Attentional localization prior to simple and directed manual responses

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The relationship between attention and the programming of motor responses was investigated, using a paradigm in which the onsets of targets for movements were preceded by peripheral attentional cues. Simple (button release) and reaching manual responses were compared under conditions in which the subjects either made saccades toward the target location or refrained from making eye movements. The timing of the movement onset was used as the dependent measure for both simple and reaching manual responses. Eye movement latencies were also measured. A follow-up experiment measured the effect of the same peripheral cuing procedure on purely visual processes, using signal detection measures of visual sensitivity and response bias. The results of the first experiment showed that reaction time (RT) increased with the distance between the cued and the target locations. Stronger distance effects were observed when goal-directed responses were required, which suggests enhanced attentional localization of target positions under these conditions. The requirement to generate an eye movement response was found to delay simple manual RTs. However, mean reaching RTs were unaffected by the eye movement condition. Distance gradients on eye movement latencies were relatively shallow, as compared with those on goal-directed manual responses. The second experiment showed that the peripheral cue had only a very small effect on visual detection sensitivity in the absence of directed motor responses. It is concluded that cue-target distance effects with peripheral cues are modulated by the motor-programming requirements of the task. The effect of the peripheral cue on eye movement latencies was qualitatively different from that observed on manual RTs, indicating the existence of separate neural representations underlying both response types. At the same time, the interactions between response modalities are consistent with a supramodal representation of attentional space, within which different motor programs may interact.

Providing an advanced cue to a location in the visual field at which a visual stimulus is likely to appear causes a reduction in motor response times (RTs) to stimulus onsets. This effect is usually attributed to the operation of *spatial attention*, defined as the process through which we select one object or location in the visual field for enhanced sensory processing (perceptual attention) or as the target for a motor response (referred to here as motor programming¹). Previous studies have examined the effect of attentional cues on simple (buttonpress) manual RTs, as well as on the latencies of goal-directed saccadic eye movements (see, e.g., Crawford & Müller, 1992;

Hodgson & Müller, 1995; Kustov & Robinson, 1996; Posner, 1980; Posner & Cohen, 1984; Reuter-Lorenz & Fendrich, 1992; Walker, Findlay, & Kentridge, 1995). In this work, we extend previous findings by measuring the RTs of goal-directed hand movements under similar conditions. We also assess to what extent the effect of attentional cues on motor RTs is mediated by an effect on sensory or motor processing.

Two different procedures can be used to orient spatial attention to locations in the visual field. A *precue* may consist of a brief flash at the to-be-attended location in the periphery, known as a *peripheral cue*. Alternatively, a symbolic representation of the likely target position, such as an arrow or a digit, may be presented at a central location, referred to as a *central cue*. On most trials, the cue refers to the correct target location, but it can sometimes indicate a different location than that at which the target subsequently appears. For inaccurately cued targets (invalid trials), RTs are usually found to increase as the spatial distance between the cue and the target locations increases. This has been termed the *distance effect*

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(Downing & Pinker, 1985; Klein & McCormick, 1989; McCormick & Klein, 1990). As well as a distance effect, some results show an effect that is due to the relative direction of the cue and target, with targets appearing in the opposite direction to the cue relative to fixation producing increased RTs over and above the effect of cue-target distance. This is known as a *meridional effect* and appears to be most consistently observed with central cues and at longer temporal intervals (500+ msec) between the cue and the stimulus onsets (Hughes & Zimba, 1987; Reuter-Lorenz & Fendrich, 1992; Rizzolatti, Riggio, Dascola, & Umiltà, 1987).

It has been suggested that distance and meridional effects on simple manual RT reflect the preprogramming of oculomotor responses toward cued locations. Rizzolatti et al. (1987) propose that eye movement programs are generated to cued locations and have to be modified on invalid trials, even when an eye movement response is not required to the target onset. Meridional and distance effects reflect the time required to reprogram the direction and amplitude of a preprogrammed eye movement. However, it is possible that, as well as activating eye movement programs, orienting to attentional cues might also result in preparation for other forms of action. For example, Georgopoulos (Georgopoulos, Lurito, Retridges, Schwartz, & Massey, 1989) has described neural activity in the motor cortex of the monkey that reflects the internal reprogramming of arm movement direction when a response has to be executed toward a location some distance away from the position of a visual cue. A similar reprogramming of movements might also be apparent in distance effects on RTs when manual reaching responses are preceded by attentional cues. If this were the case, there should be a strong distance effect on manual reaching RT. This effect should be reduced in magnitude or absent with simple manual RT, as there would be no need to reprogram the parameters of the button-press response on invalid trials.

The effect of attentional cues on RTs may also show qualitative dissociations between different response modalities because of the different coordinate organizations of individual motor systems. For example, in the saccadic system, there is little evidence that eye movements are coded in discrete multidirectional channels above the level of the brain stem, and oculomotor centers are known to represent space within an oculocentric reference frame (Findlay & Harris, 1984; Goldberg, Bushell, & Bruce, 1986). In contrast, activity prior to arm movements in the motor and premotor cortices codes the direction of reaching movements independently of amplitude, and this code is thought to function within a body-centered reference frame (Georgopoulos, 1990). Consistent with these different spatial coordinate codes, previous work using peripheral attentional cues that has measured hand and eye responses in isolation has reported qualitative dissociations between results with simple manual RT and saccadic latencies, including differences in the magnitude of cue-target distance and meridional effects (Crawford & Müller, 1992; Hodgson &

Müller, 1995; Reuter-Lorenz & Fendrich, 1992). Here, we measure both hand and eye RTs to test whether dissociations exist between the effect of precues on the two response types, reflecting differences in the internal representations subserving these movements.

Despite the fact that the brain represents hand and eye movements within quite different coordinate systems, our subjective experience is of a coherent attentional space, suggesting that, at some level, there is a common spatial representation for the two response systems. Behavioral evidence also indicates that the hand and eye movement systems are closely linked. Hand and eye RTs have been shown to be closely correlated (Biguer, Jeanerrod, & Prablanc, 1982), whereas eye movement responses usually precede manual responses and appear to enhance the accuracy of reaching responses, even when visual feedback is removed (Abrams, Meyer, & Kornblum, 1990). At the same time, there appears to be little explicit neurophysiological evidence for the existence of a central attentional representation of space subserving both responses. Here, we examine how the simultaneous programming and execution of hand and eye responses interact with one another. For example, concurrent programming of an eye movement response may be expected to modulate distance and meridional effects or absolute manual RT, indicating that at some level the different motor programs interact.

