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Oculomotor mechanisms activated by imagery and memory: eye movements to absent objects

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Abstract It is hypothesized that eye movements are used to coordinate elements of a mental model with elements of the visual field. In two experiments, eye movements were recorded while observers imagined or recalled objects that were not present in the visual display. In both cases, observers spontaneously looked at particular blank regions of space in a systematic fashion, to manipulate and organize spatial relationships between mental and/or retinal images. These results contribute to evidence that interpreting a linguistic description of a visual scene requires a spatial (mental model) representation, and they support claims regarding the allocation of position markers in visual space for the manipulation of visual attention. More broadly, our results point to a concrete embodiment of cognition, in that a construction of a mental image is almost "acted out" by the eye movements, and a mental search of internal memory is accompanied by an ocolumotor search of external space.

Introduction

Recent research in visual perception and language comprehension has taken advantage of observers' eye movements as a unique, and relatively unobtrusive, window into the moment-by-moment perceptual/cognitive processes produced by a time-dependent stimulus in an interactive visuomotor environment (Ballard, Hayhoe, & Pelz, 1995; Land, Mennie, & Rusted, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). In the present work, eye-movement patterns were used as an index of how observers integrate visual input with stored representations to construct and interrogate spatial mental models (e.g., Bower & Morrow, 1990; Johnson-Laird, 1983, 1996). As a form of "perceptual simulation" (Barsalou, 1999), the construction and interrogation of spatial mental models typically involves linguistic input activating memory representations, and in turn those memory representations may partially activate perceptual representations (e.g., Farah, 1995; Finke, 1986; Kosslyn, Thompson, Kim, & Alpert, 1995). The present study demonstrates that, even in the absence of an appropriate visual stimulus, oculomotor responses associated with those perceptual representations are also activated.

When instructed or trained to do so, humans and nonhuman primates are able to make saccadic eye movements to remembered locations, even in the absence of a physical stimulus in that location (e.g., Funahashi, Bruce, & Goldman-Rakic, 1991; White, Sparks, & Stanford, 1994; Zivotofsky, Rottach, Averbuch-Heller, Kori, Thomas, Dell'osso, & Leigh, 1996). However, under what circumstances would an observer *spontaneously* look at a particular blank region of space? In fact, there are many everyday circumstances in which elements of a spatial mental model must be interfaced with the on-line visual input to solve some visuomotor task. For example, when deciding where to hang a picture, one tends to look at particular blank regions of a wall and imagine the picture with its spatial relationships to other furniture. Likewise, when trying to remember an image that had been drawn on a chalkboard, and later erased, one might find oneself staring at the particular region of the board where the image had once been.

The present study had two goals: one theoretical, one methodological. In terms of a theoretical understanding of spatial mental models, it is an important finding that motor mechanisms are tightly coupled with the perceptual and cognitive mechanisms that subserve mental representation. In terms of advancing the

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methodology of eyetracking, it is important to note that, while recent eyetracking experiments have begun to demonstrate that eye movements can be informative about real time perception and cognition in a stimulus environment containing visible objects that are relevant for action, the present findings occur in a stimulus environment where there are no visible objects relevant for action.

Experiment 1

More than 30 years ago, Hebb (1968) (see also Hebb, 1949; Neisser, 1967) suggested that the very same scanpaths associated with *viewing* an object may be automatically elicited (via transcortical cell assemblies) when a person is *imagining* that object; and empirical support for this claim has recently been reported. When viewing a blank screen and being instructed to imagine a previously viewed simple grid pattern, observers produced eye-movement scanpaths that bore some resemblance to the scanpaths during original viewing of the actual grid pattern (Brandt & Stark, 1997).

