Cognition 169 (2017) 1–14

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

Where you are affects what you can easily imagine: Environmental geometry elicits sensorimotor interference in remote perspective taking

Bernhard E. Riecke[a,b,*], Timothy P. McNamara[a]

[a] Vanderbilt University, USA
[b] Simon Fraser University, Canada

ARTICLE INFO

Article history:
Received 11 May 2016
Revised 29 July 2017
Accepted 31 July 2017
Available online 9 August 2017

Keywords:
Spatial cognition
Perspective-taking
Sensorimotor interference
Concurrent reference frame alignment/interference
Reference frame conflicts
Spatial memory
Spatial updating

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.

© 2017 Elsevier B.V. All rights reserved.

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

* Corresponding author at: School of Interactive Arts & Technology (SIAT), Simon Fraser University, 250-13450 102nd Ave, Surrey, BC V3T 0A3, Canada.
E-mail address: ber1@sfu.ca (B.E. Riecke).
URL: http://iSpaceLab.com/Riecke (B.E. Riecke).

http://dx.doi.org/10.1016/j.cognition.2017.07.014
0010-0277/© 2017 Elsevier B.V. All rights reserved.

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.

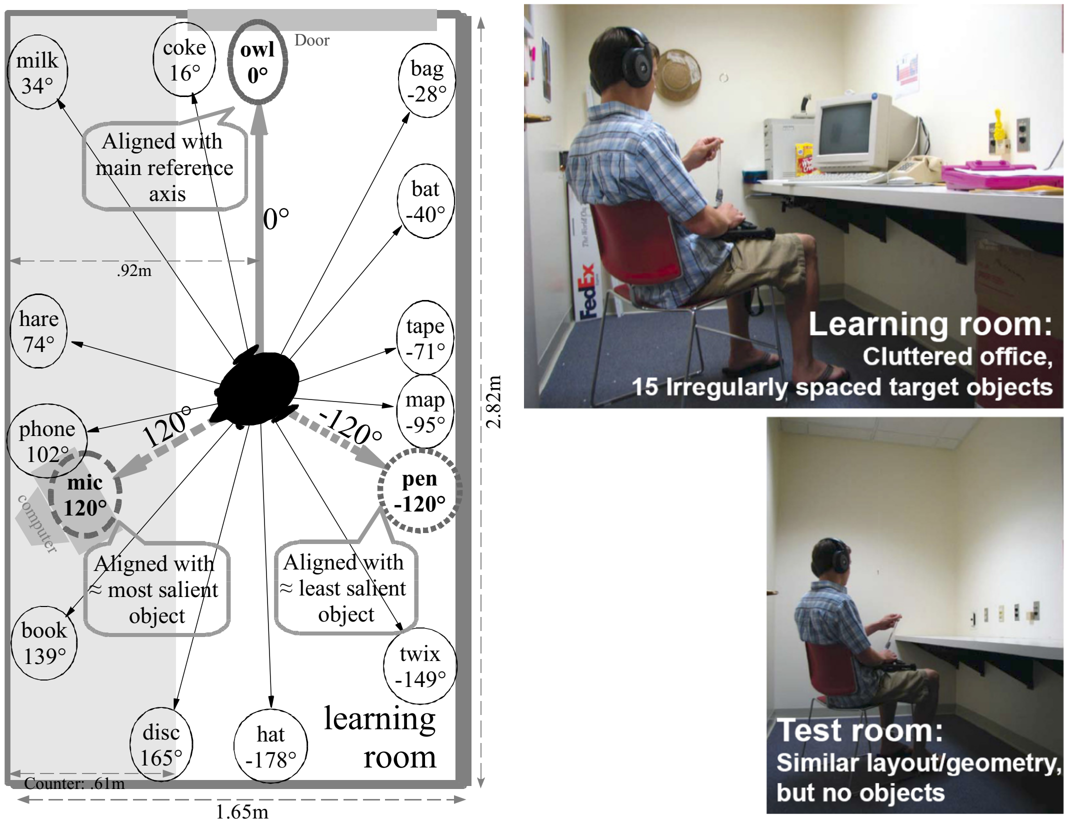

Fig. 1. **Left**: Top-down schematic of the learning room, depicting an observer facing 120°. **Right**: Picture of actual learning room (top) and test room (bottom), with a participant seated facing 120°. Note the similar room geometry.

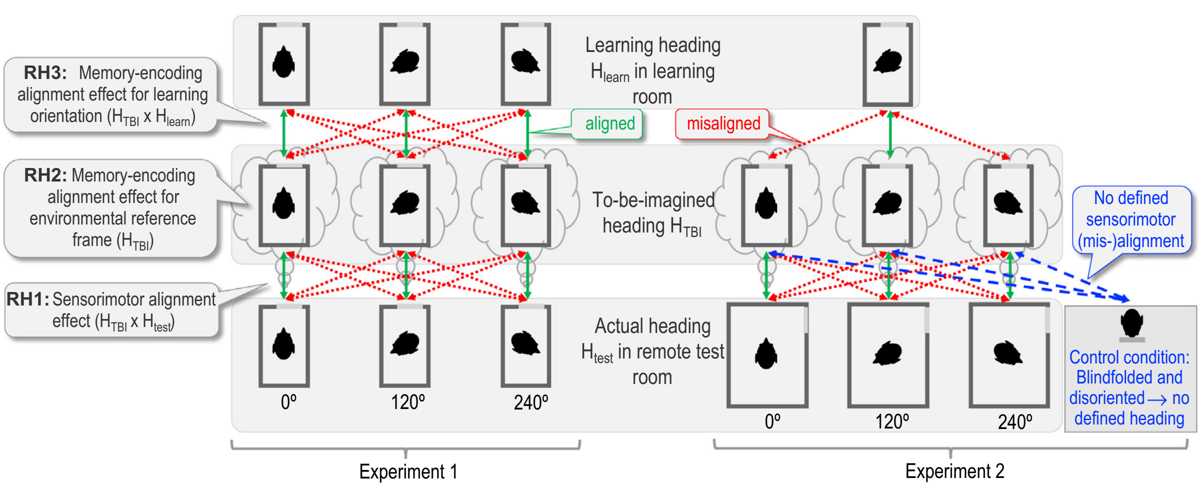

Fig. 2. Schematic overview of the experimental conditions for Experiment 1 (left) where learning and test room had similar geometry, and Experiment 2 (right) where the test room was larger and had a different geometry and layout. Solid green lines indicate the aligned conditions where the to-be-imagined heading H_{TBI} (middle row) is aligned with the actual heading H_{test} during testing (bottom row, research hypothesis RH1) or the participants' heading H_{learn} during learning (top row, RH3). Misaligned conditions are depicted as dotted red lines. Disoriented and blindfolded control conditions where sensorimotor alignment is undefined are depicted as blue dashed lines. To give an example, the far-left column describes an experimental condition in Experiment 1 in which participants who learned the learning room facing $H_{learn} = 0°$ were asked to imagine facing $H_{TBI} = 0°$ while being seated facing $H_{test} = 0°$ in the actual room. As learning, imagined, and actual headings were all aligned in this condition (H_{learn} = -$H_{TBI} = H_{test} = 0°$), the connecting vertical arrows for this condition are both depicted in green.

2.3.2. Materials

We used a natural, cluttered office as the learning room and selected 15 target objects with one-syllable names that were positioned irregularly throughout the room (see Fig. 1). The test room had similar size, but was completely empty apart from a wall-mounted countertop (see Fig. 1, bottom right). Pointing was performed using a modified wireless Logitech Freedom 2.4 joystick that was mounted on a wooden board positioned on the participant's lap. To increase pointing accuracy, the handle of the joystick was replaced by a 20 × 0.9 cm Plexiglas rod (see Fig. 1, right), and participants were asked to hold the tip of the joystick handle with their index finger and thumb using a precision grip. Participants were asked to point as accurately and quickly as possible to target objects announced via pre-recorded text-to-speech sound files played over wireless headphones (Sennheiser HDR 130). They were asked not to sacrifice pointing accuracy for speed. For each JRD block, participants were instructed via headphones to "imagine facing X", where X was one of the three facing objects, followed by consecutive pointing trials ("point to Y") to six different randomly selected target objects (other than the facing object). Throughout the test phase, participants were asked to keep their eyes open. We did not provide explicit instructions or preprocessing time to cognitively re-anchor in the learning room (cf., Kelly et al., 2007; May, 2007; Shelton & Marchette, 2010).

2.3.3. Procedure

Participants did not experience the spatial relationship between the learning and the test rooms. After providing informed consent, participants were seated on a swivel chair, blindfolded, and disoriented by slowly spinning and moving them around for about one minute before wheeling them to the learning room. Once facing the learning heading, H_{learn}, of 0°, 120°, or -120° relative to the door and main symmetry axis of the room, the blindfold was removed, participants moved to a stationary chair positioned in the center of the learning room (see Fig. 1) and written and verbal instructions were provided. Participants could freely turn their head and upper body to explore the room and learn the target objects as long as they remained seated. The three learning headings were chosen to disambiguate between the influence of alignment with the main reference axis provided by the room geometry for the 0° condition, on the one hand, and a salient facing object (a computer at 120°), on the other hand (see Fig. 1). In the -120° condition, participants were facing a pen that was taped to the wall and was not expected to be a salient object. The relative angular difference between the main room axis (0°), oblique salient direction (120°) and the oblique non-salient direction (-120°) was the same to allow for direct comparison of headings.