Finally, *premotor* theories of covert perceptual attention suggest that manual and ocular response programming itself results in a benefit in visual perceptual sensitivity to the relevant spatial location. The present study does not directly test this hypothesis, although we acknowledge that it is plausible that precuing effects on motor RT, although associated with the requirement to generate a motor response, may be mediated through interactions between motor centers and visual perceptual sensitivity (i.e., visual perceptual attention). However, Experiment 2 describes the effect of attentional cues on visual sensitivity in the absence of directed motor responses. In this way, we determine to what extent the effect of peripheral cues in Experiment 1 can be attributed to the motor aspects of the task rather than to the purely perceptual effect of the cue.

EXPERIMENT 1

In Experiment 1, a peripheral cue was used to indicate the location at which a visual target was likely to appear. Goal-directed reaching responses were compared with simple manual responses, to investigate whether they differed in the pattern of distance and meridional effects on RTs. Both types of response were made under two conditions. In the first, the subjects were instructed to maintain ocular fixation on the central location throughout the experiment. In the second condition, the subjects were instructed to fixate the peripheral target stimulus at the same time as making a reaching or simple manual response. The effect of the cue on ocular latencies was also measured and compared with that observed on manual RTs.

Method

Subjects. Eight subjects took part in Experiment 1. Five subjects were male, 3 female. Their ages ranged from 19 to 32 years. All reported having normal or corrected-to-normal vision. All the subjects considered themselves predominantly right-handed and used their right hand for the manual response task.

Apparatus. The stimuli were displayed on an Acorn Archimedes 540 computer. The same computer was also used to measure manual response RTs and movement times via an array of seven response keys. The keys were arranged horizontally on an elongated keypad. This was positioned across the computer screen so that each response key was directly underneath each of seven possible cue/stimulus locations. The screen was marked out with seven dimly illuminated boxes on a dark background (luminance, approximately 0.05 cd/m^2). The boxes subtended 2° of visual angle on each side. One was positioned at the central location. The six other boxes were positioned horizontally at 3° , 6° , and 9° eccentricity to the left and right of fixation (Figure 1). A cue signal consisted of a brightening of one of the target boxes (cue luminance, approximately 15 cd/m^2). Target stimuli were luminance increment stimuli (size, 0.25° ; luminance, approximately 20 cd/m^2), which could appear at the center of one of the peripheral boxes. The subject sat approximately 50 cm away from the screen, which was arranged in such a way that the screen surface was angled toward the subject at 15° from the horizontal plane, so that arm movements could be freely made to press the target buttons. Experiments were carried out in a dimly illuminated room.

Eye movement measurement. Eye movements were monitored in all the subjects, using a Skalar-IRIS, infrared, limbus tracker device, configured to record the horizontal movements of both the left and the right eyes. The experimenter received a trial-by-trial display of the subject's eye movements via an Apple Macintosh Quadra 950 computer and could reject trials that contained inappropriate changes in fixation. Trials for which subjects made eye movement errors were rejected from the main analysis of manual RTs. Eye movement errors were classified as trials on which the subject either failed to fixate the target directly in the eye movement condition or made an inappropriate saccade in the no eye movement condition. The percentage of eye movement errors in each main condition was analyzed separately.

Analysis of the latency and amplitude of eye movements was carried out. Eye movement data from each one of 2,592 trials per subject was visualized individually in order to eliminate eye blink artifacts and to identify the start of the eye movement. The start of the saccade was defined as the first sample of a series of three for which the instantaneous velocity exceeded 30° per sec.

Procedure. A trial commenced with the presentation of a fixation point at the central location. Five hundred milliseconds later, a cue signal appeared for 80 msec at one of the peripheral locations. After a period of either 100 or 500 msec from the onset of the cue (the stimulus onset asynchrony, or SOA), the central fixation point was extinguished, and a small target stimulus appeared in the center of one of the marked locations in the periphery. The target remained illuminated until the subject executed the required manual response or until $1,000 \text{ msec}$ had elapsed. The next trial commenced $1,000 \text{ msec}$ after the end of the previous trial. On 56% of the trials, the cue could appear with equal probability at any of the six eccentric locations, and the target appeared at the cued location (valid trials). On 37% of the trials, the cue was invalid, and the target was equally likely to occur at any of the other target locations (invalid trials). Finally, on 7% of the trials, a cue was presented at the central location, and the target could appear with equal likelihood at any one of the eccentric locations (neutral trials). Each response and eye movement condition was run in a separate experimental session. During each session, the subject received four blocks of 324 trials, with the first block in each condition being a practice block (a total of 5,184 trials per subject). Four of the subjects completed the reaching response conditions first, whereas the other 4 commenced with the simple release response conditions. Within each response condition, the order in which the two eye movement conditions were completed was counterbalanced across subjects. The subjects were instructed to respond as quickly as possible to target onsets without making errors in which manual responses or eye movements were directed to the cue rather than to the target location.

Conditions. There were two different manual response conditions. In the *simple release* condition, the subjects started the trial with their index finger on the central key and were told to attend to the cue signal and to respond as quickly as possible to the peripheral target onset by releasing their finger from the central key. The dependent measure was the time between target onset and release of the central button (simple manual RT). In the *reaching response* condition, the subjects had to respond as quickly as possible to the target onset by moving their hand to press the peripheral response button just below the target location. The subjects were free to move their arm from the shoulder and elbow. They were instructed to position themselves so that they could easily move their hand to touch all the response buttons. Again, the dependent measure was the time between target onset and release of the central button (reaching RT).

Both simple release and reaching tasks were run under two eye movement conditions. In the *eye movements to target* condition, the subjects were required to make an eye movement to the target when it appeared in the periphery. Any trials on which an eye movement

Figure 1. Schematic representation of the task in Experiment 1, showing an example of an invalid trial in which the cue and target appeared at different locations (cue and target were separated in time by the stimulus onset asynchrony period). Response keys were positioned directly underneath the seven marked locations.

was not executed or on which the subjects fixated the cue signal were rejected on line. The subjects were instructed to only make eye movements and to keep head movements to a minimum. In the *no eye movements to target* condition, the subjects were required to maintain fixation at the central location throughout the procedure. Any break in fixation during the trial resulted in the trial being rejected.

