Gaze-Centered Updating of Visual Space in Human Parietal Cortex

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Introduction

The posterior parietal cortex (PPC) is important for spatial processing and visually guided action (Goodale and Milner, 1992; Jeannerod et al., 1995; Andersen et al., 1997; Colby and Goldberg, 1999). In the monkey, different regions within the PPC process information for different actions. For example, the lateral intraparietal sulcus (LIP) codes target location for eye movements called saccades (Gnadt and Andersen, 1988; Barash et al., 1991; Duhamel et al., 1992a; Colby et al., 1996; Mazzioli et al., 1996), whereas the adjacent parietal reach region (PRR) codes the same for impending reaching movements (Galletti et al., 1997; Snyder et al., 1997; Batista et al., 1999).

Both areas have been shown to encode this information explicitly in a gaze-centered, eye-fixed frame of reference, which must be updated across eye movements to remain accurate (Duhamel et al., 1992a; Batista et al., 1999) as opposed to a head or body-centered frame, which would be independent of eye movements (Scherberger et al., 2003). It is also thought that eye position, head position, and vestibular signals in these regions may be used to transform this gaze-centered information into other frames of reference (Andersen et al., 1985; Brotchie et al., 1995; Snyder et al., 1998).

Human neuroimaging studies have also implicated the PPC in saccades and arm movements (for review, see Corbetta et al., 1998; Connolly et al., 2000; DeSouza et al., 2000; Culham and Kanwisher, 2001; Sereno et al., 2001), with a topographic organization related to different directions of target location (Sereno et al., 2001). Without varying eye position, however, it is unclear whether this topography is related to a gaze-centered frame of reference, let alone whether the human PPC shows spatial updating across eye movements. Here we performed two functional magnetic resonance imaging (fMRI) experiments to investigate whether the human PPC demonstrates gaze-centered coding and updating of spatial information for saccades and pointing movements.

Materials and Methods

MRI scanning and data analysis. Data were collected with a 4.0 Tesla Varian Siemens whole-body imaging system. Six male subjects (aged 21–35 years) viewed stimuli that were backprojected, using an NEC VT540 LCD projector (refresh rate, 70 Hz) with custom optics, onto the ceiling of the magnet bore. All subjects but one were right-handed, and all pointing movements were made using the right hand. During experiment 1, 19 contiguous slices were used to image the entire parietal lobe. Functional data were obtained using navigator echo corrected T2*-weighted segmented gradient echoplanar imaging (echo time (TE), 15 msec; flip angle (FA), 45°; field of view (FOV), 19.2 × 19.2 cm; repetition time (TR), 2 sec; in-plane pixel size, 3 × 3 mm; thickness, 4 mm). During experiment 2, five of the initial 19 slices, which included the region of interest identified in experiment 1, were scanned at a higher temporal resolution (FA, 22°; TR, 0.5 sec). Functional data were superimposed on high-resolution inversion prepared three-dimensional T1-weighted anatomical images of the brain (typically 128 slices; 256 × 256; FOV, 19.2 × 19.2 cm; TE, 5.5 msec; TR, 10.0 msec) using a phase reference image that corrected for high-field geometric distortions. In separate sessions, subjects were rescanned using a birdcage-style head coil to obtain full brain anatomical images. A high-resolution inversion prepared three-dimensional T1-weighted sequence was used (FA, 15°; voxel...
size, 1.0 mm in-plane; 256 × 256; 164 slices; TR, 0.26 sec; TE, 5.3 msec). Analysis was performed using Brain Voyager 4.6 software (Brain Innovation, Maastricht, The Netherlands) and Matlab software (MathWorks, Natick, MA). Surface coil images were realigned manually to head-coil images. Anatomical images for each subject were segmented at the gray–white matter boundary, rendered and inflated for visualization purposes only. For functional data analysis, we excluded any scans in which motion artifacts were observed. Time courses within each voxel were corrected for linear drift. Anatomical and functional images were transformed to Talairach space to obtain coordinates for the regions of interest.