However, Demarais and Cohen (1998) warn against possible effects of experimenter demand when the participant knows that his/her eye movements are being recorded, as was the case in Brandt and Stark (1997). Demarais and Cohen placed EOG electrodes on their participants and told them that they were measuring surface temperature due to blood flow. Their participants solved auditorily presented syllogisms (containing left/right or above/below relational terms and three or four elements) while wearing the EOG electrodes in a sound-attenuated light-proof room. It was found that syllogisms containing the words "left" and "right" elicited more horizontal eye movements, and syllogisms containing the words "above" and "below" elicited more vertical eye movements. One question that might arise here is whether the eye movements that were elicited are actually responding to mental imagery or simply to associations between the relational terms (left, right, above, below) and regions of space.

To further explore this general paradigm, and extend it to richer and more complex images, our first experiment looked not at imagining recently viewed static objects or solving logic problems, but instead played pre-recorded descriptions of spatiotemporally dynamic scenes, and recorded participants' eye movements while they listened to the descriptions and faced a blank white screen. We ensured that our participants did not know that their eye movements were being recorded at the time, and the critical portions of all but one of our scene descriptions avoided explicit directional terms such as "up", "below", "left", etc. [although the critical portion of our rightward story did contain the word "right", the critical portion of our leftward story actually contained the word "down", as in "further down the (leftward extending) train."].

Method

Participants

Ten undergraduates participated in this experiment for monetary compensation. All participants had normal, or corrected with contacts, vision.

Apparatus and procedure

Eye movements were monitored by an ISCAN eyetracker mounted on top of a lightweight headband. The camera provided an infrared image of the left eye sampled at 60 Hz. The center of the pupil and the corneal reflection were tracked to determine the direction of the eye relative to the head. A scene camera, yoked with the view of the tracked eye, provided an image of the participant's field of view. Gaze position (indicated by crosshairs) was superimposed over the scene camera image and recorded onto a Hi8 VCR with 30 Hz frame-by-frame playback. Accuracy of the gaze position record was approximately 0.5 degrees of visual angle. The video record was synchronized with the audio record for all data analysis.

One concern we had about tracking participants' eye movements during an imagery experiment was that they might easily deduce the experimental hypothesis, and since oculomotor control is not entirely automatic (cf. Findlay & Walker, 1999), such participants might intentionally provide supportive data. To prevent participants from guessing the experimental hypothesis, we had them participate in a sham experiment that involved following eight pre-recorded instructions to move objects around on a table. During a break, participants rotated the chair to face a white projector screen, and were told that the eyetracker was being turned off (but not to remove the headband because that would require a recalibration when they returned to the experiment). They were instructed to relax and listen to some descriptions of visual imagery which would last for about 5 min, after which the eyetracker would be turned back on and they would return to the experiment. During this break, the pre-recorded scene descriptions were played, and participants' eye movements were recorded. Five pre-recorded scene descriptions (with upward, downward, leftward, rightward, and nondirectional spatiotemporal dynamics) were presented in random order (see Table 1).

Results and discussion

Three of the participants closed their eyes during the imagery session, and one guessed the hypothesis at the end of the experiment. We analyzed the data from the remaining six participants (all of whom reported being unaware that the eyetracker was in fact recording during the 'break').

While participants were facing the blank white projector screen, and were unaware that their eye movements were being recorded, they tended to make saccades in the same direction as the spatiotemporal dynamics of the auditorily presented scene description. Figure 1 shows the percentage of saccades (greater than 2° of visual angle) in all directions during scene descriptions with upward, downward, leftward, and rightward spatiotemporal dynamics. In the center of Fig. 1, the percentage of saccades in all directions during a control scene description that had no particular directionality shows a roughly circular polar plot.

