggio, & Rizzolatti, 1994, also see Rizzolatti et al., 1987, for a particularly relevant premotor theory of attentional shifting related to saccade programming), areas with connectivity to the superior colliculus and/or demonstrated roles in attentional orienting may be prime candidates for involvement in these planning and exe-

cutio processes. Such areas include the frontal eye field (FEF; e.g., Schall, 2002), supplementary eye field (e.g., Olson, Gettner, Ventura, Carta, & Kass, 2000), and lateral intraparietal sulcus (LIP; e.g., Hamed & Duhamel, 2002). Among these, FEF and LIP are known to play an important role in covert orienting and are highly interconnected (e.g., Ferraina, Pare, & Wurtz, 2002). Within the FEF, electrical stimulation in topographically selective areas is known to produce attention-like effects at corresponding locations in the visual field (Moore & Fallah, 2001). Moreover, the FEF also appears to have separate neural populations for target selection and saccade execution (Schall, 2002), which could correspond, respectively, to neural populations involved with the “planning” and “execution” phases of attentional shifts.

In humans, functional magnetic resonance imaging studies of attentional orienting have identified a frontoparietal network, along with other brain regions involved in attentional orienting (reviewed in Corbetta & Shulman, 2002). In this work, concordant with single-unit studies, the FEF and regions on or near the intraparietal sulcus have frequently been implicated in attentional shifting. To date, however, these studies have mainly isolated activity triggered by endogenous cues in cued-attention paradigms, which would be expected to include processing activity related to “attentional orienting” as a whole. The present results suggest that it may be possible, using event-related neuroimaging, to dissociate these broader attention control networks into distinct subnetworks, including those that plan attentional shifts, those that execute them, and those that maintain deployed attention and bias sensory cortices for enhanced processing of stimuli. In addition, future studies using event-related potential and magnetoencephalography may also have the potential to distinguish planning and execution processes based on their timing, as planning must happen before execution, and planning activity can also be distinguished by the distance dependence of its duration, as demonstrated here.

Conclusions

These findings support a model of attentional shifting in which (a) shifts have dissociable planning and execution stages and (b) shift distance affects the duration of only the planning stage. This suggests a mechanism with separate and, at least partly, serial planning and execution processes, wherein the planning process may require neural activation to shift through adjacent neural zones representing adjacent parts of space, thereby taking longer to complete the planning for shifts over a greater distance. In the future, additional experiments that control when subjects plan versus execute shifts of attention can be used to dissociate the broader network of areas known to be related to “attentional control”

into more specific subunits corresponding to these stages of the attentional shifting process.

METHODS

Experiment 1A: Distance Dependency

Eleven subjects (5 men, 6 women, age 18–40, all right-handed) participated in Experiments 1A and the associated control Experiments 1B and 1C. Figure 1A shows the stimulus configuration. These stimuli were presented on a CRT, with subjects seated 40 cm from the screen. At this distance, the center of each box in the perimeter was 6.6° from the center, with each box subtending $1.8^\circ \times 1.8^\circ$ square. Figure 1B illustrates the attentional paths formed by the far (orange arrows) and near (yellow arrows) covert movements of attention during the experiment. Each trial began with a first cue presented at fixation, which instructed subjects to covertly shift their attention to either the left or right upper box. After a 1500-msec delay, a second cue was presented at the cued upper box position. This cue pointed to either a bottom (“far”) or lateral (“near”) box on the presently cued side (left or right, as already determined by the first cue), thereby instructing subjects to make a second covert shift of attention. At the location thus cued, subjects performed an “A” versus “H” discrimination and responded by pushing one of two buttons with their right hand. Concurrent with the second cue arrow (at a top left or top right position), all the other target boxes were filled with a random assortment of “A” and “H” stimuli. The simultaneous presentation of these irrelevant target stimuli in the other boxes was used to avoid any differential influence of reflexive/exogenous attention for each trial type.

