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Spatial reference frame of incidentally learned attention

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ABSTRACT

Visual attention prioritizes information presented at particular spatial locations. These locations can be defined in reference frames centered on the environment or on the viewer. This study investigates whether incidentally learned attention uses a viewer-centered or environment-centered reference frame. Participants conducted visual search on a monitor laid flat on a tabletop. During training, the target was more likely to appear in a "rich" quadrant than in other "sparse" quadrants. Although participants were unaware of this manipulation, they found the target faster in the rich quadrant than in the sparse quadrants, showing probability cuing. In a subsequent testing phase, participants were reseated to change their viewpoint by 90°. In addition, the target became equally likely to appear in any quadrant. Spatial attention continued to be biased for several hundred trials. Critically, the attentional bias moved with the participant, shifting to a previously sparse quadrant on the screen. Incidental learning of a target's likely locations led to a persistent, egocentric spatial bias.

1. Introduction

Spatial attention is critical for selecting perceptual information that may need to be identified and, possibly, acted upon. What is the nature of the spatial representation underlying visual attention? For example, when an online ad captures your attention, is the attended location coded relative to you (e.g., in the upper right visual field) or relative to the external environment (e.g., on the right side of the screen)? This study investigates the spatial reference frame that supports one type of visual attention: incidentally learned attention. We examine whether incidentally learned attention is referenced relative to the viewer or to the environment.

Viewer-centered and environment-centered reference frames meet different computational demands. An environment-centered reference frame provides stability in the face of locomotion and changes in viewpoint. Yet it is computationally expensive. Neurons in the visual cortex are retinotopically mapped (Engel, Glover, & Wandell, 1997; Gardner, Merriam, Movshon, & Heeger, 2008; Golomb & Kanwisher, 2011; Saygin & Sereno, 2008). In the parietal cortex, neurons code space relative to the eyes, head, or trunk (Andersen, Snyder, Bradley, & Xing, 1997; Colby & Goldberg, 1999). Location information that is coded in parietal cortex would therefore need to be transformed to an environmental reference frame if one is used for attentional processes. A viewer-centered reference frame is computationally less expensive, but it is also less likely to survive changes in viewer movement and perspective (Farah, Brunn, Wong, Wallace, & Carpenter, 1990). For example, when a viewer turns 90° to his right, a cup that used to be in front of him is now to his left. Although the cup's location is stable in the environment, it has changed relative to the viewer. Despite this instability, a viewer-centered representation is often reported for spatial navigation (Wang & Spelke, 2000; Wang et al., 2006). Viewers apparently remap external space as they move through the environment (Farrell & Robertson, 1998; Mou, McNamara, Valiquette, & Rump, 2004; Rieser, 1989; Shelton & McNamara, 2001; Simons & Wang, 1998; Wang & Brockmole, 2003a, 2003b; Wang et al., 2006).

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1.1. Attention and spatial reference frames

Empirical data offer evidence that spatial attention may involve multiple mechanisms that utilize diverse frames of reference. Data from patients with hemifield neglect suggest that viewer-centered and environment-centered reference frames may co-exist. When these patients lie on their sides, visual neglect is most severe in the quadrant that is both on the left side of the patients' body and on the left side of the environment assuming an upright posture (Calvanio, Petrone, & Levine, 1987; Farah et al., 1990).

Studies on normal adults have also demonstrated that attentional processes use multiple references frames (Mathot & Theeuwes, 2010; Pertzov, Avidan, & Zohary, 2011). These studies generally use a cuing paradigm in which a cue directs attention to a particular location on the screen. By including conditions in which the eyes move during the brief interval between the cue and target, these studies are able to determine whether the spatial location of the cue is coded relative to the eyes (retinotopically) or according to another reference frame centered on the head, body, or external environment (spatiotopically) (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Wurtz, 2008). If the spatial bias resulting from cuing is retinotopically coded, it should move with saccadic eye movements. But if it is spatiotopically centered, the bias should remain in the same screen location after the eyes have moved. This logic was used to study the nature of attention involved in inhibition of return, the finding that people are slower to respond to stimuli at recently attended locations (Klein, 1988; Posner & Cohen, 1984; Tipper, Driver, & Weaver, 1991). Following an eye movement, the inhibited location does not move with the eyes, but stays at the screen location where the cue was presented (Maylor & Hockey, 1985; Pertzov, Zohary, & Avidan, 2010; Posner & Cohen, 1984). However, inhibition of return can sometimes stay at the retinal location of the cue, particularly when people make an eye movement toward a target rather than a manual, keypress response (Abrams & Pratt, 2000).