Eccentricity correction. We found that there was a strongly significant increase in manual RT with the eccentricity of the target stimulus. The analysis of high-level effects, such as distance and meridional effects, required the removal of this effect of target eccentricity on RTs. The procedure used to achieve this for each response, eye movement condition, and subject was as follows.

The mean RT on neutral trials was calculated across target eccentricities ($RT(\text{neutral mean})_{\text{all targets}}$). The mean RT on neutrally cued trials was then calculated for each of the six target positions individually ($RT(\text{neutral mean})_{\text{target-x}}$). The former value was then subtracted from the latter values to give six correction factors in milliseconds, corresponding to the six target locations. This procedure is summarized in the equation for the correction factor for target location x , below:

$$\text{Correction factor}_{\text{target-x}} = RT(\text{neutral mean})_{\text{target-x}} - RT(\text{neutral mean})_{\text{all targets}}$$

The procedure was repeated for each condition (SOA, manual and saccadic response type) and for each subject. The relevant correction factors were then subtracted from the uncorrected data, which were then examined according to cue–target distance and meridional direction in the analyses below. Neutral trials were used as the basis for this eccentricity correction, as it was assumed that these represented a *neutral attention* condition. Analysis of the RT data in this experiment showed that there was no increase in the effect of eccentricity in this condition, relative to the valid and invalid cue conditions.

The uncorrected raw manual RT data for each cue and target location are presented in the Appendix. The target eccentricity cor-

rection made little difference to the higher level analysis of the results. Significant cue–target distance effects (Figure 3) are only found in the same direction as the cue when eccentricity effects are removed. However, when the effect of eccentricity is not corrected for, distance effects are present in the opposite as well as the same direction as the cue, because of an increase in mean target eccentricity in the larger cue–target distance conditions.

Results

Subject errors. Manual response errors, in which the subject anticipated the target onset (defined as a manual RT of less than 150 msec) or failed to press the correct response key, occurred on 2.7% of all the trials. Analysis showed no significant variation in error rates between conditions.

Interaction between hand and eye movement conditions. A significant interaction was found between the eye movement and manual response conditions [response $\times$ condition, $F(1,7) = 12.085, p < .02$]. Simple release responses without eye movements were found to be fastest overall, whereas the condition in which an eye movement was also required showed the longest RTs. In contrast, there was no significant difference in the RT of reaching responses with and without concurrent eye movements to the target stimulus (Figure 2).

Cue–target distance effects. The eccentricity-corrected RT data were examined in terms of the spatial distance between the cue and the target. Trials were grouped according to cue–target distance from 0° (valid trials) to 18° . A four-way analysis of variance (ANOVA) was carried out, with response type, eye movement con-

Figure 2. Intersubject mean and standard errors of response time for reaching and simple release responses under conditions during which either no eye movements were permitted or eye movements were required to the target (Experiment 1).

dition, SOA, and cue–target distance as factors. As expected, the analysis showed a main effect of the distance between the cue and the target. RTs increased as a function of the distance between the cued location and the target location [$F(6,42) = 22.54, p < .001$]. Furthermore, the results also showed a three-way interaction between distance, type of response, and eye movement condition [$F(6,42) = 1.80, p < .02$]. Distance gradients were reduced for simple release RTs without saccades to the target, when compared with all other response and eye movement conditions (Figure 3). Cue–target distance was also found to interact with SOA, with stronger gradient effects at the longest SOA period [$F(6,42) = 3.27, p < .01$].

Meridional effects. The eccentricity-corrected RT data were examined in terms of the relative direction of the cue and target positions relative to the central location. Trials were grouped according to whether the cue and the target appeared in the *same* direction or in *opposite* directions, relative to fixation. In order to avoid confounding cue–target distance and meridional effects, only trials with a cue–target separation of 6 deg were used in this

analysis. A four-way ANOVA was carried out, with response type, eye movement condition, SOA, and relative cue–target direction (same vs. opposite) as factors. The analysis revealed a significant two-way interaction between SOA and meridional effects [$F(1,7) = 8.85, p < .02$]. Significant meridional effects were only present at the longest SOA period (100-msec SOA: same, 385 ± 12 msec; opposite, 384 ± 10 msec; 500-msec SOA: same, 335 ± 14 msec; opposite, 358 ± 16 msec). Finally, the analysis showed a marginally significant interaction between the type of manual response and the effect of SOA on meridional effects [$F(1,7) = 4.07, p < .1$], consistent with the possibility that manual response preparation may modulate meridional effects.

Eye movement responses. Eye movements were monitored on each trial between the onset of the fixation point and the offset of the target stimulus. Errors in fixation, in which the subject fixated either the cue or the target in the no eye movement condition or either failed to fixate the target or fixated the cue in the eye movement condition, accounted for 1.9% of all the trials. There was no significant variation in error rates between conditions.

Figure 3. Intersubject mean and standard errors of manual response times (RTs) and saccadic latencies against cue–target distance (Experiment 1). Results for reaching and simple release manual responses are shown for each eye movement condition (no eye movements to target/eye movements to target). The mean RTs for neutral trials in each condition are indicated by the horizontal lines running across each of the cue–target distance curves. All values are corrected for the effect of target eccentricity on RTs.

Trials on which an error occurred were excluded from further analysis. An analysis of the gain of saccadic eye movements in all the conditions produced no significant variation in gain with either cue position or the manual response condition. When trials were compared on which the cue was near or far to fixation relative to the target location, no variation in gain was found [$F(1,8) = 0.94$; cue near, 0.82; cue far, 0.88]. This demonstrates that the subjects were not making a high proportion of eye movements directed toward the cue; nor was there any strong spatial averaging of the ocular response between the cued and the target locations.

We also analyzed the latency of saccadic responses under each condition. Unlike the manual responses, we found only a very weak effect of cue–target distance on mean saccadic latencies, which was most apparent at the longest SOA period [$F(6,42) = 2.41, p < .05$]. The type of manual response to be executed concurrently with the eye movement did not affect the shallow distance gradients observed with eye movements (Figure 3). However, the manual response condition was found to have an effect on meridional costs (response $\times$ side interaction, $F(1,7) = 13.60, p < .01$). A meridional effect was observed on eye movements under simple release response conditions. However, when a reaching response was to be executed, eye responses showed a reverse meridional effect (release: same, 231 ± 14 ; opposite, 247 ± 15 ; reach: same, 235 ± 13 ; opposite, 227 ± 13).