The trial sequence is illustrated in Figure 1C. All trial types (near/far, left/right, A/H) were randomized by a no-replace, first-order counterbalancing algorithm. In all experiments, subjects were instructed and trained to make their responses as quickly as possible while maintaining an accuracy of roughly 90%. To ensure that the “A” versus “H” discrimination required full attentional focus, the discrimination difficulty was titrated for each subject during a pilot session by altering the contrast, sharpness, and shape of the stimuli. The boxes themselves remained on screen at all times. Notice that for any “first cue” to the left or right, the “second cue” could instruct subjects to make a near move (to lateral boxes) or a far move (to bottom boxes) (see Figure 1B), with far movements subtending a visual angle of 4.7° greater than that of near movements. Trials were rejected from analysis in all experiments if they were incorrectly answered or if responses were more than 2 *SD* from the mean RT for that subject. EOG recordings of left vertical, right vertical, and horizontal eye movements (collected continuously at 250 Hz, with a low pass of 50 Hz, high pass of 0.05 Hz, and a gain of 500) were

also made during these sessions to monitor any inadvertent eye movement and for later comparison to overt orienting (see below). These EOG data were also used to reject from behavioral analysis any trial during which a blink or pronounced eye movement may have occurred. Video monitoring was also used continuously throughout the experiment to help ensure that subjects were maintaining fixation.

Experiment 1B: Control for Target Position

Subjects participating in Experiment 1A also participated in two control experiments during the same session (1B and 1C). The first of these was run to ensure that discriminations at the “near” and “far” box positions did not differ based merely on their positions, despite the fact that they were of equally eccentric from fixation. The same stimulus layout from Experiment 1A above was used. However, a single cue was presented at the central position, pointing directly toward one of the four lower boxes. Simultaneously, A/H stimuli were presented at all noncentral positions. Subjects were instructed to shift their attention directly to the location indicated by this cue to perform an A/H discrimination at the cued location, responding by pressing one of two buttons with the right hand. Again, trials that occurred during blinks or eye movements, along with incorrect or outlying responses were rejected from the analysis.

Experiment 1C: Control for Possible Eye Movement

An additional control was run to determine the effects, if any, of possible eye movements made during Experiment 1A. This was done by repeating the stimulus sequence used in Experiment 1A, but instructing subjects to make full overt saccades for each shift of attention. EOG data from Experiment 1C were also used for selective rejection of behavioral data. For Experiments 1A and 1B, any trials with large eye movements or blinks were removed by rejecting all trials with values that were 110 μV above or below baseline, using epochs baselined by the mean value for 100 msec before each trial began. These data allowed us to determine the magnitude of EOG deflection corresponding to eye movements of known magnitude, yielding a scaling factor that allowed us to estimate in degrees the amount of eye movement that was present in EOG data from Experiments 1A and 1B. Although it would be ideal to use this information to reject any trial with more than a given amount of eye movement, the noise on individual trials makes this unfeasible. Instead, we removed from analysis any trials with any EOG channel exceeding a value of 110 μV (positive or negative) to eliminate trials with blinks and very large eye movements. Among the remaining trials, EOG data

from Experiment 1A indicated a very small ($<0.85^\circ$) amount of eye movement during that experiment.

Experiment 2A: Preplanning Effect

Twelve subjects (8 women, 4 men, age 18–40, right-handed) participated in Experiment 2A and its companion control for target position (2B). Again the same configuration of stimuli was used (Figure 1A), although the task differed. The first cue was presented at the center position with a duration of 100 msec, pointing this time to one of the four lower boxes. At the location thus cued, a difficult go/no-go discrimination was presented 1500 msec later. A diamond at the cued position indicated a “go” trial, while a circle indicated a “no-go” trial. On “no-go” trials, subjects did nothing and prepared for the next trial. On “go” trials, however, subjects were instructed to shift their attention upward to the “top” box on the same side of the screen. To ensure that this go/no-go discrimination was extremely demanding of attentional resources, these stimuli were adjusted in contrast and duration for each subject. Notice that in this experiment, subjects had information after the first cue about the position of a possible target (because targets were always in the top box on the same side to which the first-cue directed their attention), but had to delay the execution of the shift until completing the difficult discrimination at the cued lower position.

Experiment 2B: Control for Target Position

Subject participating in Experiment 2A also completed a control experiment (2B) in the same session. This control for target position as used in Experiment 2A again served to ensure that stimuli placed at the positions used for near shifts and far shifts did not require different amount of time to process simply by virtue of their positions. The design was similar to Experiment 1B, except this time, subjects were cued from the center position to shift their attention to one of the four lower boxes, where they performed a discrimination between the same “circles” and “diamonds” used at those positions in Experiment 2A. Responses were made to diamonds only (to remain comparable to the “go/no-go” task) by pressing a button with the right hand.