For statistical analysis, percentage of saccades was averaged across the pair of 30° bins centered on a cardinal direction and compared to averages across other

Table 1 Pre-recorded scene descriptions from Experiment 1 (text in italics indicates sentences during which eye movements were analyzed)

Upward story	"Imagine that you are standing across the street from a 40 story apartment building. At the bottom there is a doorman in blue. *On the 10th floor, a woman is hanging her laundry out the window. On the 29th floor, two kids are sitting on the fire escape smoking cigarettes. On the very top floor, two people are screaming*."
Downward story	"Imagine you are standing at the top of a canyon. Several people are preparing to rappel down the far canyon wall across from you. *The first person descends 10 feet before she is brought back to the wall. She jumps again and falls 12 feet. She jumps another 15 feet. And the last jump, of 8 feet, takes her to the canyon floor*."
Leftward story	"Imagine a train extending outwards to the left. It is pointed to the right, and you are facing the side of the engine. It is not moving. *Five cars down is a cargo holder with pink graffiti sprayed on its side. Another six cars down is a flat car. The train begins to move. Further down the train you see the caboose coming around a corner*."
Rightward story	"Imagine a fishing boat floating on the ocean. It's facing leftward from your perspective. *At the back of the boat is a fisherman with a fishing pole. The pole extends about 10 feet to the right beyond the edge of the boat. And from the end of the pole, the fishing line extends another 50 feet off to the right before finally dipping into the water*."
Control story	"Imagine you are on a hill looking at a city through a telescope. *Pressing a single button zooms a specific block into view. Another button brings a gray apartment building into focus. Finally a third button zooms in on a single window. Inside you see a family having breakfast together. A puppy appears and begs for a piece of French toast*."

bins. In a repeated measures analysis of variance, saccades in a directionally biased scene description's preferred direction were significantly more likely than saccades in that same direction during the control scene description (13.6% vs. 8.5%); $F(1, 5) = 8.84$, $P < 0.05$. Moreover, among the directionally-biased scene descriptions, the biased direction elicited a greater proportion of saccades than did the unbiased directions (13.6% vs. 7.3%); $F(1, 5) = 15.19$, $P < 0.02$. (These results were still significant when the rightward story was excluded from the analysis due to it containing the explicit directional term, "right".)

As seen in related eye-movement data from an imagery task while the eyes were closed (Spivey, Tyler, Richardson, & Young, 2000), some of the stories tend to elicit eye movements in two directions. In Fig. 1, it is apparent that the leftward and rightward stories each produced an almost equal proportion of leftward and rightward eye movements. Nonetheless, it is noteworthy that these two conditions clearly show an unmistakable preference for horizontal eye movements over vertical eye movements. These bimodal distributions may not be surprising when one considers the fact that the participant simply could not continue to make only leftward or only rightward eye movements indefinitely. At some point, an eye movement in the opposite direction may become necessary to "re-center" the imagined scene in head-centered coordinates. Moreover, some participants may simply choose to "inspect" some previously mentioned components of the imagined scene, thus producing regressive saccades. Due to this bimodality, in computing summary statistics for the direction of the eye movements, we report modes (which are computed on the circle in essentially the same fashion as on the line, cf. Mardia, 1972) instead of means. The modal direction of our participants' eye movements during the upward story was 100 deg. The modal direction of our participants' eye movements during the downward story was 274 deg. The two modal directions of our participants' eye movements during the leftward story were 166 deg. and 349 deg. The two modal directions of our participants' eye movements during the rightward story were 9 deg. and 177 deg.

These results indicate that when people are *imagining* a complex event, they activate some of the same perceptual-motor mechanisms used for *viewing* that complex event. This suggests that oculomotor behavior responds to perceptually-based spatial mental models that are computed during language comprehension and mental representation (e.g., Bower & Morrow, 1990; Johnson-Laird, 1983, 1996).

It is worth noting that, although these results demonstrate a compelling physical embodiment of internally generated visual information, they say nothing about the functional role of eye movements in imagery. These eye movements may be purely reflexive in this situation. That is, visual imagery may automatically, in a feed-forward fashion, activate oculomotor coordinates that are associated with real perception of the imagined scene – but without feedback from the oculomotor representations to the imagery representations, the eye movements would not affect the imagery itself. Thus, it may be the case that eye movements respond to imagery, but imagery does not respond to eye movements (Pinker, 1980; but cf. Ruggieri, 1999). Future work will be necessary to further examine the functional role of these eye movements during imagery. Such work might involve looking at more fine-grain properties of the eye movements, such as metric relationships between distances in the imagined scene (Kosslyn, Ball, & Reiser, 1978) and length of saccades, overtly controlling eye movements and fixation (Pinker, 1980; Ruggieri, 1999), and also examining the eye movement patterns of imagery-impaired populations (Riddoch, 1990).