Experiment 1: delayed-movement task. Subjects fixated a central letter, S, P, or F, referring to a delayed-saccade task (S), a delayed pointing task (P), or a fixation task (F), respectively (see Fig. 1A) (Snyder et al., 1997; Batista et al., 1999; Sereno et al., 2001). Then, a brief peripheral dot was presented for 250 msec, to either the left or right at random horizontal eccentricities from the continuous interval between 10 to 25°. Subsequently, a band of distractors (70° horizontal × 8° vertical; eccentricity of the dot, 0.8°; density, 0.14 dots per square degree) blinked (at 5 Hz) for 2.5 sec, during which the subjects maintained central fixation (and pointed to the central letter P when in pointing mode). Then, at distractor offset, subjects made either a saccade or a pointing movement to the remembered target location and immediately back to center. Subjects made no movement in the fixation (F) task. During the pointing task, they were instructed to maintain central fixation of the eyes at all times. Pointing movements consisted of wrist rotations, such that the index finger pointed to the remembered target location (DeSouza et al., 2000). The subject’s view of the hand was rotated to a delayed-saccade task (S), a delayed pointing task (P), or a fixation task (F), respectively. After a brief peripheral dot was presented, a horizontal band of distractors blinked for 2.5 sec. Subsequently, subjects made either a saccade or a pointing movement to the remembered target location and immediately back to center. Subjects made no movement when in fixation (F) task. 8. The intervening saccade task. In this paradigm, two targets were briefly flashed sequentially, a green (the goal target) and red (refixation target for the first saccade) target. After a 6 sec delay, subjects made a saccade to refixate at the remembered location of the red target and, after a subsequent 12 sec period, made either a saccade (Saccade–Saccade Task) or a pointing movement (Saccade–Point Task) to the location of the remembered goal target and immediately back to center.

Each scan contained 12 epochs (25 sec each), in which the four conditions were pseudorandomly interleaved. Three to four scans were run for both the saccade–saccade and the saccade–point task. For each scan, the mean fMRI signal at volumes 6–8 across all 12 epochs was taken as baseline. Data was temporally smoothed using a moving average filter with a span of 5 (volumes). For additional data analysis, for each condition, a mean signal and SD were computed at each voxel. Further, a mean fMRI signal at volumes 6–8 across all 12 epochs was taken as baseline. Data was temporally smoothed using a moving average filter with a span of 5 (volumes). For additional data analysis, for each condition, a mean signal and SD were computed at each voxel. Furthermore, when differences between conditions were computed, uncertainties were determined using standard statistical rules for uncertainty combination.

Movement recordings. Each subject extensively practiced all tasks before imagining to ensure that these were performed correctly. In addition, eye movement recordings (Applied Science Laboratories, Bedford, MA) were performed on three of our subjects outside the scanner for the saccade–saccade and the saccade–point task to confirm that they followed the instructions correctly. This also confirmed that subjects were able to keep fixation while making pointing movements. Moreover, the fMRI experiment was self-controlling for eye movements: the pseudorandom interleaving of the conditions was designed so that positive results (like those we observed) would only be obtained if subjects made eye movements to the correct locations. Pointing movements were not recorded. However, in our fMRI analysis, we focused on brain activity in the delay periods before the pointing movements, so any small errors made during the subsequent movement would likely be reflected in brain events that we did not record.
movements (blue regions), with fewer voxels activated exclusively by saccades (orange regions) (Connolly et al., 2000; DeSouza et al., 2000). We also observed activation in occipital and frontal areas, but here we focus on possible analogs of primate LIP and PRR in human PPC.

Which of these regions are topographically organized for saccades? To determine this at a simple level, we compared the PPC activation for leftward and rightward target locations. Red regions (Fig. 2B) indicate a stronger activation for remembered target locations to the left than to the right, whereas green voxels represent the opposite pattern. In the parietal cortex, a topographic zone was located at a medial branch of the intraparietal sulcus, in agreement with results by Sereno et al. (2001). As can be seen, the left hemisphere maps targets in the right hemifield, whereas the right hemisphere maps targets in the left hemifield. All subjects tested demonstrated an equivalently organized area in their PPC, mostly located within a small sulcus running medially from the intraparietal sulcus. Interestingly, the same set of PPC voxels also showed lateralized responses in the delayed-pointing task, as demonstrated by Figure 2C. Thus, the same PPC region showed topography for both saccades and pointing movements.