Like inhibition of return, studies examining sustained attention have demonstrated the use of both retinotopic and spatiotopic reference frames. For example, when attention must be sustained at a remembered screen location for several seconds, it stays at the retinal location of the memory cue for a brief period of time following a saccade (Golomb, Chun, & Mazer, 2008). Facilitation at the spatiotopically-mapped location is also found when the location is task relevant and there is sufficient time for spatiotopy to develop (Golomb, Nguyen-Phuc, Mazer, McCarthy, & Chun, 2010a; Golomb, Pulido, Albrecht, Chun, & Mazer, 2010b; Golomb et al., 2008).

In sum, previous studies investigating relatively short-lived attentional effects have found evidence for both retinotopic reference frames (which are viewer-centered) and spatiotopic reference frames (which could be either viewer- or environment-centered). The dominant form of representation partly depends on the task (e.g., manual versus oculomotor response) and the type of attention (transient exogenous attention or sustained attention). These studies suggest that both types of reference frames are important for attentional orienting, and in some cases, they may coexist (Golomb et al., 2010b; Mathot & Theeuwes, 2010; Pertzov et al., 2011). However, because of the transient nature of the cuing effects, these studies do not permit locomotion or changes in position during the interval between the cue and the target. Therefore, they have been unable to dissociate viewer-centered from environment-centered reference frames.

This study will focus on the spatial reference frame used by one type of attention – incidentally learned attention. In contrast to attentional cueing, incidentally learned attention persist over long periods of time, providing a unique opportunity to dissociate viewer-centered from environment-centered reference frames.

1.2. Incidentally learned attention

Extensive research demonstrates that people can allocate spatial attention based on their previous experience, often without any intention to learn (Chalk, Seitz, & Series, 2010; Chun & Jiang, 1998; Geng & Behrmann, 2002; Jimenez, 2003; Umemoto, Scolari, Vogel, & Awh, 2010). For example, in one type of implicitly learned attention, *probability cuing*, attention is biased to locations that were likely to contain a search target in the past (Geng & Behrmann, 2002; Jiang, Swallow, Rosenbaum, & Herzig, 2012). Unlike other types of attentional biases, those developed from probability cuing persist over long periods of time, lasting as long as one week (Jiang, Swallow, Rosenbaum, et al., 2012). They are also highly resistant to extinction. When the target's location becomes evenly distributed, participants continue to prioritize the previously rich locations, even after several hundred trials of extinction training (Jiang, Swallow, & Rosenbaum, 2012; Jiang, Swallow, Rosenbaum, et al., 2012).

Incidentally learned attention differs from more traditional forms of attention in at least two important ways. First, unlike other forms of attention that reflect a transient change in the environment and task, incidental learning occurs over hundreds of trials and reflects stable properties of the environment. As a result, it may be advantageous to code learned attentional biases relative to the external world. In addition, probability cuing exists on a much longer time scale than do other forms of attentional cuing. Exogenous attention peaks about 150 ms after the onset of the cue, turning into inhibition of return after about 300 ms (Nakayama & Mackeben, 1989; Posner & Cohen, 1984). Endogenous attention is more sustained, but it critically depends on the validity of the cue (Müller & Rabbit, 1989; Posner, 1980). Priming of popout, the facilitation in response when targets repeat their locations or features on successive trials, may last several seconds (Ball, Smith, Ellison, & Schenk, 2009, 2010; Maljkovic & Nakayama, 1996). Yet it is still much shorter than probability cuing, which persists for at least a week after training (Jiang, Swallow, & Rosenbaum, 2012; Jiang, Swallow, Rosenbaum, et al., 2012). Because of these differences, probability cuing may use a different reference frame than the more transient forms of attention.

1.3. Current study

In three experiments we investigated the spatial reference frame used in probability cuing. In contrast to most