Experiment 2

In addition to projecting an entire (linguistically induced) imaginary scene onto a blank screen, eye movements may also be used for projecting remembered objects onto an existing viewed scene. In a

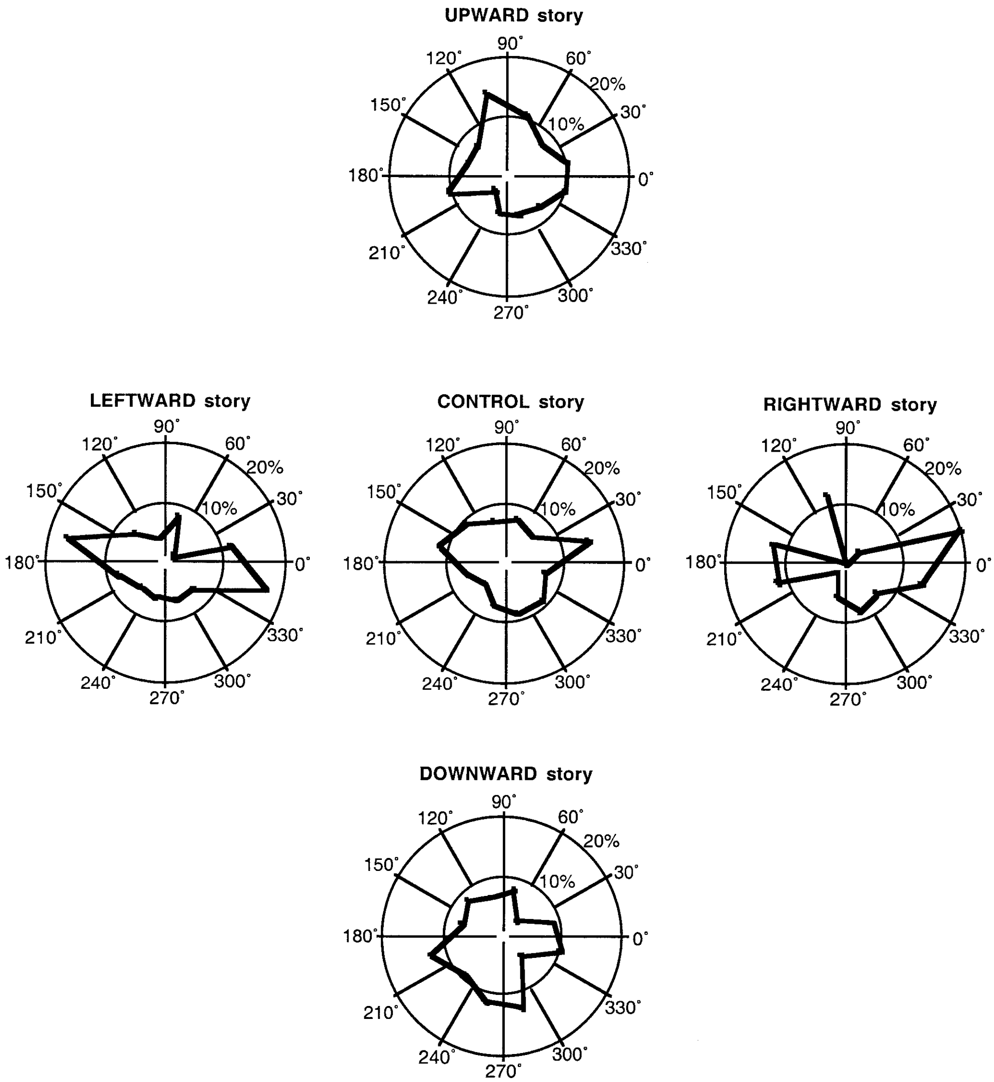

Fig. 1 Polar plots of the percentage of saccades in all directions during scene descriptions. Saccades were pooled over sentences in the scene description that exhibited explicit directionality (or over all sentences during the control scene description). For example, the upper plot is taken only from saccades during sentences 3–5 of the upward scene description (see Methods for scene description). While facing a blank screen, participants' eye movements showed a clear bias toward the direction of the spatiotemporal imagery in the scene description