In learning phase 1, the computer named each target once in random order, and participants were asked to locate the object and point to it using the joystick. The computer provided auditory feedback about the signed pointing error (e.g., "left, 18°") throughout the learning phase. In learning phase 2, participants were asked to close their eyes during the target announcement and pointing to make sure that they properly learned all target objects. They were free to open their eyes in-between blocks of pointing trials. Target objects were presented in random order until participants had pointed to each target three times with less than 10° absolute error.

Participants were blindfolded upon finishing the learning phase, disoriented, and wheeled on a circuitous path into the test room while the experimenter talked to the participant. This disorientation and distraction procedure was expected to remove participants' egocentric sensorimotor representation of the learning environment, such that subsequent JRD tests should only be based on their long-term memory representation of the learning environment (Waller & Hodgson, 2006). Post-experimental debriefing confirmed that participants had no clue about the relative orientation of learning and test room, and responded at chance level when asked to guess. Once positioned in the test heading, H_{test}, the blindfold was removed for the rest of the experiment.

As illustrated in Fig. 2, participants were seated facing heading directions, $H_{test} = 0°, 120°$, or $-120°$ (3 sessions, within-subject, counterbalanced order), and asked to perform judgments of relative direction using rapid pointing as if they were seated in the center of the learning room facing one of the 3 to-be-imagined headings ($H_{TBI} = 0°, 120°$, or $-120°$, e.g., imagine facing "pen", point to "phone"). For each of the 3 physical headings, participants made 108 pointing judgments, 6 blocks of 6 pointing trials each at each of the 3 imagined headings. Imagined heading was fixed within a block of trials. Target objects were randomly selected within blocks and blocks were presented in a counterbalanced order. The experimenter was never present during testing, but could observe participants through an observation window to ensure that they followed the instructions and kept their eyes open throughout the experiment. Pilot studies and a control study showed that participants seemed to distract themselves from the potentially interfering visual stimulus by closing their eyes or looking at the ceiling or floor (Riecke & Hastings, 2011).

2.3.4. Design

Participants were randomly assigned to three gender-balanced groups of equal size (N = 12 each), one for each of the three learning headings, H_{learn}. As illustrated in Fig. 2, the experimental design comprised a factorial design of 3 learning headings ($H_{learn} = \{0°, 120°, -120°\}$; between-subject) × 3 physical headings during testing ($H_{test} = \{0°, 120°, -120°\}$; within-subject, in three separate sessions in counterbalanced order) × 3 to-be-imagined headings during testing ($H_{TBI} = \{0°, 120°, -120°\}$; within-subject, counterbalanced order) × 6 blocks × 6 pointing trials per block. Each participant therefore completed a total of 324 JRD pointing trials, lasting a total of 35–60 min.

After completing the three test sessions, participants were debriefed, asked to draw the target object layout on a piece of letter-sized paper in their preferred orientation, paid, and thanked for their participation. The map-drawing was used to infer the preferred orientation of participants' mental representation of the target layout (Shelton & McNamara, 1997; Waller, Lippa, & Richardson, 2008).

2.3.5. Dependent measures

Pointing performance was quantified in terms of three dependent measures:

1. Response time was defined as the time between the end of the pointing target announcement and the pointing response, which was registered when the joystick was deflected by more than 90%.
2. Absolute pointing error assessed the accuracy of participant's representation for the different conditions.
3. Configuration error was defined as the mean angular deviation of the signed pointing error, averaged over the six pointing trials per JRD block. The mean angular deviation is the circular statistics analog to the linear standard deviation (Batschelet, 1981, chap. 2.3). Configuration error measures the relative accuracy of pointing to a collection of objects and is an index of the consistency of interobject spatial relations in memory (Wang & Spelke, 2000). Unlike absolute pointing error, configuration error is independent of overall heading errors.

Although these three dependent variables measure distinct and complementary aspects of participants' performance, we expected them to show similar effects based on prior research (May, 2004; Riecke, Cunningham, & Bülthoff, 2007; Wang & Spelke, 2000) and the assumption that they all reflect aspects of overall task difficulty.

2.4. Results and discussion

Pointing data were analyzed in separate 3 (H_{learn}) × 3 (H_{test}) × 3 (H_{TBI}) mixed-model ANOVAs (Table 1) and planned pair-wise contrasts for the dependent variables absolute pointing error, configuration error, and response time. Greenhouse-Geisser correction was applied where needed. Participants' actual heading in the test room H_{test} showed no direct effect on performance and no interaction with learning heading H_{learn} (cf. Table 1).

Table 1
ANOVA results for Exp. 1 for the different main effects and interactions for the independent variables learning heading H_{learn}, test heading H_{test}, and to-be-imagined heading H_{TBI}.

Independent variable	Hypothesis	Absolute pointing error					Configuration error					Response time				
		df	F(df, 33)	p	η_p^2	power	df	F(df, 33)	p	η_p^2	power	df	F(df, 33)	p	η_p^2	power
H_{learn}		2	1.72	0.195	0.094	0.335	2	10.33	0.277	0.075	0.267	2	00.34	0.717	0.020	0.099
H_{test}		2	1.65	0.199	0.048	0.337	2	1.00	0.372	0.029	0.218	2	1.60	0.209	0.046	0.328
$H_{test} \times H_{learn}$		3.52	1.14	0.346	0.064	0.314	3.89	0.92	0.458	0.053	0.270	3.68	0.11	0.973	0.007	0.070
H_{TBI}	RH2✔	**2**	**13.48**	**<0.001**	**0.290**	**0.997**	1.69	0.68	0.486	0.020	0.150	**2**	**9.68**	**<0.001**	**0.227**	**0.978**
$H_{TBI} \times H_{learn}$	RH3✔	**3.57**	**9.11**	**<0.001**	**0.356**	**0.998**	**3.38**	**8.00**	**<0.001**	**0.326**	**0.992**	**3.87**	**4.44**	**0.003**	**0.212**	**0.915**
$H_{TBI} \times H_{test}$	RH1✔	**4**	**46.01**	**<0.001**	**0.582**	**1.000**	**2.59**	**39.05**	**<0.001**	**0.542**	**1.000**	**2.48**	**43.02**	**<0.001**	**0.566**	**1.000**
$H_{TBI} \times H_{test} \times H_{learn}$		4.53	1.64	0.166	0.090	0.514	5.19	1.70	0.141	0.093	0.573	4.96	0.88	0.501	0.050	0.297

Significant effects are typeset in bold.

2.4.1. RH1: Sensorimotor alignment effect

There were significant interactions between participants' actual heading in the test room H_{test} and their to-be-imagined heading in the learning room H_{TBI} ($p < 0.001$, see Table 1). As predicted by research hypothesis 1 and shown in Fig. 3, performance improved when participants' heading in the empty test room was aligned with the corresponding to-be-imagined heading in the learning room ($H_{TBI} = H_{test}$) versus misaligned ($H_{TBI} - H_{test} = \pm 120°$): absolute pointing error, $F(1, 33) = 74.72$, $p < 0.001$, $\eta_p^2 = 0.694$; configuration error, $F(1, 33) = 81.63$, $p < 0.001$, $\eta_p^2 = 0.712$; response time, $F(1, 33) = 83.53$, $p < 0.001$, $\eta_p^2 = 0.717$. Power was always >0.999. The effect sizes η_p^2 averaged around 0.7, indicating that about 70% of the observed variability in the data presented in Fig. 3 was accounted for by this alignment effect, which is considered a large effect size (Cohen, 1988). Note that response times increased by 65% and absolute pointing error and configuration error increased by about 80% when participants actual heading and to-be-imagined heading mismatched.

2.4.2. RH2: Memory-encoding alignment effect for environmental reference frame

Participants' to-be-imagined heading in the learning room showed significant main effects on absolute pointing error and response time (see Table 1 and Fig. 4), indicating improved JRD performance when participants were asked to imagine facing the room-aligned heading ($H_{TBI} = 0°$) compared to the oblique heading ($H_{TBI} = -120°$): pointing error, $F(1, 11) = 11.65$, $p = 0.002$, $\eta_p^2 = 0.261$, power = 0.912; response time, $F(1, 11) = 14.07$, $p = 0.001$, $\eta_p^2 = 0.299$, power = 0.953. Configuration error showed no such benefit for imagining facing the room-aligned heading (see Table 1 and Fig. 4). This might be related to the target objects being embedded in a natural environment and rectangular room, although further research is needed to investigate this issue. Imagining facing a highly salient object (the computer at $H_{TBI} = 120°$) did not result in performance benefits compared to facing an object of low saliency (the pen at $H_{TBI} = -120°$): absolute pointing error ($F(1, 11) = 1.3$, $p = 0.262$, $\eta_p^2 = 0.038$, power = 0.198); response time ($F(1, 11) = 0.156$, $p = 0.696$ $\eta_p^2 = 0.005$, power = 0.067). These memory-encoding alignment effects highlight the importance of room geometry and intrinsic reference axis for the retrieval of spatial relations from memory.[2]

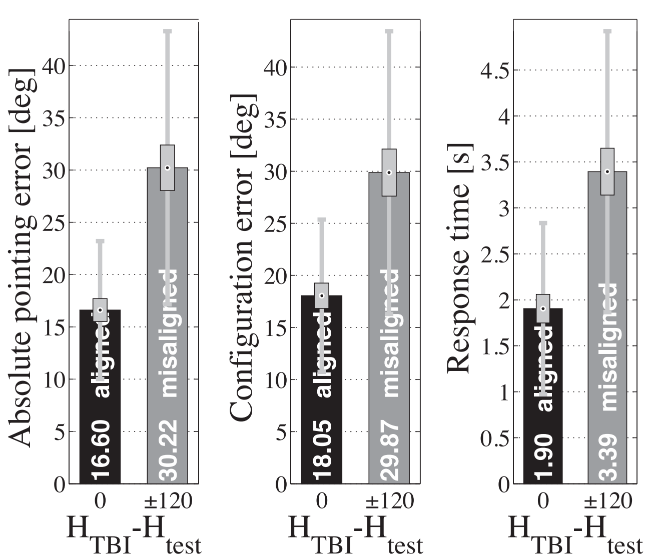

Fig. 3. Mean of dependent measures for the conditions where the to-be-imagined heading H_{TBI} was aligned with participants' current heading in the test room H_{test} ($H_{TBI} - H_{test} = 0°$, black bars) as compared to the conditions where they were misaligned ($H_{TBI} - H_{test} = \pm 120°$, gray bars). Boxes and whiskers depict ± one standard error and one standard deviation, respectively.