Finally, simple regression analysis was carried out for manual and saccadic RTs for each subject in each manual response condition. Saccadic latencies were found to be significantly correlated with manual RTs for all subjects under all conditions. Eye movement latencies were found to almost invariably precede completion of the manual response. No significant variation in the strength of the correlation was found between the two manual response conditions (mean R coefficients across subjects for reaching, $.59 \pm .05$, and for release, $.52 \pm .06$).

Discussion

Experiment 1 tested the hypothesis that distance and meridional effects are modulated by the motor-programming requirements of the task. Another issue was the effect of concurrent eye movement responses on manual RTs. The discussion deals with these issues in turn.

Cue–target distance gradients. All the conditions in which a directed motor response was required showed strong gradients of manual RT against cue–target distance (Figure 3). The only condition that did not show this effect was the one in which only a simple manual response was required. This finding indicates that distance effects with peripheral cues are modulated by the programming of goal-directed motor responses. A simple response does not depend on the location of the target and, therefore, does not have to be reprogrammed on invalid trials. Another way of viewing these cue–target distance gradients is that they reflect differing resolutions of spatial attentional localization associated with different motor re-

sponses. Directed responses require more enhanced target localization relative to the nondirected buttonpress manual response, which simply require the target onset to be detected and not localized. This enhanced localization can be viewed as integral to the programming of a directed motor response. The finding is also consistent with the existence of *action-centered* representations, the characteristics of which are dependent on the demands imposed by the particular task being performed (see, e.g., Tipper, Lortie, & Baylis, 1992).

Interestingly, when a saccadic response to the target was combined with a simple response, there was a strong distance effect on simple manual RT. This cuing effect was much stronger than that found for eye latencies in the same condition. This shows that the gradient effect on simple manual RT was not simply a result of the subjects waiting for the eye movement response to be completed before initiating the manual response. Nor does this distance effect only represent the time to program and reprogram a saccadic response. Instead, the requirement to generate an eye movement causes enhanced localization within representations underlying manual response initiation.

Meridional effects. Previous studies have failed to find strong meridional effects on manual RT with peripheral cues (Hodgson & Müller, 1995; Reuter-Lorenz & Fendrich, 1992; Umiltà, Riggio, Dascola, & Rizzolatti, 1991). In this study, meridional effects on both types of manual response were not significant at short SOAs. However, at longer SOAs, a significant meridional effect was found on manual RTs. Umiltà et al. have proposed that the lack of meridional effects normally observed with peripheral cues is due to an increased inhibition of nontarget locations within the ipsilateral, relative to the contralateral, hemifield. This is consistent with the responses observed in superficial layer cells of the superior colliculus, part of the saccadic eye movement system, when saccades to visual stimuli are prevented (Rizzolatti, Carmada, Grupp, & Pisa, 1974; Wurtz, Richmond, & Judge, 1980). However, the time course of the inhibitory component of peripheral cues (i.e., inhibition of return) would predict that meridional effects should actually be greater at shorter than at longer SOAs (Posner & Cohen, 1984). Instead, the results suggest that the meridional effect on manual response RT at longer SOAs is due to the build up of slow-acting *endogenous* attention, which is thought to subserve orienting to central precues. Central cues are known to produce large meridional effects on RTs independent of the type of motor response to be executed to target onsets (Hodgson & Müller, in press; Reuter-Lorenz & Fendrich, 1992).

Interactions between hand and eye movement responses. Experiment 1 produced an interesting interaction between eye movement responses and the RT of manual responses. Simple manual responses with accompanying eye movements to the target showed longer RTs than did simple manual responses without eye movements (Figure 2). In contrast, reaching response RTs showed an in-

significant reduction under conditions in which an eye movement was also made. It is interesting to note that simple manual responses required the finger to be released from a button located at the central location. One possibility is that preparing an eye movement to the periphery results in an inhibitory effect on spatially incompatible manual responses. The simple manual response might be considered to be a manual response directed toward the central location and may be inhibited by the requirement to generate an eye movement to the periphery. In contrast, manual responses directed to the same location as the eye movement are unaffected or even facilitated by the ocular response. Interestingly, eye latencies also showed a trend toward faster latencies when a reaching response was to be executed at the same time.

These interactions between responses are also consistent with the existence of a processing *bottleneck* and the extra demands imposed by the dual task of an ocular and a manual response (see, e.g., H. Pashler, 1994; P. Pashler, Carrier, & Hoffman, 1993). According to this account, the eye and hand responses are less likely to interfere with each other if they are directed to the same location in space. Responses to the same location may be grouped together or programmed holistically. This spatially organized interference effect implies the existence of a common spatial representation within which spatially incompatible motor programs may interact with one another.

A contrasting explanation for the effect would be that the subjects adopted a strategy of waiting for the completion of the eye movement before initiating the manual response. However, such an account does not explain why the concurrent execution of an eye movement had no significant effect on reaching manual RTs. The crucial factor producing the increase in manual RT seems to be spatial incompatibility between the ocular and the manual response. The interaction between saccadic eye movements and simple manual response RTs constitutes a spatial compatibility effect, implicating the existence of a shared representation of hand and eye space (for reports of similar interactions between hand and eye responses, see Bekkering, Adam, Vandenaarssen, Kingma, & Whiting, 1995; Frens & Erkelens, 1991; Mather & Fisk, 1985).

Saccadic responses. Analysis of the subjects' eye movement behavior showed that saccadic latencies and manual RTs were strongly positively correlated for both manual response conditions. The type of manual response to be executed was also found to influence the magnitude of meridional effects on saccadic latencies, with significant meridional effects on eye latencies observed when a simple manual response was to be executed but not when a concurrent reaching response was required. As with the interactions discussed above, these effects are consistent with the existence of a supramodal attentional representation within which motor programs from different response modalities interact.

The effects of the cue on manual and saccadic responses were found to be qualitatively different, with much shallower gradient effects observed for eye movement latencies. Together with the other findings, this suggests that representations specific to individual response systems, as well as more central mechanisms that integrate information from different modalities, both contribute to the effect of peripheral precues on motor RTs.

EXPERIMENT 2

The main findings of Experiment 1 were that cuing effects on manual RT were affected by the type of motor response (simple, reaching, with and without eye movements) to be executed at target onset. The results indicate that the effect of the cue on RTs is affected by the preparation of both manual and saccadic responses.