second experiment, participants viewed a set of four simple shapes (each with a certain color and direction of tilt) on a computer screen, followed by instructions to look at each location and then look at the central cross. The display then vanished and reappeared with one of the objects missing. When asked what color the missing object was or what direction it was tilted (left or right), the record of participants' eye movements allowed us to see whether they looked at the blank region on the computer screen where the object used to be.

Method

Participants

Thirty-two undergraduates participated in this experiment for psychology course credits. All participants had normal, or corrected with contacts, vision.

Apparatus and procedure

As in Experiment 1, eye movements were monitored by an ISCAN eyetracker mounted on top of a lightweight headband. Accuracy of the gaze position record was approximately 0.5 deg of visual angle. Stimuli were presented on a 20-inch computer monitor. Each trial began with four objects presented simultaneously in the four corners of the display. On each trial, the objects were randomly selected from a set of ten shapes, and ten randomly assigned colors, and two randomly assigned directions of tilt. A pre-recorded speech file instructed the participants to look at each of the four objects and then at the central cross. The display then went blank for one second, and returned with one of the objects missing. Another pre-recorded speech file then asked one of two probe questions: "What color was the [shape name]?", or "What direction was the [shape name] tilted?" In addition to the within-subject factor of Question Type, a between-subject factor manipulated the Spatial Context in which the objects were presented: No Frame, Frame, and a 3×3 Grid. Figure 2 shows examples of the three spatial context conditions.

Participants ran in two practice trials before beginning the 40-trial experiment. Half of the trials had color questions, and half of them had tilt questions; order was randomized. No participants reported being aware of the experimental hypothesis.

Results and discussion

Despite the fact that there was obviously no directly useful information in the blank region where the queried

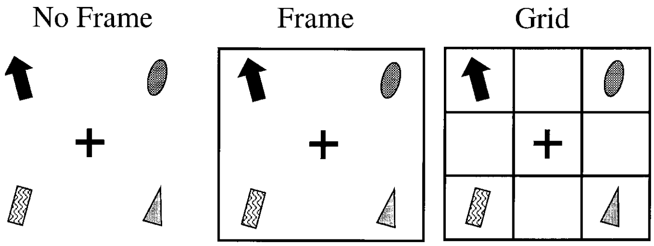

Fig. 2 Example stimulus displays from the three spatial context conditions (textures on the objects indicate different colors)

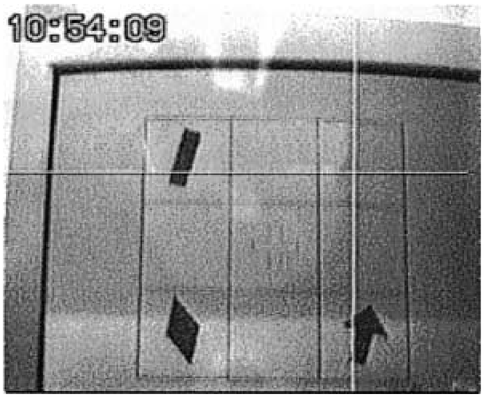

Fig. 3 The view from the scene camera, with eye position superimposed as white crosshairs, showing the participant looking at the blank region of the screen where the missing object used to be. This video frame was taken from a trial on which the participant was asked, "What direction was the [now absent] triangle tilted?"