2.4.3. RH3: Memory-encoding alignment effect for learning orientation

There were significant interactions between the learning heading and the to-be-imagined heading in the learning room for all three dependent measures (see Table 1). As predicted by research hypothesis 3 and shown in Fig. 5, participants pointed faster, more accurately, and with lower configuration error when the to-be-imagined heading H_{TBI} matched their learning heading H_{learn} (absolute pointing error, $F(1, 33) = 25.12$, $p < 0.001$, $\eta_p^2 = 0.433$, power = 0.998; configuration error, $F(1, 33) = 17.45$, $p < 0.001$, $\eta_p^2 = 0.346$, power = 0.982; response time, $F(1, 33) = 12.59$, $p < 0.001$, $\eta_p^2 = 0.276$, power = 0.931). Although there was no direct benefit of learning the room in a particular orientation (cf. Table 1), the above analysis indicates that retrieving a given perspective from long-term memory and acting upon it via pointing is easier and more accurate for the learned perspective, replicating past findings.

2.4.4. Potential mechanisms underlying sensorimotor alignment effects

Although the test room was essentially empty, did not contain any of the target objects, and thus clearly looked like a different room and participants knew that they were indeed in a different room, merely being seated in an orientation that matched the to-be-imagined heading in the learning room improved performance. This suggests that one's physical orientation in space (here: a rectangular room) can influence which orientations in a previously

[2] This primacy of room geometry over object saliency for memory-encoding alignment effects was corroborated by post-experimental data: From the 12 participants in the $H_{learn} = -120°$ condition (facing the pen), 10 participants switched to the 0° orientation (aligned with the room) when drawing a map of the target layout, while none switched to the 120° orientation (aligned with the computer). Moreover, 48.1% of participants stated that the JRD task was easiest when asked to imagine facing the owl ($H_{TBI} = 0°$), although only 1/3 of participants learned in this orientation.

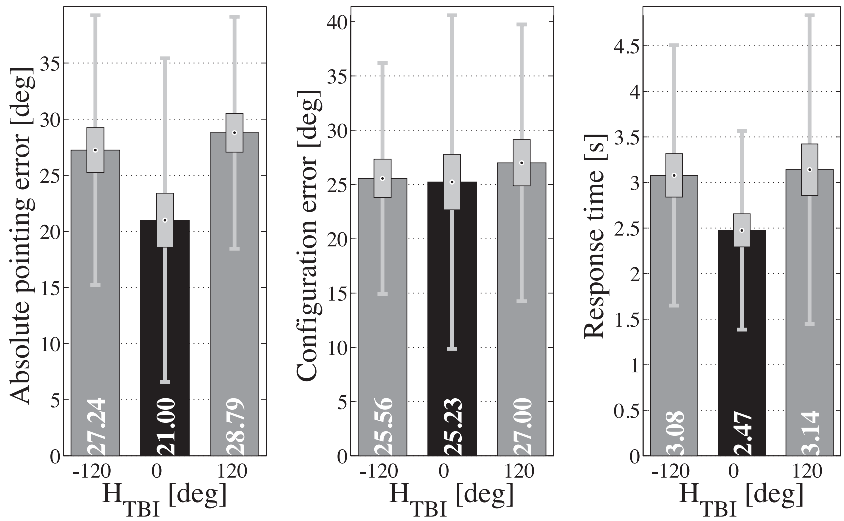

Fig. 4. Mean absolute pointing error, configuration error, and response time, each plotted with respect to the different to-be-imagined headings H_{TBI} and averaged over the other independent variables (H_{learn} and H_{test}). Boxes and whiskers depict ± one standard error and one standard deviation, respectively. Note that both pointing error and response time were reduced when the to-be-imagined perspective H_{TBI} was aligned with the main reference axis of the room (0°, indicated by black bars), but not the salient object (computer at 120°).

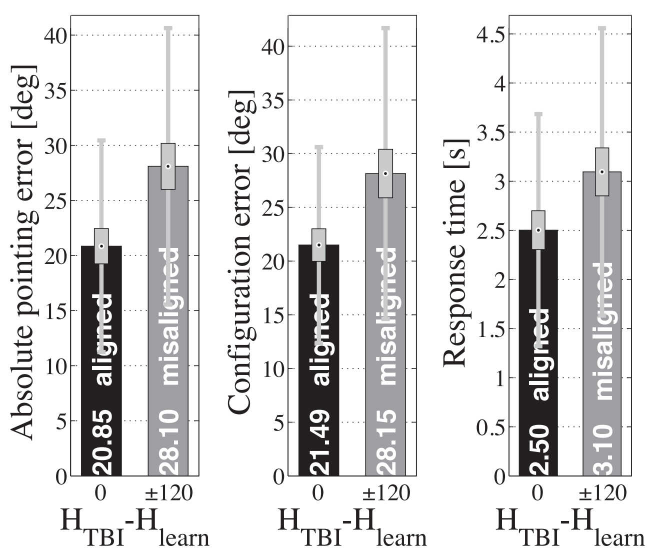

Fig. 5. Mean of dependent measures for the conditions where the to-be-imagined heading H_{TBI} was aligned with participants' heading during learning H_{learn} (H_{TBI} - − H_{learn} = 0°, black bars) as compared to the conditions where they were misaligned ($H_{TBI} - H_{learn}$ = ±120°, gray bars).

learned space are easier or harder to imagine, indicating sensorimotor alignment effects despite being in a remote test environment.

To point from a to-be-imagined perspective in the learning room, one might argue that the observer somehow needs to construct a secondary frame of reference in working memory that can be used to solve the JRD task (Presson & Montello, 1994). In most cases, however, observers will still be aware of their actual surroundings in the test room, which determines their primary (perceptual or sensorimotor) reference frame. This analysis suggests at least two possible causes for the observed interaction effect between H_{TBI} and H_{test} in the current study: Retrieval/mental transformation costs and interference costs.

The ***mental transformation hypothesis*** proposes that the observed difficulty in perspective switches stems mainly from cognitive costs associated with the retrieval of and/or required mental spatial transformations needed to establish the secondary, to-be-imagined reference frame (Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989). It is conceivable that being in a specific orientation in a rectangular room (e.g., aligned with the main room axis) might prime or facilitate the imagination of previously-learned environments from specific perspectives (e.g., also aligned with the main room axis) and thus facilitate the retrieval of spatial representations from long-term memory in that specific orientation (Avraamides & Kelly, 2008). If this were the case, then the observed difficulty of adopting a to-be-imagined orientation should be reflected in additional computational costs for the first one or two pointing trials per JRD block, but largely disappear for later pointing trials, as the retrieval/transformation costs should only apply initially to establish the secondary reference frame (see, e.g., May, 2007). Once established, there should be little or no further orientation-specific costs for maintaining this secondary egocentric representation. This would predict poorer performance for the first one or two pointing trials per JRD block as compared to the later pointing trials.

Alternatively, it is possible that there could be an ongoing, specific interference between one's actual perspective with respect to the test room orientation and the to-be-imagined perspective in the learning room (Kelly et al., 2007; May, 1996, 2004; May & Wartenberg, 1995; Wang, 2005). This ***sensorimotor interference hypothesis*** or more generally ***concurrent reference frame interference hypothesis*** might be conceptualized as a misalignment between the secondary and primary reference frames (or major room symmetry axis in this context) defined by the rectangular learning and test room geometries. Avraamides and Kelly (2008) interpret sensorimotor interference in the context of stimulus-response compatibility effects, wherein performance is impaired if the stimulus and required response are spatially incongruent (e.g., Kornblum, Hasbroucq, & Osman, 1990). Imagining a previously-learned target from an imagined orientation automatically activates sensorimotor codes of the target object in the original sensorimotor reference frame, which in turn primes an egocentric response toward this target object. To perform the JRD task from the to-be-imagined orientation, the participants need to inhibit this automatically triggered sensorimotor code, which is cognitively effortful and requires the sustained suppression of the "wrong" egocentric sensorimotor representation. Such an ongoing concurrent reference frame interference should be reflected in costs/benefits not only for the first pointing trials of each JRD block (i.e., the adoption of a new perspective via retrieval from long-term memory), but throughout the whole JRD block (May, 2007). To disambiguate between the mental transformation and sensorimotor interference hypotheses, we included the independent variable pointing trial number in two additional ANOVAs for response time and absolute pointing error (configuration error was excluded, as it cannot be defined for individual pointing trials). We also re-ran the initial ANOVAs and contrast analyses with the first two pointing trials per JRD block removed.