However, the results are also consistent with a slightly different account. Rather than reflecting motor preparation or motor attention, the distance and meridional effects observed in Experiment 1 may be due to the operation of visual perceptual attention—that is, an effect of the precue on the process of detecting the target onset. The simple manual response condition in Experiment 1 may be a special case in which subjects adopt a less conservative criterion for detecting target onsets and initiating responses—that is, there may be a tendency for subjects to anticipate target onsets in the simple manual response condition. This in itself would be expected to produce shallower distance effects on RT. Experiment 2 was designed to determine whether a peripheral precue affects visual detection performance in a manner similar to the effect of the cue on goal-directed manual RTs. If the effects of cue–target distance and relative direction on manual RTs are exclusively associated with advanced motor programming, they should not be observed on visual detection performance in the absence of an overt motor response.

Another aim of Experiment 2 was to investigate the effect of the central flash that was used as a neutral, uninformative cue in Experiment 1. This was chosen as the baseline condition, so that any prewarning or diffuse effect of the cue onset on visual and motor processes was identical for valid, neutral, and invalid trials. However, it is possible that this type of cue may have had an attentional *engagement* effect, causing visual attention to be focused on the central location, which resulted in an increase in RTs overall on neutral trials (see Gawryszewski, Riggio, Rizzolatti, & Umiltà, 1987). In Experiment 2, a new condition was introduced in which no cue was presented before a judgment had to be made about the presence or absence of a luminance increment target. All the trials were preceded by the presentation of an auditory warning signal to indicate to the subjects when the trial was about to start. Any differences observed in visual sensitivity between the central flash, neutral condition and the no cue con-

dition are likely to reflect the operation of the engagement of perceptual attention.

Method

Subjects. Six subjects (3 male, 3 female), between 19 and 31 years of age, participated in the experiment. Four of the subjects had previously taken part in Experiment 1. All had normal or corrected-to-normal vision.

Display. The display parameters (target location layout, target/cue size, cue luminance, background luminance, etc.) were identical to those used in Experiment 1 (see Figure 1), except that no response keys were presented below the display. The stimuli were displayed on a 24-bit color, 75-Hz, 16-in. monitor, controlled by a Macintosh 950 computer, which was positioned in the normal vertical orientation directly in front of the subject. The target luminance was adjusted by the experimenter so that it was approximately at threshold level (75%) for each subject. Target luminances ranged from 0.1 cd/m² to 0.2 cd/m² across the 6 subjects.

Procedure. A peripheral precue referred to the likely location at which the subjects were to be required to make a judgment as to the presence or absence of a target probe stimulus. The probability of occurrence of valid, neutral, and invalid trials was identical to that in Experiment 1, except that an additional no cue condition was added, equal in probability to the neutral trial condition (central flash cue). This no cue condition was included in order to assess whether visual detection performance in the neutral condition was affected by the presentation of the central flash prior to target onsets. The cue indicated to the subjects the location at which they were most likely to be asked to make a judgment as to the presence or absence of a visual target stimulus (Hawkins, Shafto, & Richardson, 1988). They were told to allocate attention to the location of the peripheral flash cue, but to maintain ocular fixation at the central location throughout the experiment. Each trial commenced with an auditory warning signal, followed 500 msec later by the presentation of the peripheral cue (80-msec duration). This was followed by an SOA period of either 100 or 500 msec, after which a target stimulus was presented in the center of one of the marked locations for 50 msec. After target offset, a masking stimulus (consisting of seven gray squares superimposed on the seven marked locations) was immediately presented, obscuring all the possible target locations. After a period of 850 msec, an arrow stimulus appeared above the location at which the subject was required to make a judgment as to whether a target was present or absent (the probed location). At the same time, a response template appeared beneath the stimulus array, and the subjects indicated their chosen response with a mouse movement. A target stimulus was present at the probed location on 50% of the trials, with no target being present on the remaining 50% of the trials. The subjects could respond with one of four possible responses: *certain absent*, *absent*, *present*, or *certain present*. The trials were presented in blocks of 372, with 32 blocks for each subject, giving a total of 11,904 trials per subject. In addition, the threshold (75% correct) target stimulus luminance was determined for each subject in several practice blocks of 240 trials, in which no cue stimulus was presented on each trial. After each practice block, the subject's overall performance was measured in terms of percent correct, and the target luminance was adjusted accordingly on the next block until performance stabilized at approximately 75% correct. The number of practice blocks required before the subjects reached stable performance ranged from 1 to 3 blocks.

Results

Detection sensitivity. Visual detection sensitivity was measured using the P_a sensitivity parameter, denoting the area under the receiver-operating characteristic (ROC) curve. This was calculated using the maximum-likelihood

approach developed by Dorfman and Alf (1969). P_a values are superior to the more commonly used d' measure, as they do not rely on assumptions about the normality and variance homogeneity of the underlying noise and signal-plus-noise distributions. P_a values also fall within a range of 0.5 (no sensitivity) to 1 (maximum sensitivity), making them a more illustrative measure of detection sensitivity.

P_a values were calculated for each subject and each SOA, cue, and target condition. The data were analyzed, using a three-way ANOVA with SOA (100/500 msec), cue location (six locations plus neutral), and target location (six locations) as factors. Overall, there was no reliable main effect of SOA [$F(1,5) = 3.83, p > .1$]. There was a significant effect of target location on sensitivity [$F(5,25) = 11.074, p < .0001$]. This took the form of a decrease in detection sensitivity as target eccentricity increased. There was also a significant interaction between the effect of cue and target eccentricity [$F(30,150) = 2.36, p < .0005$], indicating that the peripheral precue influenced visual detection sensitivity.

Two more analyses were carried out on the P_a data, with the effect of target location on detection sensitivity being subtracted from the data, using an identical method to that used to correct for the effect of target eccentricity in the RT data in Experiment 1. This correction was based on the effect of target eccentricity on detection sensitivity for neutral trials, in which a flash cue was presented at the fixation point. This type of neutral condition was found not to differ in terms of detection performance overall or in terms of the effect of target eccentricity on detection performance, when compared with the no cue condition in which no flash was presented at the central position [two-way interaction, cue type $\times$ target position, $F(5,25) = 0.95, n.s.$; mean P_a values: neutral condition, 0.777; no cue, 0.784].