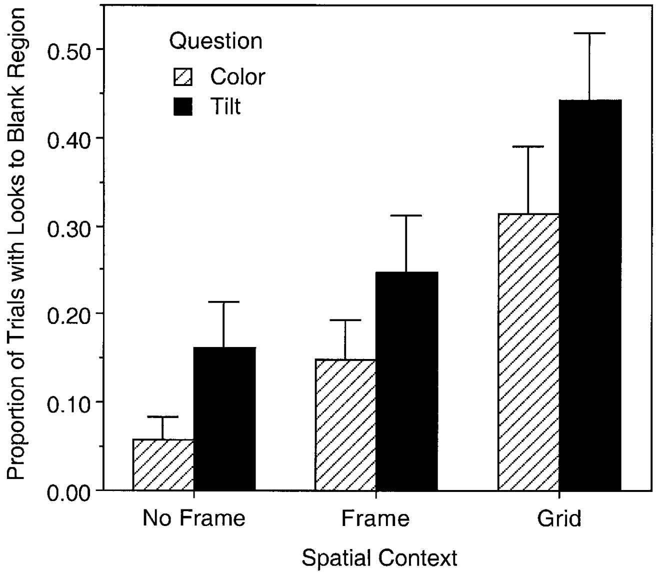

Fig. 4 Trials in which the participants made saccades to the blank region that used to contain the missing object. Tilt questions elicited more such eye movements than color questions, and richer spatial context increased the frequency of such eye movements

object used to be, participants frequently fixated that blank region (overall, 24.4% of the trials) when trying to recall the information requested (Fig. 3). The remaining 76% of trials usually involved maintenance of fixation on the central cross throughout the question period. However, the regions with visible objects were each fixated about 7% of the time, and participants occasionally looked outside the entire stimulus display (2% of the trials) while answering the probe question.

The main effect of Question Type showed that participants were overall more likely to look at the missing object's empty location following tilt questions (30%) than following color questions (18.7%); $F(1, 29) = 14.98$, $P < 0.001$. Additionally, participants were more likely to look at the blank region where the missing object used to be when the display had a rich spatial context, such as a 3×3 grid (37.8%), than when the display merely had a circumscribing frame (19.8%), or when there was no frame (aside from that provided by the computer monitor itself) (10.9%); $F(2, 29) = 5.18$, $P < 0.02$. There was no interaction; $F < 1$ (Fig. 4).

Looking at the blank region of the display is not likely to be an 'informative' fixation, given that there is no visual information there to directly aid in recall. Moreover, the positions for the objects are central enough in the visual field to allow the observer to easily perceive in peripheral vision that the critical location is indeed empty. Nonetheless, participants systematically "looked at nothing" when attempting to recall something. Thus, in line with recent arguments for position being a property of visual perception deserving of special treatment (e.g., van der Heijden, 1993; van der Heijden, Müsseler, & Bridgeman, 1999; and Hommel, Automatic integration of spatial information, submitted), it would appear that spatial position of the now-absent object is a salient enough attribute to attract an eye movement even when it is irrelevant to the probe question. It is as though participants have stored their memory of that now-absent object not only in their minds but also in a particular location in external space, and their cognitive search in memory is paralleled by an oculomotor search in space.

A similar kind of finding by Glenberg, Schroeder, and Robertson (1998) demonstrated that when participants attempt to answer difficult questions, they tend to avert their gaze from engaging visual stimuli (presumably to reserve processing resources for answering the question). However, an important difference between the findings of Glenberg et al. and the present result is that the participants in these experiments did not look at just *any* nothing, such as the many other empty areas of the computer screen, or the wall behind it; they looked at a *particular* nothing – perhaps one that had a visual pointer (Ballard, Hayhoe, Pook, & Rao, 1997) or spatial index (Pylyshyn, 1989) allocated to it, which was activated by the probe question.