The **mental transformation hypothesis** predicts that the first pointing trials should require additional retrieval/mental transformation costs, yielding increased response times and/or errors predicting a main effect of pointing trial number. If the observed benefit of sensorimotor alignment ($H_{TBI} = H_{test}$) was *solely* caused by initial retrieval/mental spatial transformation costs, it should (a) largely disappear for later pointing trials, which would be (b) reflected in significant 3-way interactions between pointing trial number, H_{TBI}, and H_{test}. Conversely, the **sensorimotor interference hypothesis** predicts that the interference between primary sensorimotor and to-be-imagined secondary reference frame persists even when initial additional retrieval/mental transformation costs have decayed, such that the observed benefit for $H_{TBI} = H_{test}$ should (a) persist for later pointing trials, and thus (b) yield no significant 3-way interaction between pointing trial number, H_{TBI}, and H_{test}.

ANOVA showed a significant main effect of the pointing trial number on response time, $F(142, 165) = 5.43$, $p = 0.015$, $\eta_p^2 = 0.141$, power = 0.726, confirming initial retrieval/transformation costs. None of the other factors or interactions reached significance. The corresponding data are plotted in Fig. 6, and show that the first and second pointing trials took about 500 ms and 250 ms, respectively, longer than the last four pointing trials. Planned contrasts showed only a marginal response time decrease between the first and second pointing trials, $F(1, 175) = 3.39$, $p = 0.067$. Compared to the last four pointing trials per JRD block, the first two pointing trials were significantly slower, however, $F(1, 175) = 20.88$, $p < 0.0001$.

However, the absence of any significant interactions between pointing trial number, actual heading H_{test} and to-be-imagined heading H_{TBI} suggests that the JRD benefit for $H_{TBI} = H_{test}$ was largely caused by ongoing and persistent sensorimotor facilitation/interference and not exclusively by initial retrieval/mental transformation costs. This was further corroborated by re-analyzing only the last 4 pointing trials per JRD block (see Fig. 7). Comparing Figs. 7 and 3 and re-running the initial ANOVAs and contrast analyses shows that removing the first two pointing trials from the data did not affect results noticeably: Sensorimotor aligned conditions ($H_{TBI} = H_{test}$) showed as before significantly reduced absolute pointing errors, $F(1, 33) = 72.20$, $p < 0.001$, $\eta_p^2 = 0.686$; configuration errors, $F(1, 33) = 67.72$, $p < 0.001$, $\eta_p^2 = 0.672$; and response times, $F(1, 33) = 105.49$, $p < 0.001$, $\eta_p^2 = 0.762$. Average effects sizes η_p^2 were 0.707 and thus equally high as with all six pointing trials included (0.708). That is, even after removing the first two pointing trials per JRD block the clear benefit for sensorimotor alignment (black bar, $H_{TBI} = H_{test}$) persisted, corroborating the existence of ongoing and persistent sensorimotor facilitation/interference. Pointing trial number showed no significant effect on response time for the last four pointing trials per JRD block, suggesting that retrieval and mental transformation costs were either constant or had largely subsided after the first two pointing trials.

In conclusion, although participants needed additional time for the first pointing trial or trials per JRD block, which suggests additional processing costs for the initial retrieval/mental transformation of the desired secondary reference frame, these retrieval/mental transformation costs alone cannot explain the current data as the sensorimotor alignment effect persisted beyond the first pointing trials per JRD block. Instead, we found clear and persistent sensorimotor alignment effects as well as memory-encoding alignment benefits for the learning heading. These findings suggest not only an ongoing general interference between the primary and secondary reference frame, but also a specific interference when the main axis of the primary and secondary reference frames were misaligned (i.e., $H_{TBI} \neq H_{test}$).

In addition to interference effects, there might also be a facilitation effect when primary and secondary reference frame are aligned. Physically facing the main room axis in the test room might prime or otherwise facilitate retrieval or imagination of the test room in the corresponding orientation. For example, participants might have visually imagined or mentally overlaid the learning room objects onto the currently seen test room (Kelly et al., 2007). Due to the similar geometry of the rooms, this might seem feasible.

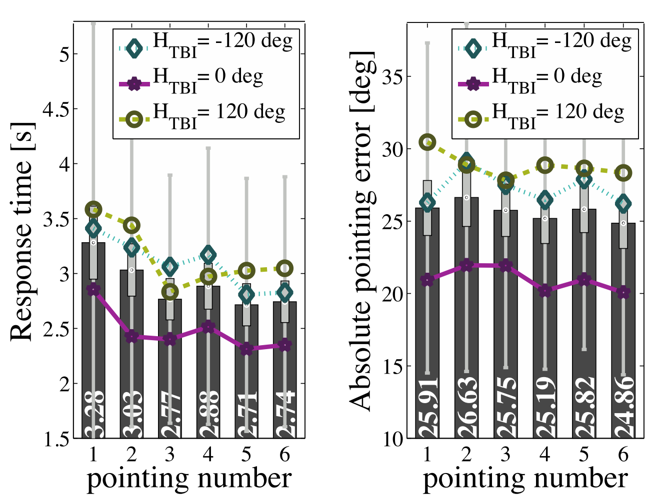

Fig. 6. Average response times and absolute pointing errors for each of the six pointing trials per JRD block.

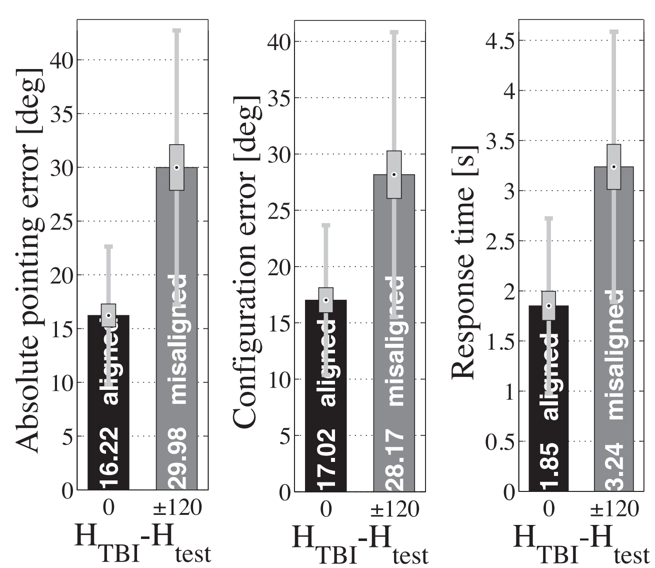

Fig. 7. Interaction between H_{TBI} and H_{test} plotted as in Fig. 2, but with the first two out of six pointing trials per block removed to exclude transient retrieval/mental transformation costs.

Experiment 1 did not include a control condition that would allow for disambiguating between potential effects of facilitation versus interference. This motivated us to include in Experiment 2 a blindfolded disoriented condition as a baseline (May, 1996) to distinguish between facilitation and interference effects. May demonstrated that adopting a new perspective was greatly facilitated if blindfolded participants were disorientated beforehand, supposedly due to reduced interference and the lack of reliable sensorimotor information about one's actual orientation (see also Mou, McNamara, Rump, & Xiao, 2006; Waller & Hodgson, 2006; Waller et al., 2002). Following May's reasoning, blindfolding and completely disorienting participants was intended to circumvent all potential orientation-specific interference and facilitation, as participants were no longer aware of their actual location or orientation in space. Thus, the immediate environment can no longer automatically activate sensorimotor codes that could facilitate or inhibit specific imagined perspectives (Avraamides & Kelly, 2008). Furthermore, we hypothesized that blindfolded disorientation and re-location should largely reduce the saliency and relative weighting of the sensorimotor reference frame of the physical surroundings, or even completely remove it. Thus, the disoriented condition will serve as a no-interference, no-facilitation baseline condition in Experiment 2 against which to assess the eyes-open facilitation/interference effects of both Experiment 1 and 2, as illustrated in Fig. 8.

The main motivation for Experiment 2 was, however, to investigate whether the observed sensorimotor alignment effects would generalize to other, less similar test rooms. To this end, Experiment 2 used the same learning room but a larger and quite different-looking, cluttered test room of different overall size, aspect ratio, and relative location of door vs. desk vs. main room reference axis. In addition, a disoriented condition was introduced to serve as a no-interference, no-facilitation baseline condition, as discussed previously.

3. Experiment 2

The experiment was designed to test six hypotheses. RH1-RH3 were the same as in Experiment 1, although we expected reduced effect sizes for sensorimotor interference (RH1) in Experiment 2.

3.1. RH4a: Sensorimotor interference

If the hypothesized sensorimotor alignment effects between H_{TBI} and H_{test} (Research Hypothesis 1) were caused mainly by interference when $H_{TBI} \neq H_{test}$, the disorientation procedure should yield performance similar to the aligned condition ($H_{TBI} = H_{test}$), as disorientation should have largely removed any potential interference (Avraamides & Kelly, 2008; May, 1996, 2000, 2004; May & Wartenberg, 1995; Presson & Montello, 1994; Wang, 2005). Conversely, misaligned conditions should yield reduced performance compared to the interference-free disoriented condition, as illustrated in Fig. 8.