The data were collapsed according to the relative distance between the cue and the target locations (distance effect). A two-way ANOVA was then carried out with SOA and cue–target distance (seven levels: valid [i.e., 0 deg] to 18 deg) as factors. The results showed a significant effect of cue–target distance [$F(6,30) = 4.95, p < .002$]. Validly cued targets showed the best detection performance overall, with poorest performance at locations 3 deg adjacent to the cued location. At more distant locations (larger than 3-deg cue–target distance), however, performance did not differ relative to neutral and no cue trials. Planned means comparisons showed that valid cues significantly improved performance relative to neutral and all invalid locations, apart from the 18-deg cue–target distance condition (all comparisons significant at $p < .02$, except for the 18-deg distance condition, $p > .05$). The important finding was that detection performance showed only a small benefit at the valid location and did not show the pattern of distance effects found with goal-directed manual responses (Figure 4).

A two-way ANOVA was used to analyze the effect of relative cue and target directions (meridional effects).

Figure 4. The effect of relative cue-target distance on intersubject mean and standard errors of visual detection sensitivity in Experiment 2 (P_a). The line bisecting the curve indicates the sensitivity measured on neutrally cued trials.

This analysis showed no significant meridional effect overall [$F(1,5) = 5.29, p > .05$]. Although the intersubject mean sensitivity tended to be greater in the same direction as the cue at the longer SOA, the interaction between SOA and relative cue-target direction was not significant [$F(1,5) = 3.80, p > .1$].

Response bias. A measure of response bias (β ; Dorfman & Alf, 1969) was calculated for each subject and condition. $\beta = 1$ indicates perfect unbiased performance, whereas scores higher than 1 show an absent response bias

and scores lower than 1 a bias toward responding present. There was no significant effect of target eccentricity on response bias. However, β was affected by cue-target distance [$F(8,40) = 4.064, p < .002$], with the subjects showing a steady increase in their bias toward absent responses as the spatial distance between the cue and the target increased. This appeared to be the case at locations in the same as well as in the opposite direction to the cued location. The effect of relative cue and target direction did not reach significance [$F(1,5) = 5.012, p < .1$], al-

Figure 5. The effect on response bias (β) of the relative distance between the cue and target (degrees) and the relative cue and target directions (same-opposite) in Experiment 2.

though there was a tendency toward more present responses on the side opposite to the cued location (Figure 5). As with the P_a data, there was no difference in response bias between the neutral condition and the no cue condition ($\beta = 0.894$ and 0.895 , respectively).

Discussion

The most important result of Experiment 2 was the spatial organization of the effect of the peripheral cue on visual detection sensitivity. Experiment 1 showed that when a goal-directed motor response has to be executed to a target location, manual RTs increase markedly with the distance between the cue and the target locations. When only a simple manual response is to be made to the target, the gradients of RT against cue–target distance are greatly reduced, suggesting that these distance effects are associated with the requirement to generate directed motor responses and that the effect of the cue on simply detecting visual target onsets is relatively small. The results of Experiment 2 show that the effect of a peripheral precue on visual sensitivity in the absence of concurrent motor programming consists of only a small improvement in performance at the cued location, relative to neutral and invalidly cued locations. Experiment 2 therefore confirms that the strong RT against cue–target distance gradients observed in Experiment 1 are associated with the requirement to generate directed motor responses.

This does not preclude the existence of cue–target distance gradients in simple manual RT. We find a small gradient effect on isolated buttonpress responses in Experiment 1, which is qualitatively similar to the effect on visual sensitivity in Experiment 2. Other studies report significant distance effects on simple manual RT (e.g., Henderson, 1991; Klein & McCormick, 1989; Reuter-Lorenz & Fendrich, 1992). We find that the requirement to execute a hand or an eye movement to the target results in much stronger gradient effects on manual RT (Figure 3). Other tasks that require the selection of a spatially directed motor response (i.e., a choice RT task) might also be expected to produce similar changes in cue–target distance effects, reflecting the enhanced localization demands of the task.

A detailed analysis of the variation in detection sensitivity revealed another interesting effect. The locations adjacent to the cued location showed a decrement in sensitivity, relative to valid and neutral trials, whereas all other invalid locations showed no difference in sensitivity, relative to the baseline condition. This pattern of results is suggestive of a *center-surround* organization of visuospatial attention activated by peripheral cues. Processing at the cued location was facilitated, whereas processing at adjacent uncued locations was inhibited (Figure 4). The fact that a benefit for detection performance was observed at the cued location suggests that, although peripheral cues inevitably exert a forward visual-masking

effect on stimuli appearing at the cued location, a significant processing benefit is conferred by the cue on visual sensitivity even at short SOAs (see Chastain, 1992). Other work has implied that there may be differences in the processes underlying detection of masked and unmasked stimuli (Shiu & Pashler, 1995). These authors report that an attentional precue modulates visual acuity when a stimulus is partially masked, but not when presented in isolation. This would predict that the effect of the precue on detection sensitivity may be even smaller when stimuli are presented in isolation.

Another finding of Experiment 2 was that a measure of the subject's internal response criterion, also described as response bias (β), varied systematically with the location of the precue. Although this measure (β) is independent of the index of visual sensitivity (P_a) used in Experiment 2, it might be expected to produce an effect on simple manual RT as used in Experiment 1. Simple buttonpress RT on its own is, therefore, an unreliable measure of visual detection sensitivity and produces distance and meridional effects on RT dependent on variation in the subject's response bias/criterion rather than on changes in visual detection sensitivity (Downing, 1988; Duncan, 1980; Müller & Findlay, 1987; Müller & Humphreys, 1991). Care should be taken in interpreting simple RT data as reflecting modulations in *visual processing*. For the same reason, studies that measure the effect of attentional cues on perceptual processes using untransformed *percent correct* measures are also flawed. Previous studies using simple manual responses and peripheral cues have shown reverse meridional effects on simple manual RT, whereas goal-directed saccades under the same conditions do not show this effect (Hodgson & Müller, 1995; Reuter-Lorenz & Fendrich, 1992). The variation in β observed in Experiment 2 showed an insignificant tendency for an increased bias toward present responses in the opposite direction to the precue (Figure 5). This tendency may account for the reversed meridional effect reported with simple manual RT elsewhere.

