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Where you are affects what you can easily imagines environmental geometry elicits sensorimotor interference in remote perspective taking

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ABSTRACT

Imagined perspective switches are notoriously difficult, a fact often ascribed to sensorimotor interference between one's to-be-imagined versus actual orientation. Here, we demonstrate similar interference effects, even if participants know they are in a remote environment with unknown spatial relation to the learning environment. Participants learned 15 target objects irregularly arranged in an office from one orientation (0°, 120°, or 240°). Participants were blindfolded and disoriented before being wheeled to a test room of similar geometry (exp.1) or different geometry (exp.2). Participants were seated facing 0, 120°, or 240°, and asked to perform judgments of relative direction (JRD, e.g., imagine facing "pen", point to "phone"). JRD performance was improved when participants' to-be-imagined orientation in the learning room was aligned with their physical orientation in the current (test) room. Conversely, misalignment led to sensorimotor interference. These concurrent reference frame facilitation/interference effects were further enhanced when the current and to-be-imagined environments were more similar. Whereas sensorimotor alignment improved absolute and relative pointing accuracy, sensorimotor misalignment predominately increased response times, supposedly due to increased cognitive demands. These sensorimotor facilitation/interference effects were sustained and could not be sufficiently explained by initial retrieval and transformation costs. We propose that facilitation/interference effects occurred between concurrent egocentric representations of the learning and test environment in working memory. Results suggest that merely being in a rectangular room might be sufficient to automatically re-anchor one's representation and thus produce orientation-specific interference. This should be considered when designing perspective-taking experiments to avoid unintended biases and concurrent reference frame alignment effects.

1. Introduction

People commonly imagine places that differ from their actual location, as in planning a route, giving directions, or daydreaming about a future vacation. Is one's ability to imagine a distant place affected by one's physical orientation in the local environment? This is the question we hoped to answer in the present research.

To imagine a distal environment, one must adopt a perspective in that space. Perspective taking tasks are typically easier in a remote environment than in the immediate environment (May, 1996, 2000; Waller, Montello, Richardson, & Hegarty, 2002; Wang, 2003). Both local and remote perspective switches require us to establish an additional reference frame of the to-be-imagined environment in the to-be-imagined orientation in spatial working memory. For local perspective switches, however, there is an additional challenge as one's actual orientation in the environment conflicts with the to-be-imagined perspective, leading to sensorimotor interference costs (Avraamides & Kelly, 2008; May, 2004, 2007; May & Wartenberg, 1995; Wang, 2005).

In this study, we demonstrated that interference between actual and to-be-imagined orientations can occur even if the to-be-imagined environment is remote and participants do not know their physical orientation with respect to the to-be-imagined orientation. This effect has implications for our understanding of facilitation and interference effects in human spatial memory, and suggests that facilitation or interference effects might occur both in psychological testing of human spatial memory and in applications such as virtual environments and teleoperation.

Although cognitive models of human spatial memory differ in specific details, much of the evidence agrees on the existence of three components or subsystems: An **allocentric** subsystem

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comprising long-term spatial memories that are orientation dependent and structured around a small number of environment-centered reference axes; a **viewpoint dependent** subsystem that represents the appearances of landmarks and scenes; and an **egocentric** subsystem that computes and represents transient self-to-object spatial relations needed for online actions, such as avoiding obstacles, following paths, and pointing to objects in the proximal environment (e.g., Avraamides & Kelly, 2008; Burgess, 2006, 2008; Easton & Sholl, 1995; May, 2004; Mou, McNamara, Valiquette, & Rump, 2004; Sholl, 2001; Valiquette & McNamara, 2007; Waller & Hodgson, 2006; Wang & Spelke, 2002).

To study the organization of long-term spatial memories, researchers commonly remove participants from the environment to avoid potential sensorimotor interference (***remote testing***), and then employ perspective-taking tasks such as judgment of relative direction (JRD) tasks (e.g., "imagine standing in the middle of your office, facing the computer, point to the door"). Acting on an imagined perspective using a bodily response like pointing requires that the spatial relations be retrieved from long-term memory and mentally transformed into a body-centered representation in spatial working memory in the intended perspective (Avraamides & Kelly, 2008; Sholl, 2001). Remote perspective-taking should thus be facilitated and mental transformation costs reduced when the to-be-imagined heading is already aligned with the main reference axis or axes used to encode the environment in long-term memory.