3.2. RH4b: Sensorimotor facilitation

The sensorimotor facilitation hypothesis proposes that alignment effects between H_{TBI} and H_{test} (Hypothesis 1) originate from facilitation if the to-be-imagined and actual heading match ($H_{TBI} = H_{test}$) (Avraamides & Kelly, 2008). Thus, the disorientated condition should yield performance levels similar to the misaligned condition ($H_{TBI} \neq H_{test}$), as disorientation should have largely removed any potential facilitation due to alignment (see Fig. 8). Conversely, the aligned conditions should yield improved performance compared to the disoriented conditions, as illustrated in Fig. 8.

3.3. RH5: Sensorimotor alignment effects decrease with environmental dissimilarity

Relative to the disoriented conditions, we expected interference and facilitation effects to be less pronounced in Experiment 2 than in Experiment 1, as test and learning room were less similar in Experiment 2.

3.4. Method

The method was identical to the previous experiment except for the changes described below. Twelve new participants (gender-balanced) completed the experiment. Participants were aged 18–31 years (mean = 22.3 years).

3.4.1. Materials

To reduce the experimental complexity, only the $H_{learn} = 120°$ learning heading was used. As illustrated in Fig. 9, the new test room was much larger than the learning room (3.59 × 2.73 m vs. 2.82 × 1.65 m) and had a different aspect ratio of the wall length (1.71:1 vs. 1.32:1). Moreover, the new test room was a cluttered office instead of the almost empty test room in Experiment 1, and the relative locations of the door and the desk were different. Pilot studies suggested that the main reference axis of the new test room was aligned with the long wall, so we used this direction to define the 0° orientation.

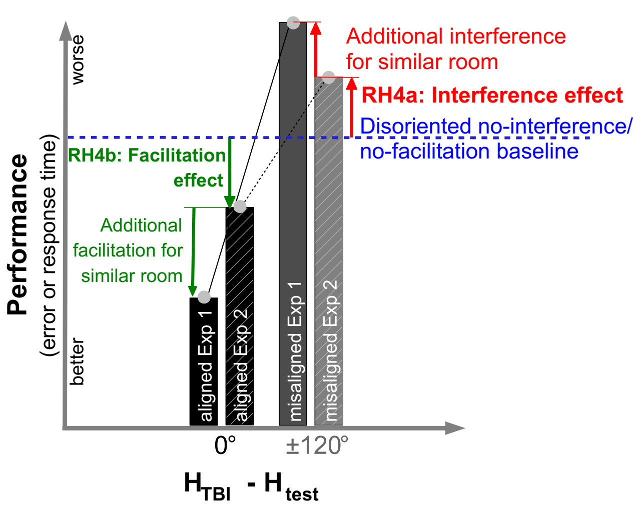

Fig. 8. Illustration of the hypothesized interference and facilitation effects.

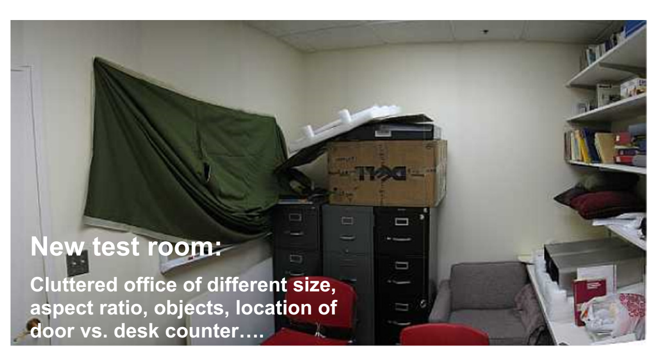

Fig. 9. Picture of the new test room in Experiment 2. Note the larger size and difference in aspect ratio and types and location of objects as compared to the learning room.

Table 2
ANOVA results for the two independent variables H_{TBI} and H_{test} of Experiment 2.

Independent variable	Hypo-thesis	Absolute pointing error					Configuration error					Response time				
		df	F(df, 22)	p	η_p^2	power	df	F(df, 22)	p	η_p^2	power	df	F(df, 22)	p	η_p^2	power
H_{test}		2	1.08	0.357	0.089	0.215	2	0.73	0.492	0.062	0.158	2	0.66	0.528	0.056	0.146
H_{TBI}	RH2✓	**2**	**9.15**	**0.001**	**0.454**	**0.955**	**2**	**4.69**	**0.020**	**0.299**	**0.727**	**1.24**	**9.65**	**0.006**	**0.467**	**0.869**
$H_{TBI} \times H_{test}$	RH1✓	**4**	**6.16**	**<0.001**	**0.359**	**0.978**	**4**	**3.09**	**0.025**	**0.219**	**0.767**	1.46	1.14	0.326	0.094	0.189

Significant effects are typeset in bold.

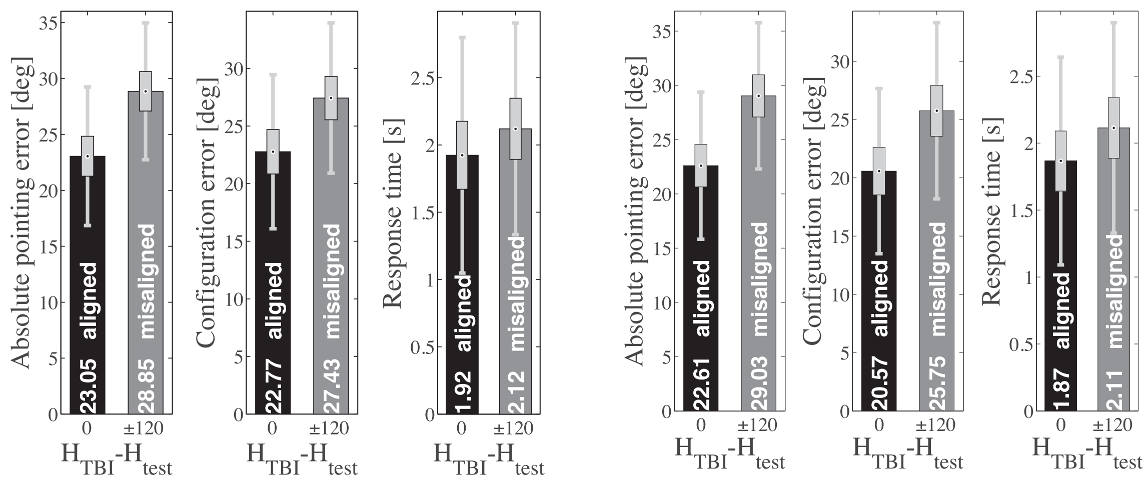

Fig. 10. **Left**: Means for the conditions where the to-be-imagined heading was aligned with participants' current heading in the test room ($H_{TBI} - H_{test} = 0°$, black bars) as compared to the conditions where they were misaligned ($H_{TBI} - H_{test} = \pm 120°$, gray bars). **Right**: Same plot, but with the first 2 pointing trials removed per block to exclude initial memory retrieval and transformation effects.

3.4.2. Procedure and design

One additional disoriented condition was added, in which participants were seated on a swivel chair, blindfolded, and disoriented by repeatedly spinning them slowly in different directions. During this disorientation procedure, participants were also wheeled into a separate adjacent test room while conversing with the experimenter. This procedure was intended to remove all knowledge or anticipation of where or in which orientation participants were with respect to the learning or eyes-open test room. Post-experimental debriefing indicated that participants were indeed unaware of the relative position and orientation of learning room and both test rooms, and responded at chance when asked to guess their relative position and orientation.

The experimental design comprised a factorial design of 3 physical headings during testing ($H_{test} = \{0°, 120°, -120°\}$; within-subject, in three separate sessions in balanced order) × 3 to-be-imagined headings during testing ($H_{TBI} = \{0°, 120°, -120°\}$; within-subject, balanced order) × 6 JRD blocks × 6 pointing trials per block. Half of the participants performed the blindfolded disoriented session before these three eyes-open sessions, the other half afterwards. The disoriented session consisted of 3 to-be-imagined orientations ($H_{TBI} = \{0°, 120°, -120°\}$; within-subject, balanced order) × 6 JRD blocks of 6 pointing trials per block.

3.5. Results and discussion

ANOVA results and corresponding data plots are presented in Table 2 and Figs. 10–12 and further investigated using planned contrasts or t-tests.

3.5.1. RH1: Sensorimotor alignment effect

ANOVA results indicated a significant interaction between participants' to-be-imagined heading H_{TBI} in the learning room and actual heading H_{test} in the test room for absolute pointing error and configuration error, but not response time (see Table 2). In support of RH1, Fig. 10 and pair-wise contrasts showed significantly reduced pointing and configuration errors when participants' actual heading in the test room was aligned with the corresponding to-be-imagined heading in the learning room ($H_{TBI} = H_{test}$) as compared to the misaligned conditions ($H_{TBI} \neq H_{test}$), $F(1, 11) = 14.79$, $p = 0.003$, $\eta_p^2 = 0.573$, power = 0.937 for absolute pointing error and $F(1, 11) = 17.52$, $p = 0.002$, $\eta_p^2 = 0.614$, power = 0.967 for configuration error.