No difference in detection performance was noted in the neutral (central flash) condition, relative to the no cue condition, showing that attentional engagement (Gawryszewski et al., 1987) did not affect visual detection performance under these conditions. There was also no difference in the effect of target eccentricity on P_a between the two neutral conditions. This clearly shows that a central flash does *not* interact with the effect of target location on visual sensitivity and does not produce an attentional engagement effect on visual sensitivity. It also confirms that eccentricity effects on RT are not related to visual attentional factors.² Furthermore, the result calls into question the concept of engagement of visual attention independent of motor processes (see also Bekkering, Pratt, & Abrams, 1996; Kingstone & Klein, 1993; Walker et al., 1995).

GENERAL DISCUSSION

Response Programming and Perceptual Attention

This paper described two experiments in which the effect of spatial attention on motor and visual processes was investigated. It was concluded from Experiment 1 that the effects of peripheral cues on motor response RT are related to the motor requirements of the task. When a similar analysis of the spatial distribution of attention was carried out, using a signal detection paradigm in the absence of goal-directed movements, a different pattern of results was observed. Only a small benefit in visual detection performance was found at the cued position. This finding confirms that the effect of a peripheral pre-cue on purely visual detection sensitivity is rather small and that strong distance effects on RTs (with peripheral cues) are associated with the preparation of goal-directed motor responses.

One possibility that the present study does not exclude is that, although being associated with motor programming, distance and meridional effects still represent an effect of the cue on visual detection sensitivity (i.e., perceptual attention; Deubel, Shimojo, & Paprotta, 1997; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Rizzolatti, Riggio, & Sheliga, 1994; but see Klein, 1980; Klein & Pontefract, 1994). A direct assessment of this possibility would require experiments in which the preparation of motor responses to locations is combined with the measurement of visual detection performance at target and nontarget locations (using measures derived from signal detection theory that distinguish between modulations in perceptual sensitivity and response bias). Movement programming (not necessarily followed by movement execution) should benefit visual detection performance at the movement's target location. It is also possible that the requirement to localize a target stimulus, independent of whether a motor response is to be executed or not, may itself affect the distribution of visual sensitivity effects described in Experiment 2. However, this possibility would be difficult to address experimentally, inasmuch as measuring the degree to which the subject has localized the target would essentially involve the execution of a directed motor response.

A Shared Attentional Representation of Space?

The results of Experiment 1 revealed an interaction between the eye movement response condition and simple manual RTs. Simple manual responses with accompanying eye movements to the target showed longer RTs than did simple manual responses without eye movements (Figure 2). In contrast, reaching response RTs showed no difference between conditions with and without saccadic eye movements. One explanation of this result is that preparing an eye movement to the periphery results in an inhibition of manual responses to locations that are spatially separate from the target for the eye movement. Meanwhile, manual responses directed to the same loca-

tion as the eye movement are unaffected or facilitated by the ocular response. This implies that, at some level, the hand and eye movement systems share a representation of attentional space, within which spatially incompatible ocular and manual motor programs interfere with one another.

The absolute magnitude of distance effects differed between eye and hand RTs (Figure 3). This finding is consistent with the fact that the hand and the eye movement systems use quite different spatial coding systems for representing target locations (Georgopoulos, 1990). The present results suggest that there may be a much shallower gradient of target localization within oculomotor centers prior to an eye movement than there is in hand movement centers when a reaching response is to be executed. These dissociations are not at odds with the proposal that the two systems are controlled by a central attentional representation at some level. Activity within multiple motor centers may directly contribute to the effect of peripheral cues on RTs. These specialized motor centers may also influence RTs via reciprocal neural connections with a supramodal attentional representation of hand and eye space. This organization would explain the findings of response dependency in terms of meridional and distance effects as well as the existence of interactions between different response modalities.

An area of the brain that is a candidate for this shared representation of attentional space, where information from the hand and the eye movement systems may be integrated, is the posterior parietal cortex. This area contains cells whose retinotopically coded visual responses are modulated by the position of the eyes in the orbit (Andersen, 1989, 1997). Although the cells code target position relative to the head, their responses to visual stimuli are still retinotopically coded. Hence, there is a neural organization in the posterior parietal cortex that can produce retinotopically coded eye movements, while still providing target location information suitable for driving arm movements in a body-centered coordinate system. There appears to be no explicit neural spatiotopic map in this part of the brain, as is found in motor centers such as the superior colliculus. Instead, this area of the cortex represents spatial information in a distributed manner. Rather than a map of attentional space, the function of the posterior parietal cortex has been described as being more like the index one finds at the back of a map book (Stein, 1992)—each entry consisting of a spatial location linked to the learned motor coordinates for each possible response system.

Conclusions

The effect of a peripheral cue on manual RTs was found to be modulated by the motor programming component of the task. Interactions between hand and eye movements and qualitative differences between the effects of attentional cues on hand and on eye RTs were found. The findings suggest that the initiation of hand and eye movement responses are under the control of a

shared attentional representation. At the same time, peripheral cues also modulate RTs via response-specific representations.

Further studies that directly examine the trajectories of hand movements concurrent with the orienting of attention and eye movements would shed further light on the relationship between manual response programming and attention (see, e.g., Howard & Tipper, 1997). Neuropsychological investigations in patients with localized lesions in the posterior parietal cerebral cortex would also be of interest. These studies could directly assess the contribution of this brain region to the interactions between response modalities that we report.

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NOTES

1. The motor aspect of attention has been variously termed *motor programming*, *intention* (Andersen, 1997), or *motor attention* (Rushworth, Nixon, Renowden, Wade, & Passingham, 1997).
2. We have also compared the no cue with the cue condition for simple manual RT in 4 subjects. We find no difference between the effect of eccentricity on RTs in the two baseline conditions.