Acknowledgments

We thank Daniel Weissman and Ken Roberts for valuable comments and discussions. This work was supported by NIMH grants to M. G. W. (MH60415).

Reprint requests should be sent to Marty G. Woldorff, Center for Cognitive Neuroscience, Duke University, Box 90999, Room B203, LSRC Building, Durham, NC 27708-0999, USA, or via e-mail: woldorff@duke.edu.

Notes

1. Note that if the execution phase itself was dependent on distance, we would expect all of these studies to exhibit a distance effect in their RTs, which is clearly not the case in the literature.
2. This debate has frequently been characterized as one between “analog” and “digital” shifting models in the literature (see reviews by Egeth & Yantis, 1997; Egly & Homa, 1991; Yantis, 1988; Eriksen & Murphy, 1987). We do not use the *analog* and *digital* terminology here, however, as those terms may refer to models with properties that we do not wish to make claims about, such as whether the spotlight of attention “remains on” as it travels. Moreover, these terms become rather ambiguous at the mechanistic level, as *analog* movements could be achieved by a mechanism that appears to be very *digital* or vice versa.

REFERENCES

- Cooper, L. A., & Shepard, R. N. (1984). Turning something over in mind. *Scientific American*, *261*, 106–107.
- Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: Identical, independent, or overlapping neural systems? *Proceedings of the National Academy of Sciences, U.S.A.*, *95*, 831–838.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*, 201–215.
- Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology*, *48*, 269–297.
- Egly, R., & Homa, D. (1991). Reallocation of visual attention. *Human Perception and Performance*, *17*, 142–159.
- Eriksen, C. W., & Murphy, T. D. (1987). Movements of attentional focus across the visual field: A critical look at the evidence. *Perception & Psychophysics*, *42*, 299–305.
- Ferraina, S., Pare, M., & Wurtz, R. H. (2002). Comparison of cortico-cortical and cortico-collicular signals for the generation of saccadic eye movements. *Journal of Neurophysiology*, *87*, 845–858.
- Gitelman, D. R., Parrish, T. B., LaBar, K. S., & Mesulam, M. M. (2000). Real-time monitoring of eye movements using infrared video-oculography during functional magnetic resonance imaging of the frontal eye fields. *Neuroimage*, *11*, 58–65.
- Hamed, S. B., & Duhamel, S. R. (2002). Ocular fixation and visual acuity in the monkey lateral intraparietal area. *Experimental Brain Research*, *142*, 512–528.
- James, W. (1890). *The principles of psychology*. New York: Holt.
- Kwak, H., Dagenbach, D., & Egeth, H. (1991). Further evidence for a time-independent shift of the focus of attention. *Perception & Psychophysics*, *5*, 473–480.
- Moore, T., & Fallah, M. (2001). Control of eye movements and spatial attention. *Proceedings of the National Academy of Sciences, U.S.A.*, *98*, 1273–1276.
- Nobre, A. C., Gitelman, D. R., Dias, E. C., & Mesulam, M. M. (2000). Covert visual spatial orienting and saccades: Overlapping neural systems. *Neuroimage*, *11*, 210–216.
- Olson, C. R., Gettner, S. N., Ventura, V., Carta, R., & Kass, R. E. (2000). Neuronal activity in macaque supplementary eye field during planning of saccades in response to pattern and spatial cues. *Journal of Neurophysiology*, *84*, 1369–1384.

- Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *2*, 160–174.
- 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.
- Schall, J. D. (2001). Neural basis of deciding, choosing and acting. *Nature Reviews Neuroscience*, *2*, 33–42.
- Schall, J. D. (2002). The neural selection and control of saccades by the frontal eye field. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, *357*, 1073–1082.
- Schulman, G., Remington, R., & McLean, J. (1979). Moving attention through visual space. *Journal of Experimental Psychology*, *5*, 522–526.
- 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.
- Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology*, *17*, 551–560.
- Yantis, S. (1988). On analog movements of visual attention. *Perception & Psychophysics*, *43*, 203–206.