Although effect sizes are somewhat smaller than in Experiment 1, this sensorimotor alignment effect was still highly significant, and explained more than 57% of the variability in the pointing and configuration error data. This suggests that the sensorimotor alignment effect does indeed generalize to test environments that are quite dissimilar to the learning environment.[3]

As in Experiment 1, removing the first two pointing trials per JRD block to circumvent potential influences of initial retrieval and mental transformation processes hardly changed the data pattern (see Fig. 10, right). Aligned conditions ($H_{TBI} = H_{test}$) yielded significantly reduced absolute pointing errors and configuration errors as compared to the misaligned conditions ($H_{TBI} \neq H_{test}$), *F*

[3] This was corroborated in participants' verbal reports during debriefing; e.g., "*I had to mentally rotate the wall so I was facing it properly, which took some time. Strange that the orientation with respect to the wall matters*". Another participant remarked *"Facing the owl was now easier, because I'm facing the wall kind of in the right orientation in the room*".

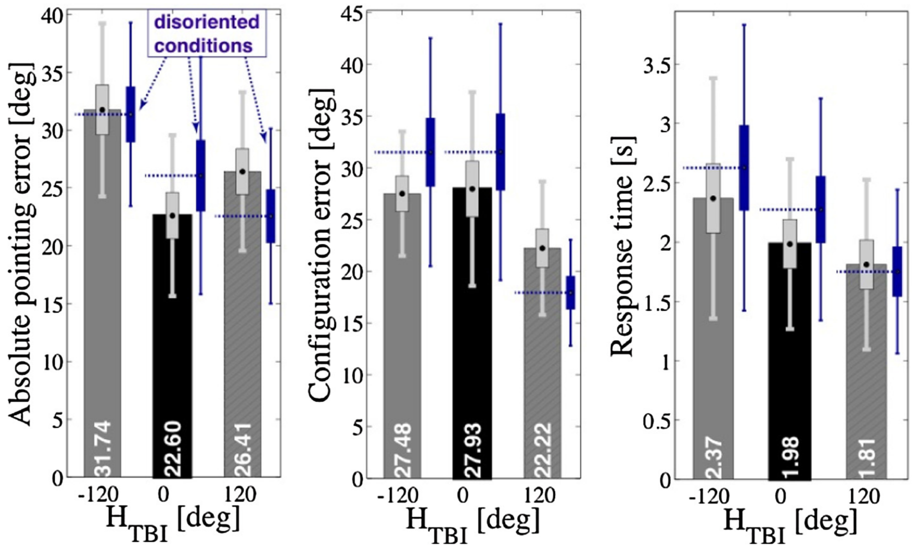

Fig. 11. Mean absolute pointing error, configuration error, and response time, each plotted with respect to the different to-be-imagined headings H_{TBI} and averaged over the different test headings H_{test}. The right hatched bar for H_{TBI} = 120° represents the case where $H_{TBI} = H_{learn}$. The thin blue boxes and whiskers adjacent to each bar represent the data from the disoriented baseline condition where participants were blindfolded and disoriented before testing. Boxes and whiskers depict one standard error of the mean and one standard deviation, respectively.

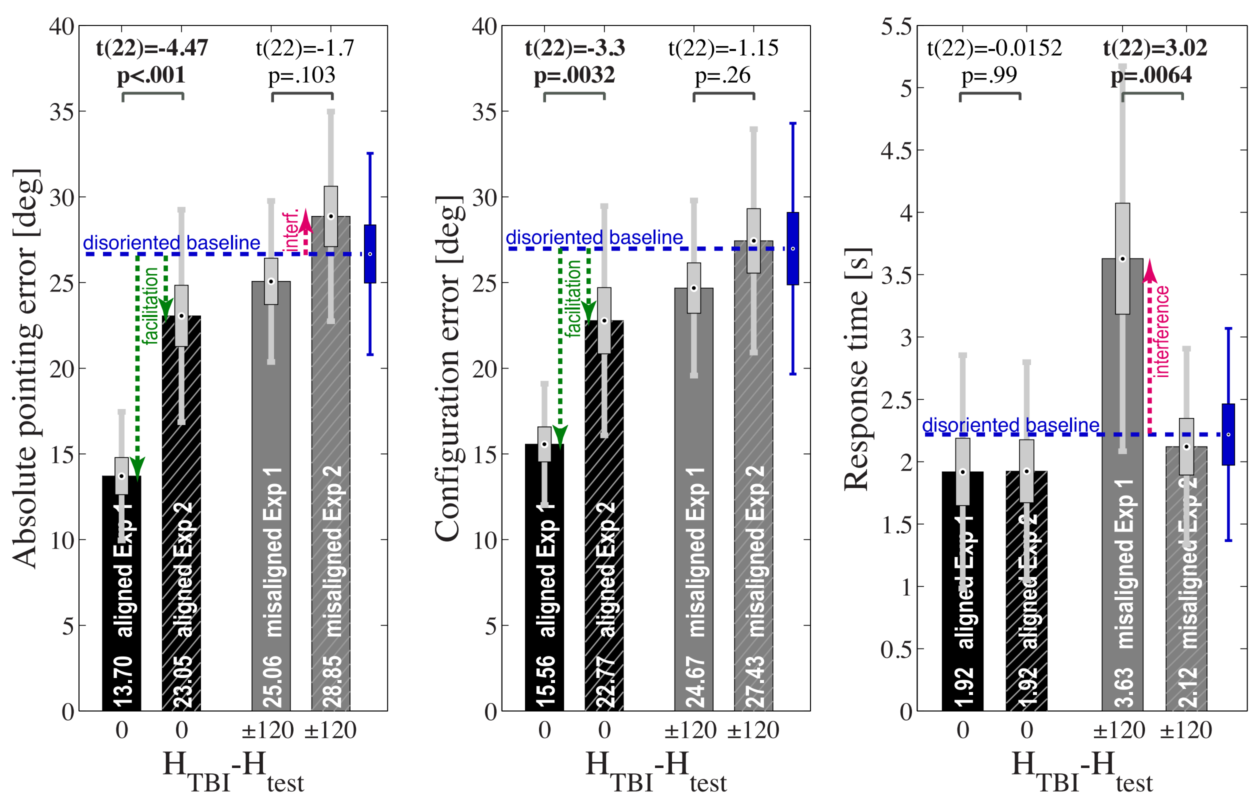

Fig. 12. Mean of dependent measures for the eyes-open conditions in which the to-be-imagined heading H_{TBI} was aligned with participants' current heading in the test room H_{test} ($H_{TBI} - H_{test}$ = 0°, black bars) as compared to the conditions in which they were misaligned ($H_{TBI} - H_{test}$ = ±120°, gray bars). Data from Experiment 2 (hatched bars) are compared with the H_{learn} = 120° group in Experiment 1 (solid bars), with corresponding *t*-test comparisons displayed in the top inset of each plot.

(1, 11) = 14.88, $p = 0.003$, $\eta_p^2 = 0.575$, power = 0.939 for absolute pointing error and $F(1, 11) = 11.84$, $p = 0.006$, $\eta_p^2 = 0.518$, power = 0.879 for configuration error. Moreover, pointing trial number did not show any significant effects.

Together, these results suggest that the first pointing trials were no more difficult than later pointing trials, which in turn suggests that the initial cognitive effort of retrieving the to-be-imagined perspective from long-term memory was either small or operated on a time scale so short that it did not allow us to assess it in the current procedure. Given the findings from May (2007) and our earlier observation that response times in Experiment 1 decreased from the first toward later pointing trials, it seems likely that the time scale for initial retrieval/transformation is in the order of several seconds to about 15 s. This analysis suggests that initial retrieval/transformation costs in Experiment 2 might have been lower than in Experiment 1, potentially due to the reduced interference between actual and to-be-imagined heading when the test environment was more dissimilar to the learning environment (see also analysis of research hypothesis 5 below). Moreover, as the room alignment effects between actual and to-be-imagined headings persisted unchanged over the course of the six pointing trials per JRD block in Experiment 2, we posit that the effect was dominated by interference/facilitation effects and not by initial retrieval or mental transformation costs, which should have at least somewhat decayed over the course of the six pointing trials as they did in Experiment 1.

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

The ANOVA results showed significant main effects of the to-be-imagined heading H_{TBI} on all dependent measures (see Table 2). Fig. 11 and the contrast analysis indicated that participants pointed more accurately and faster when asked to imagine a heading aligned with the main reference axis of the room ($H_{TBI} = 0°$) as compared to the oblique, non-learned heading $H_{TBI} = -120°$, supporting RH2 (absolute pointing error, $F(1, 11) = 15.38$, $p = 0.002$, $\eta_p^2 = 0.583$, power = 0.945; response time, $F(1, 11) = 12.44$, $p = 0.005$, $\eta_p^2 = 0.531$; power = 0.894). Configuration error, however, showed no such benefit for $H_{TBI} = 0°$, $F(1, 11) = 0.008$, $p = 0.929$, $\eta_p^2 = 0.001$, power = 0.051.

Comparing the two oblique views ($H_{TBI} = \pm 120°$) showed that performance was improved in all dependent variables if the to-be-imagined orientation was aligned with the learning heading ($H_{TBI} = 120° = H_{learn,}$ facing the computer) as compared to a non-learned heading ($H_{TBI} = -120°$, facing the pen), thus supporting RH3 (absolute pointing error, $F(1, 11) = 6.19$, $p = 0.030$, $\eta_p^2 = 0.360$, power = 0.621; configuration error, $F(1, 11) = 1.24$, $p = 0.008$, $\eta_p^2 = 0.482$, power = 0.829; response time, $F(1, 11) = 1.4$, $p = 0.008$, $\eta_p^2 = 0.486$, power = 0.835).