APPENDIX

Intersubject Means and Standard Errors of Manual Response Times (in Milliseconds) for Each Response Condition and Cue and Target Combination in Experiment 1

Cue Type	Target Position					
	9 Left	6 Left	3 Left	3 Right	6 Right	9 Right
Simple Manual RT, No Eye Movements						
SOA 100						
9 left	343 ± 17	338 ± 16	342 ± 19	345 ± 21	352 ± 28	353 ± 26
6 left	356 ± 22	341 ± 19	330 ± 21	344 ± 25	341 ± 21	341 ± 21
3 left	357 ± 20	333 ± 20	339 ± 21	336 ± 19	346 ± 19	357 ± 25
3 right	355 ± 30	338 ± 23	335 ± 17	328 ± 17	338 ± 21	365 ± 26
6 right	325 ± 21	355 ± 25	356 ± 23	328 ± 20	337 ± 18	345 ± 18
9 right	355 ± 22	342 ± 23	341 ± 17	345 ± 21	346 ± 23	336 ± 22
Neutral	376 ± 22	349 ± 15	339 ± 16	347 ± 17	346 ± 18	373 ± 16
SOA 500						
9 left	278 ± 18	276 ± 19	304 ± 24	296 ± 27	288 ± 16	297 ± 15
6 left	283 ± 22	270 ± 21	280 ± 29	278 ± 23	286 ± 24	309 ± 25
3 left	282 ± 22	274 ± 28	283 ± 18	300 ± 26	300 ± 26	305 ± 24
3 right	268 ± 23	294 ± 22	303 ± 23	272 ± 22	274 ± 19	286 ± 21
6 right	293 ± 23	297 ± 23	285 ± 19	290 ± 25	273 ± 21	284 ± 20
9 right	298 ± 22	278 ± 23	294 ± 24	278 ± 20	277 ± 21	276 ± 20
Neutral	319 ± 21	291 ± 18	283 ± 20	274 ± 19	278 ± 25	289 ± 20
Simple Manual RT, With Eye Movements						
SOA 100						
9 left	395 ± 24	401 ± 26	390 ± 29	410 ± 24	424 ± 30	446 ± 25
6 left	415 ± 33	381 ± 23	384 ± 24	397 ± 23	416 ± 37	407 ± 24
3 left	418 ± 28	379 ± 29	374 ± 24	380 ± 23	408 ± 27	426 ± 27
3 right	416 ± 19	404 ± 27	392 ± 27	366 ± 25	387 ± 23	388 ± 24
6 right	424 ± 19	414 ± 21	394 ± 17	368 ± 27	375 ± 23	394 ± 24
9 right	423 ± 26	409 ± 23	393 ± 17	393 ± 31	390 ± 21	391 ± 27
Neutral	420 ± 25	395 ± 24	389 ± 24	374 ± 18	406 ± 32	419 ± 28
SOA 500						
9 left	339 ± 21	333 ± 17	336 ± 22	359 ± 24	366 ± 20	410 ± 32
6 left	328 ± 27	321 ± 25	343 ± 26	370 ± 25	365 ± 24	383 ± 31
3 left	334 ± 26	340 ± 28	316 ± 24	358 ± 22	366 ± 28	380 ± 25
3 right	381 ± 23	398 ± 31	372 ± 25	312 ± 25	336 ± 25	353 ± 30
6 right	396 ± 27	381 ± 23	376 ± 27	331 ± 23	314 ± 22	328 ± 31
9 right	401 ± 27	398 ± 20	379 ± 18	333 ± 21	339 ± 32	340 ± 28
Neutral	359 ± 21	360 ± 29	337 ± 19	346 ± 30	347 ± 25	381 ± 33

APPENDIX (Continued)

Cue Type	Target Position					
	9 Left	6 Left	3 Left	3 Right	6 Right	9 Right
Reaching Manual RT, No Eye Movements						
SOA 100						
9 left	369 ± 16	379 ± 20	375 ± 17	384 ± 20	405 ± 22	414 ± 22
6 left	378 ± 18	353 ± 13	362 ± 18	395 ± 23	398 ± 20	410 ± 21
3 left	412 ± 21	381 ± 17	335 ± 13	380 ± 23	411 ± 25	427 ± 21
3 right	453 ± 26	417 ± 18	386 ± 14	329 ± 15	376 ± 18	409 ± 21
6 right	433 ± 17	409 ± 17	397 ± 17	357 ± 22	351 ± 16	363 ± 19
9 right	430 ± 18	410 ± 16	399 ± 16	361 ± 20	376 ± 20	352 ± 19
Neutral	427 ± 20	421 ± 22	365 ± 19	364 ± 19	398 ± 21	400 ± 18
SOA 500						
9 left	333 ± 19	343 ± 18	334 ± 21	360 ± 19	371 ± 23	407 ± 18
6 left	350 ± 20	314 ± 15	314 ± 20	350 ± 25	368 ± 18	381 ± 22
3 left	376 ± 21	377 ± 23	293 ± 13	343 ± 14	360 ± 20	382 ± 19
3 right	394 ± 20	372 ± 22	344 ± 17	290 ± 16	334 ± 18	372 ± 22
6 right	393 ± 17	403 ± 21	357 ± 19	323 ± 23	304 ± 19	321 ± 19
9 right	399 ± 17	388 ± 19	363 ± 18	328 ± 16	328 ± 16	319 ± 20
Neutral	369 ± 19	358 ± 21	332 ± 19	334 ± 21	339 ± 22	350 ± 21
Reaching Manual RT, With Eye Movement						
SOA 100						
9 left	368 ± 16	385 ± 24	373 ± 22	371 ± 22	378 ± 20	396 ± 19
6 left	379 ± 24	357 ± 16	352 ± 20	369 ± 20	371 ± 16	395 ± 22
3 left	391 ± 19	381 ± 22	346 ± 19	365 ± 22	389 ± 23	410 ± 17
3 right	425 ± 19	402 ± 25	376 ± 15	325 ± 15	356 ± 19	388 ± 18
6 right	421 ± 22	405 ± 21	386 ± 20	358 ± 22	342 ± 15	353 ± 15
9 right	405 ± 18	397 ± 18	386 ± 22	365 ± 20	346 ± 13	353 ± 16
Neutral	396 ± 18	380 ± 15	365 ± 20	356 ± 23	364 ± 17	386 ± 18
SOA 500						
9 left	318 ± 15	324 ± 20	319 ± 17	344 ± 20	362 ± 19	360 ± 21
6 left	311 ± 18	302 ± 15	313 ± 18	337 ± 17	350 ± 19	366 ± 27
3 left	360 ± 20	326 ± 16	288 ± 15	343 ± 22	350 ± 20	370 ± 23
3 right	384 ± 18	377 ± 25	335 ± 18	278 ± 16	299 ± 18	337 ± 18
6 right	371 ± 30	362 ± 19	356 ± 24	304 ± 19	294 ± 15	308 ± 17
9 right	379 ± 19	362 ± 19	357 ± 20	315 ± 16	319 ± 19	305 ± 15
Neutral	366 ± 27	340 ± 22	338 ± 19	319 ± 19	328 ± 19	332 ± 20

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