When people are asked to imagine perspective switches in the immediate environment (***situated testing***), however, task difficulty and cognitive effort increases, and performance drops, even with eyes closed (Presson, 1987; Presson & Montello, 1994; Rieser, 1989). This additional cost is typically attributed to sensorimotor interference between two misaligned egocentric representations of the immediate environment in spatial working memory (May, 1996, 2000, 2004; May & Wartenberg, 1995; Presson & Montello, 1994; Wang, 2005).

As sensorimotor interference is thought to originate from interference between two misaligned representations of the *same*, immediate environment in working memory, it should only occur for situated testing, but not for remote testing, as remote objects should not normally be represented in one's sensorimotor representation (May, 1996, 2000; Waller et al., 2002; Wang, 2003). However, even for remote testing, deliberate cognitive re-anchoring in the learning environment can sometimes result in interference effects for imagined perspectives that are misaligned with the re-anchored perspective, mimicking sensorimotor interference effects even though participants are not physically located in the imagined environment. These effects occur when (a) participants vividly imagine being in the original learning room while either being blindfolded (May, 2007; Shelton & Marchette, 2010) or in a virtual room that is visually identical to the learning room apart from a different wall texture (Kelly, Avraamides, & Loomis, 2007); (b) participants are uncertain about their actual location, or suspect or have sensorimotor cues indicating that they might be back in the original learning room (Kelly et al., 2007; Shelton & Marchette, 2010); or (c) the virtual test room and learning rooms are visually identical (Kelly et al., 2007, Exp. 4).

To the best of our knowledge, no study has tested whether sensorimotor or concurrent reference frame alignment effects occur when participants have their eyes open in a real remote environment and are well aware that they are no longer in the learning environment, thus avoiding any suggestion or possibility that they might back in the learning room (Kelly et al., 2007; Shelton & Marchette, 2010). In short, does the direction in which you are facing in the immediate environment affect your ability to imagine a remote environment, even if you can see and know for sure that you are *not* in the remote environment? If such interference would exist despite being in a different location (*remote testing*), this could have implications for many perspective taking tasks and would need to be considered in experiments to avoid potential confounds.

To address this question, we asked participants to learn the layout of 15 everyday office objects irregularly but naturally arranged in a rectangular cluttered office (see Fig. 1). Three participant groups learned the layout of objects at three different headings (H_{learn} = {0°, −120°, +120°}). Participants were then moved to a different test room, while being disoriented and distracted, and seated in different physical orientations in that room (H_{test} = {0°, −120°, +120°}). They were asked to perform JRDs from different to-be-imagined perspectives (H_{TBI} = {0°, −120°, +120°}) in the remote learning room. Experiment 1 used a test room that had similar layout and geometry as the learning room (but none of the objects in the learning room), whereas Experiment 2 used a cluttered, larger test room of different geometry and layout to investigate if the previously-found results would generalize to more general, naturalistic situations of largely dissimilar spaces. The experimental conditions are illustrated in Fig. 2.

2. Experiment 1

The first experiment was designed to address the following research questions and hypotheses.

2.1. RH1: Sensorimotor alignment effect

We posited that JRD performance would be facilitated if the to-be-imagined heading in the learning room matched participants' actual heading in the test room, even though participants were not aware of the relative orientation of the two rooms and received no cognitive re-anchoring instructions. Conversely, we predicted that misalignment[1] between to-be-imagined and test headings would reduce JRD performance, potentially due to interference or reference frame conflict between participants' concurrent egocentric mental representation of the to-be-imagined environment and sensorimotor-defined actual environment (Avraamides & Kelly, 2008; von der Heyde & Riecke, 2002; Riecke, 2003). The second and third hypotheses investigated two aspects of the memory-encoding alignment effect (Avraamides & Kelly, 2008).

2.2. RH2 & RH3: Memory-encoding alignment effect for environmental reference frame and learning orientation

We hypothesized that JRD performance would be improved if the to-be-imagined heading in the learning room was aligned with the main reference axis of the learning room and/or a salient object in the learning room (RH2), or aligned with the heading direction during learning in the learning room (RH3). Such results would replicate previous findings (e.g., Mou & McNamara, 2002; Shelton & McNamara, 2001), but in a more ecologically valid context (e.g., irregularly arranged objects in a cluttered, natural space).

2.3. Method

2.3.1. Participants

Thirty-six naïve participants (16 men) from the Nashville community were paid for participating (average age = 22.3 years). All experimental procedures were approved by the Vanderbilt University IRB.

[1] We use the term "alignment" and "misalignment" as generic terms to refer to the spatial match vs. mismatch between different actual, to-be-imagined, and remembered/learning orientations, without any theoretical claims about underlying processes which might well be different for sensorimotor alignment and memory-encoding alignment effects.