In summary, JRD performance improved when the to-be-imagined heading was aligned either with the main reference axis of the learning room ($H_{TBI} = 0°$, supporting RH2) or the learning heading ($H_{TBI} = 120° = H_{learn}$, supporting RH3). This suggests that some participants might have switched to using the room-defined reference axis instead of the learning heading for representing the environment in long-term spatial memory. This conjecture was confirmed by the post-experimental map drawings: Although all participants learned the environment in the $H_{learn} = 120°$ orientation, only 7 of the 12 participants (58%) started drawing it in this orientation. The remaining 5 participants (42%) started drawing it aligned with the room geometry.

3.5.3. Disoriented conditions

Analyses of the disoriented conditions alone showed significant main effects of H_{TBI} in all dependent measures (absolute pointing error, $F(2, 22) = 3.87$, $p = 0.036$, $\eta_p^2 = 0.260$, power = 0.638; configuration error, $F(2, 22) = 10.58$, $p = <0.001$, $\eta_p^2 = 0.490$, power = 0.977; response time, $F(2, 22) = 7.29$, $p = 0.004$, $\eta_p^2 = 0.398$, power = 0.900), see also Fig. 11. Subsequent contrast analysis indicated that participants pointed only marginally more accurately when asked to imagine a heading aligned with the main reference axis of the room ($H_{TBI} = 0°$) as compared to the oblique but non-learned heading $H_{TBI} = -120°$ (absolute pointing error, $F(1, 11) = 3.57$, $p = 0.085$, $\eta_p^2 = 0.245$, power = 0.407). Neither configuration error nor response time showed significant differences between the disoriented $H_{TBI} = 0°$ and $H_{TBI} = -120°$ conditions, though (configuration error, $F(1, 11) < 0.01$, $p = 0.995$, $\eta_p^2 < 0.001$, power = 0.050; response time, $F(1, 11) = 2.70$, $p = 0.129$, $\eta_p^2 = 0.197$, power = 0.323). Note that this result differs from the eyes-open conditions analyzed above, where the room-aligned $H_{TBI} = 0°$ condition yielded both more accurate and faster responses than the oblique $H_{TBI} = -120°$ condition.

Similar to the eyes-open JRD blocks, comparing the two oblique views ($H_{TBI} = \pm 120°$) in the disoriented condition showed improved performance in all dependent variables if the to-be-imagined heading was aligned with the learning heading ($H_{TBI} = 120° = H_{learn,}$ facing the computer) as compared to a non-learned heading ($H_{TBI} = -120°$, facing the pen; absolute pointing error, $F(1, 11) = 9.12$, $p = 0.012$, $\eta_p^2 = 0.453$, power = 0.785; configuration error, $F(1, 11) = 17.61$, $p = 0.001$, $\eta_p^2 = 0.616$, power = 0.968; response time, $F(1, 11) = 9.48$, $p = 0.010$, $\eta_p^2 = 0.463$, power = 0.800). Results from Experiment 1 (where learning heading was balanced) suggest that the performance benefit for $H_{TBI} = 120°$ was caused by the alignment with the learning heading, not the alignment with a salient object at 120°.

3.5.4. Sensorimotor interference (RH4a) vs. facilitation (RH4b)

To disambiguate between interference and facilitation as potential underlying causes of the observed room alignment effect, we compared eyes-open performance with performance on disoriented conditions which served as a no-interference, no-facilitation baseline, as illustrated in Fig. 8. The corresponding data and *t*-test results are summarized in Fig. 12.

In support of RH4a, misalignment between actual and to-be-imagined headings led to significantly larger absolute pointing errors as compared to the disoriented baseline, $t(11) = -2.88$, $p = 0.015$, $\eta^2 = 0.430$. In support of RH4b, participants pointed more accurately and with lower configuration error when they had their eyes open and were physically oriented in a direction that was aligned with the to-be-imagined heading ($H_{TBI} - H_{test} = 0$, hatched black bars in Fig. 12 labeled "aligned Exp. 2"), as compared to being blindfolded and disoriented (displayed as dashed horizontal line labeled "disoriented baseline", $t(11) = 2.48$, $p = 0.031$, $\eta^2 = 0.358$ for pointing error and $t(11) = 2.2$, $p = 0.050$, $\eta^2 = 0.305$ for configuration error). These results suggest that misalignment can result in sensorimotor interference effects, albeit these effects were less pronounced than the sensorimotor facilitation effects for alignment in the present experiment.

It is possible, however, that there might be a general performance benefit or detriment when being blindfolded and disoriented as compared to oriented with eyes open. Further research is needed to disambiguate these potential confounds. As average performance in the blindfolded and eyes-open conditions was similar, though, we tentatively propose that seeing one's immediate environment in a given orientation (no matter whether aligned or oblique) can facilitate mental imagery of environments in a similar orientation, and interfere if the orientations are misaligned.

3.5.5. RH5: Sensorimotor alignment effects decrease with environmental dissimilarity

Compared to Experiment 1, the aligned conditions ($H_{TBI} - H_{test} = 0$) in Experiment 2 where learning and test room were less similar, showed significantly increased absolute pointing and configuration errors (Fig. 12). Conversely, comparing the misaligned conditions ($H_{TBI} - H_{test} \neq 0$) showed significantly increased response times for the more similar test room in Experiment 1 as compared to Experiment 2, but no differences for absolute pointing error or configuration error. Together, these results indicate that facilitation/interference effects are reduced when participants were aligned/misaligned with a test room that was less similar to the to-be-imagined room, thus supporting RH5.

As shown in Fig. 12, compared to the disoriented baseline in Experiment 2, alignment between participants' actual and to-be-imagined heading in Experiment 1 yielded significantly reduced pointing and configuration errors ($t(22) = -6.44$, $p < 0.001$, $\eta^2 = 0.653$ and $t(22) = -4.87$, $p < 0.001$, $\eta^2 = 0.519$, respectively). Response times showed no significant benefits. Conversely, the misaligned conditions in Experiment 1 showed increased response times relative to the disoriented baseline in Experiment 2 ($t(22) = 2.77$ $p = 0.011$, $\eta^2 = 0.259$), but no significant differences for pointing or configuration error. One interpretation of this pattern of results is that sensorimotor alignment improved the absolute and relative accuracy of egocentric pointing directions, whereas misalignment increases the overall cognitive effort required to overcome interference between the two concurrent egocentric representations in working memory.

4. General discussion

The current study demonstrated that sensorimotor alignment effects in perspective taking can occur in remote real-world environments when participants have their eyes open, are well aware that they are not in the learning room, and have no additional pre-processing time or cognitive re-anchoring instructions. Although participants were never aware of the actual spatial relationship between learning and test rooms, their physical orientation in the test room determined which orientations in the remote room were easier or harder to imagine. These sensorimotor alignment effects occurred in both an empty office (Exp. 1) and a cluttered office that looked quite different than the to-be-imagined environment (Exp. 2).

One factor that the two environments shared is rectangular room geometry. Given the important role of environmental geometry in human and animal spatial memory (Cheng & Newcombe, 2005), we conjecture that the observed alignment effect was caused by the participant's orientation with respect to the room geometry and the salient reference directions defined by the rectangular room geometry. Future research is needed to investigate the generalizability of this effect to different room sizes and layouts. We predict that the alignment effects will diminish or completely disappear if the test environment does not have a rectangular geometry and clear intrinsic reference directions.

The current study is also among the first to disambiguate the influence of sensorimotor facilitation versus interference in perspective taking in remote environments. Whereas sensorimotor alignment improved absolute and relative pointing accuracy compared to a blindfolded and disoriented control condition, sensorimotor misalignment resulted predominately in extra processing time, presumably because of additional cognitive demands.

In addition to sensorimotor alignment effects, we also observed memory-encoding alignment effects for both the **learning orientation** and the **environmental reference frame** defined by the main room axis. These findings confirm the orientation-dependent nature of spatial long-term memory proposed by many current theories of human spatial memory, and extend such results to naturalistic, cluttered room environments with a multitude of irregularly arranged target objects, where top-down strategies are less likely to occur. Using three different learning headings ($H_{learn} = -120°$, 0°, or 120°) in Experiment 1 and crossing them with three physical headings during testing ($H_{test} = -120°$, 0°, or 120°) and three to-be-imagined headings ($H_{TBI} = -120°$, 0°, or 120°) allowed us to independently assess sensorimotor alignment affects, memory-encoding alignment effects for the learning orientation, and memory-encoding alignment effects for the environmental reference frame.

Results from pointing and map-drawing tasks suggest that several participants did not use the learning orientation as a reference direction in long-term memory, but instead switched to the environmental reference frame defined by the main axis of the room. This apparent switch to an environmental reference frame was more common for participants who learned in a less salient orientation (facing a pen attached to the wall at −120°) than for participants who learned in a more salient but equally oblique learning orientation (facing the computer and keyboard at 120°). This finding confirms earlier observations that salient environmentally-defined reference frames can dominate the effect of an experienced orientation in long-term memory (McNamara, 2003; Shelton & McNamara, 2001; Werner & Schmidt, 1999), and extends those findings to natural, cluttered office environments with irregular object layouts. Future research with larger participant samples could elucidate why certain participants switch to a preferred reference direction other than their learning direction and how this affects performance compared to those who do not switch.