For anatomic reference, the center of this region of interest for this one subject is indicated for the left and right hemispheres in D by the red and green crosses. Across subjects, the average Talairach coordinates (in millimeters) and their SDs of the peak parietal activation for saccades were \( x = 21 \) (SD = 4), \( y = -62 \) (SD = 9), \( z = 42 \) (SD = 4) (right hemisphere) and \( x = -19 \) (SD = 5), \( y = -63 \) (SD = 7), \( z = 46 \) (SD = 5) (left hemisphere), consistent with but slightly more medial than the location reported by Sereno et al. (2001). For pointing, these coordinates were \( x = 22 \) (SD = 4), \( y = -64 \) (SD = 9), \( z = 44 \) (SD = 4) (right) and \( x = -19 \) (SD = 4), \( y = -62 \) (SD = 7), \( z = 46 \) (SD = 6) (left). These were not significantly different from the location for saccades in any dimension (paired t test; \( p > 0.05 \)).

The key question here is, does this area represent and update its information in a gaze-centered frame of reference? We tested this in experiment 2 using an event-related fMRI paradigm in which subjects produced intervening saccades between seeing a goal target and generating an eye or arm movement toward its remembered location (Fig. 1B) (see Materials and Methods). In all cases, the space-fixed goal target remained stable relative to the head and body. However, the remembered location of this target would have to be remapped during the intervening saccade to correctly code its new location in eye-fixed coordinates. As illustrated by Figure 3A, the paradigm consisted of four different conditions with regard to the location of the goal target relative to gaze direction before and after the first saccade; the goal target
started and remained in the right visual hemifield (RR), or it started and remained in the left hemifield (LL), or it moved from the left into the right hemifield (LR), or vice versa (RL).

Figure 3 shows the mean response of the six subjects in the left parietal region for each of the four conditions in the saccade–saccade task. As shown, after a brief presentation of the two targets, those for the initial saccade and the final goal, cortical activation builds up gradually during the first delay period, leading to a higher activity when the two targets were in the right (contralateral) hemifield than when they were in the left (ipsilateral) hemifield. The reverse is true for initial responses in the right parietal cortex (Fig. 3C). This reflects the topographical nature of the region, as identified in experiment 1. The activity decays slightly during the first delay period, and then, when the first saccade occurs (i.e., 7.5 sec after the start of the trial), cortical activation increases again, in all four conditions.

What happens after this saccade, in the second delay period? The activation of the region depends on the location of the remembered goal target relative to current gaze direction. For the left cortex (Fig. 3B), if the remembered goal shifted from the left hemifield (ipsilateral) into the right (contralateral) hemifield (LR condition), a high sustained activation was observed in the second delay period. However, if it shifted from the right to left hemifield (RL condition), the level decreased. When the remembered goal target remained in the same hemifield after the first saccade, the activation was high if this location was contralateral (RR condition) and low if ipsilateral (LL condition). The right parietal region (Fig. 3C) showed a similar, but mirrored, pattern of activation.

Figure 3, D and E, shows a similar analysis for the four conditions in the saccade–point task. Results in the saccade–point task were not as homogeneous as those in the saccade–saccade task. The presaccadic response is somewhat less clear compared with the saccade data in B and C. However, the more important post-saccadic remapping response is just as robust and clear in the pointing data as for the saccade data. In other words, the saccade–point data showed the same gaze-centered remapping pattern, with symmetrically yoked activation between the left and right PPC. Together, these results suggest that, when the horizontal location of a remembered saccade or pointing goal reverses (left–right) with respect to gaze direction, these physical shifts are accompanied by dy-
namic shifts in cortical activity from one hemisphere to the other. This suggests that the parietal area identified here encodes and updates the remembered location of the saccade and pointing goals in eye-fixed coordinates.