Similar to the discussion of Experiment 1, one might hypothesize that participants were using eye position and the visuospatial context surrounding the blank region for facilitating a pattern completion process during recall (e.g., fulfilling a Hebbian cell assembly, cf. Pulvermüller, 1999) – similar to state-dependent memory (e.g., Eich, 1980; Kothari, Lotlikar, & Cahay, 1998; Overton, 1985). However, accuracy in recall (which averaged about 80% in each condition) was no different for trials in which participants looked at the blank region versus trials in which they did not; $F < 1$. Nonetheless, it may be that some of the eye movements to the object's now-empty location are produced precisely because the participant is unsure of the answer, and he/she is attempting some location-dependent memory cueing. Additionally, many of the trials in which the participant did not look at the empty location may have had high accuracy simply because the answer was immediately salient enough to allow a response before any exploratory eye movements could be produced.

Alternatively, it may be that when attempting to access the visual memory, the stored (or perhaps reconstructed) visual representation activates, in a predominantly feed-forward manner, the oculomotor parameters (and/or spatial index) that accompanied the forming of that visual memory. However, this oculomotor representation (and/or spatial index), once activated, may not send feedback to the memory representation, thus not facilitating any pattern completion to improve accuracy in recall. Future work will involve explicitly controlling participants' fixation to further test for influences on memory.

The difference between tilt questions and color questions may be related to the difference between dorsal and ventral pathways in visual perception (e.g., Bridgeman, 1999; DeYoe & Van Essen, 1988; Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983). Perhaps oculomotor parameters are more closely associated with (and therefore more readily activated by) representations of spatial relations, such as tilt, than with representations of intrinsic object properties, such as color. The difference between spatial context conditions is probably due to the fact that spatial context provides more readily usable visual landmarks on which the fixation system can be anchored.

Similar work on this phenomena has reported eye movements to blank regions elicited by questions about auditory and semantic – rather than visual – information acquired while fixating a particular region of the visual field (Richardson & Spivey, 2000). Future work will examine whether the oculomotor representation that gets activated is in body-centered (egocentric) or spatial (allocentric) coordinates, and whether the spatial index associated with this oculomotor representation is typically attached to locations or to objects.

General discussion

We have reported evidence for spontaneous and sophisticated use of eye movements during imagery and visual memory tasks, indicating that the same perceptual-motor mechanisms used for viewing a scene are also activated by imagining a scene, as well as remembering elements of a scene. Our findings suggest that, when constructing or interrogating a spatial mental model (e.g., Bower & Morrow, 1990; Johnson-Laird, 1983, 1996), eye movements (or perhaps spatial indexes to which eye movements respond, e.g., Ballard et al., 1997; Pylyshyn, 1989) are used to coordinate elements of the internal model with elements of the external world. Moreover, from a methodological perspective, these results demonstrate the informativeness of eyetracking even in circumstances where there is no relevant visual stimulus. Clearly, eye movements are not random behaviors. In appropriate experimental tasks – even ones that involve little or no visual stimuli – eye movements can provide a unique window into the moment-by-moment representations computed for a wide range of perceptual/cognitive processes (Ballard et al., 1995; Land et al., 1998; Tanenhaus et al., 1995).

These findings of visual imagery and memory eliciting particular eye movements fit naturally with neuroimaging evidence for visual imagery activating regions of cortex that are specialized for visual perception (e.g., Farah, 1995; Kosslyn et al., 1995). The oculomotor system should respond to a sufficiently active visual representation regardless of whether that visual representation was generated by visual input, linguistic input, or from memory. After all, how would it know the difference? Moreover, the fact that these eye movements are not directly driven by any external visual input places emphasis on the embodiment of mind (e.g., Ballard et al., 1997; Barsalou, 1999; Glenberg, 1997; Thelen, 1995; Varela, Thompson, & Rosch, 1991), whereby cognition (e.g., language processing, visual cognition, imagery, memory) is tightly coupled with what motor output is at the brain's disposal (Demarais & Cohen, 1998; Hommel & Knuf, in press; Jordan, 1999; Müsseler, 1999; Paillard, 1999; Wolff, 1999). Our findings point to an embodied mind that naturally activates 'lower-level' motor processes to accompany 'higher-level' cognitive processes because, rather than being separate functions that are triggered after the instantiation of a mental state, motor processes are intrinsic components of the mental state.

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