To analyze these findings quantitatively, in Figure 4, A and B, we plotted the difference in activation between the RL condition and the LR condition after the first saccade (time period of 17–19.5 sec, second delay period) versus the difference before that saccade (time period of 5–7.5 sec, first delay period). These volumes are indicated schematically by the gray areas in Figure 3B–E. Gaze-centered updating requires that these differences have opposite sign. Accordingly, data from the right parietal cortex should be represented in the second quadrant, whereas left parietal data should be confined to the fourth quadrant (gray zones). A failure to update this information (or representation in a head–body fixed frame) would be indicated by data points in the opposite white zones. As Figure 4A shows, the saccade–saccade data of all six subjects fell within the gaze-centered gray zones ($p < 0.001$; $t$ test). Thus, all of our subjects encoded and updated visuospatial information for saccades in a gaze-centered reference frame. When we applied the same analysis to the saccade–point task data (Fig. 4B), nearly all of the data fell within the gaze-centered remapping zones ($p < 0.05$; $t$ test).

**Discussion**

Our results show that the topographic representation for goal-directed eye and pointing movements in human PPC is organized in gaze-centered, eye-fixed coordinates and is spatially updated across eye movements. This is consistent with the known physiology of the monkey PPC (Gnadt and Andersen, 1988; Duhamel et al., 1992a; Mazzoni et al., 1996; Batista et al., 1999) and with human psychophysics (McIntyre et al., 1997; Henriquez et al., 1998; Medendorp and Crawford, 2002), which suggest an eye-fixed coordinate system for representing reaching and pointing targets in both near and far space. This result does not contradict the idea that the same parietal regions might also be involved in implicitly transforming these gaze-centered signals into other coactivated during arm movements (even when the saccade is suppressed) as part of some eye–hand coordination strategy (Snyder et al., 2000).

To distinguish whether our area specifically represents movements other than saccades, it would be useful to perform experiments that explicitly disassociate saccade planning from pointing movements (Snyder et al., 1997).

Our results could also mean that saccade and arm movement neurons are coningled in the same region with a greater preponderance of the former or a lesser need to sustain gaze-centered activity for pointing. Consistent with this, a recent report shows that neurons with arm-specific intention activity lie on both banks of the monkey intraparietal sulcus (Calton et al., 2002). Moreover, it is clear that damage to the human PPC results in deficits in programming both eye and arm movements (Duhamel et al. 1992b; Grea et al., 2002), and some of these reaching deficits are best explained in terms of a gaze-centered mechanism like that reported here (Khan et al., 2002). In summary, although our fMRI measurements cannot differentiate the proportion of cells involved in eye versus pointing movements, the simplest interpretation of our data are that human PPC is probably organized in a similar way as monkey PPC, i.e., there appears to be a regional overlap for eye and pointing movements.

Why would the human PPC operate in eye-fixed coordinates? Perhaps it is not surprising that the locations of targets for saccades are mapped relative to the current fixation point. At first glance, however, it might be unexpected that this also holds for pointing movements. It would seem more logical to code these in egocentric coordinates relative to the body. If, however, the function of the PPC is to select targets for action and the effectors to perform these actions (Snyder et al., 1997), it is critical that computations occur in a common coordinate frame. It would appear that this common coordinate frame is gaze centered (Batista et al., 1999). Ultimately, however, even the remapped input representations must be transferred into output coordinates. Indeed, this seems to be the case at the level of the frontal cortex (Grazi-
ano et al., 2002). From primate studies, it is known that the PPC also possesses information on hand position (possibly also in eye-fixed coordinates; Buneo et al., 2002), eye position (Andersen et al., 1985), and head position (Brotchie et al., 1995). This places it in a unique position to begin the neural computations required for an accurate arm movement in motor coordinates, without the need for intervening high-level coordinate frames (Smith and Crawford, 2001). Together with the gaze-centered remapping mechanism described here, this provides the substrate for an economical, biologically compact visuomotor control system.

References