4.1. Potential factors underlying the observed sensorimotor alignment effects

Avraamides and Kelly (2005) proposed that perspective switching costs resulted from time required to move attentional focus and time required to update viewpoints. We agree with this assessment and assume that both factors likely contributed to performance in the current study: Whereas the overall cost for switching attentional focus from the actual surroundings to the to-be-imagined remote environment suggests a general increase in task difficulty, the cost of mentally adopting the to-be-imagined perspective in different orientations might indeed represent the cost of transforming the stored representation to align with the instructed perspective. The latter costs were reflected in memory-encoding alignment effects for both the learning orientation and the environmentally-defined reference direction. We propose further that there might be sustained costs for maintaining multiple representations in spatial working memory.

Neither transformation costs, retrieval costs, the costs of shifting attentional focus, nor maintaining multiple representations in working memory can explain the observed orientation-specific sensorimotor alignment effects between participants' current and to-be-imagined orientation, as these factors predict equal cost independent of participants' actual orientation in the environment. Moreover, neither pointing errors nor sensorimotor or memory-encoding alignment effects decreased over the course of the six pointing trials per to-be-imagined perspective. This pattern of results suggests that although there were likely some initial retrieval, attentional shift, and mental transformation costs especially in Experiment 1, those costs cannot explain the sustained memory-encoding alignment effects and sensorimotor alignment effects (May, 1996, 2004, 2007).

We propose that the observed orientation-specific alignment effects are based on specific interactions between two concurrent egocentric reference frames in spatial working memory, one automatically triggered by sensory cues from the actual environment via bottom-up processes, the other one activated by the imagination instructions and thus top-down processes. We posit that the occurrence and strength of facilitation and interference effects depends on the compatibility, similarity, and relative alignment of the concurrent egocentric representations. Because perspective switches in the current experiments included only rotation, but not translations, these sensorimotor alignment effects can be conceptualized as *head-direction disparity* effects (i.e., based on the rotational misalignment between to-be-imagined and physical participant heading) without additional *object-direction disparity* effects (i.e., without additional differences in object bearings between to-be-imagined and physical participant heading; May, 2004).

Avraamides and Kelly (2008) have proposed that stimulus–response compatibility effects might be a useful framework for understanding these concurrent reference frame interactions. If the pointing target is included in the sensorimotor representation, an instruction to point to it from an imagined perspective automatically activates sensorimotor codes for that target and primes the target direction in the sensorimotor reference frame, even before the actual pointing response. If imagined and sensorimotor perspectives are misaligned, effortful inhibition of the automatically activated sensorimotor target direction is required to point from the imagined perspective, especially if a manual (embodied) pointing method is used.

The stimulus-response compatibility effect explanation proposed by Avraamides and Kelly (2008) would need to be extended to explain the current data. Blindfolded remote JRD testing has been shown to produce orientation-specific interference effects when explicit re-anchoring instructions were used (May, 1996, 2000, 2007; Shelton & Marchette, 2010; Waller et al., 2002; Wang, 2003, 2004) or participants suspected that they might be back in the original, to-be-imagined environment (Kelly et al., 2007; Shelton & Marchette, 2010). In the current study, however, participants had their eyes open during testing and received no re-anchoring instructions or pre-processing time and never came close to believing that they were back in the learning environment during testing. In fact, they were at chance when asked to guess about the relative location and orientation of learning and test environment. This suggests that the learning environment was not part of or directly spatially linked to participants' sensorimotor representation of the test environment. That is, while the facilitation/interference effects observed in May (2007) and Shelton and Marchette (2010) could be interpreted as facilitation/interference between the first imagined and thus explicitly re-anchored egocentric representation of the learning room and the subsequent and co-existing to-be-imagined perspective in working memory, participants in the current study showed facilitation/interference effects between the sensorimotor representation of the test environment and the to-be-imagined perspective in the learning room.

Compared to prior work that showed interference effects in remote room perspective taking (Kelly et al., 2007; May, 2007; Shelton & Marchette, 2010), the facilitation/interference in the current study occurred by simply seating participants in a rectangular test room, without any imagination or re-anchoring instructions (May, 2007; Shelton & Marchette, 2010) and without any extra pre-processing time (May, 2007). Moreover, participants in the current study were not uncertain about their actual location and did not suspect or have sensorimotor cues indicating that they might be back in the original learning room (Kelly et al., 2007; Shelton & Marchette, 2010). Finally, the current facilitation/interference effects occurred without learning and test rooms looking identical (Kelly et al., 2007, Exp. 4); instead, sustained facilitation/interference effects occurred both in Experiment 1 when the learning and test room were similar in geometric layout but quite different in appearance (empty test room versus cluttered learning room, and in Experiment 2 where learning and test room were dissimilar in both geometric layout and appearance.

We propose that alignment effects in our study occurred in working memory between the concurrent egocentric representations of the test environment automatically activated by sensorimotor cues and the to-be-imagined learning environment. That is, we propose that alignment effects can not only occur between imagined and automatically activated sensorimotor egocentric target directions (Avraamides & Kelly, 2008), but also between concurrent imagined and automatically activated sensorimotor representations of different environments and especially their geometric layout.

Indeed, some participants in our study mentioned that they tried to mentally or visually "overlay" or willfully imagine the to-be-imagined learning room or objects onto the current environment. For each to-be-imagined perspective they seemed to have tried to embed the to-be-imagined environment onto the current (sensorimotor-defined) environment. This task was apparently easier when the two reference frames were more congruent (Exp. 1 vs. 2). That is, whereas blindfolded participants in (May, 2007; Shelton & Marchette, 2010) seemed to have imagined and re-anchored themselves in the learning environment (with more or less success depending on instructions and procedures), it seems that participants in the current study were unable to imagine themselves easily in the learning room. This difficulty probably occurred because participants had a stronger, automatically-triggered sensorimotor representation of the actual test room, because they were required to keep their eyes open, and because they were well aware that they were not in the learning room. Thus, instead of imagining being in the learning environment, many of them seem to have tried to imagine the learning room in the context of the immediate environment, thus essentially trying to re-anchor or embed the to-be-imagined remote environment within the sensorimotor representation of the test room. This process was apparently easier when actual and imagined perspectives were aligned than when they were misaligned, which might explain why we found both sensorimotor facilitation (for alignment) and interference effects (for misalignment). This way, spatial compatibility and reference-frame-compatibility between actual and to-be-imagined environments might have resulted in improved stimulus-response compatibility, yielding sensorimotor facilitation effects. This interpretation might also help to explain why facilitation effects in the current study were overall more frequent and more pronounced than interference effects. Although these proposed underlying processes are speculative in nature and meant as working hypotheses, we believe that they may be helpful in guiding further research and produce testable predictions.

4.2. Conclusions

In conclusion, the current study shows that one's facing direction in the immediate, proximal environment can affect one's ability to imagine a distal environment. This effect is largely caused by sensorimotor alignment effects (or more generally concurrent reference frame alignment effects) rather than by mental transformation or retrieval effects. These sensorimotor alignment effects consist of both facilitation and interference effects when the concurrent reference frames are aligned and misaligned, respectively. These findings further challenge the view that sensorimotor facilitation/interference should not occur in remote perspective taking tasks.

Our results should be considered when designing experiments involving perspective-taking tasks in order to avoid unintended biases and sensorimotor alignment effects. In addition, our findings suggest that sensorimotor facilitation/interference effects might occur not only between sensorimotor and imagined perspectives, but also between concurrent egocentric representations of one's physical environment and mediated environments like virtual environments, computer games, or even movies (see Riecke, 2003; von der Heyde & Riecke, 2002).

Acknowledgements

Support: Vanderbilt University; NIMH grant 2-R01-MH57868; P30-EY008126; NSF Grant HCC 0705863; and Simon Fraser University.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2017.07.014.

References

Avraamides, M. N., & Kelly, J. W. (2005). Imagined perspective-changing within and across novel environments. *Spatial cognition IV, Reasoning, Action, Interaction, 3343*, 245–258. http://dx.doi.org/10.1007/978-3-540-32255-9_15. Lecture Notes in Computer Science.

Avraamides, M. N., & Kelly, J. W. (2008). Multiple systems of spatial memory and action. *Cognitive Processing, 9*, 93–106. http://dx.doi.org/10.1007/s10339-007-0188-5.

Batschelet, E. (1981). *Circular statistics in biology*. London: Academic Press.

Burgess, N. (2006). Spatial memory: How egocentric and allocentric combine. *Trends in Cognitive Science, 10*(12), 551–557. http://dx.doi.org/10.1016/j.tics.2006.10.005.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences, 1124*, 77–97. http://dx.doi.org/10.1196/annals.1440.002.

Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic Bulletin & Review, 12*, 1–23. http://dx.doi.org/10.3758/BF03196346.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Erlbaum.

Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory and Cognition, 21*(2), 483–500.

Kelly, J. W., Avraamides, M. N., & Loomis, J. M. (2007). Sensorimotor alignment effects in the learning environment and in novel environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(6), 1092–1107. http://dx.doi.org/10.1037/0278-7393.33.6.1092.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility – a model and taxonomy. *Psychological Review, 97*, 253–270. http://dx.doi.org/10.1037/0033-295X.97.2.253.

May, M. (1996). Cognitive and embodied modes of spatial imagery. *Psychologische Beiträge, 38*(3/4), 418–434.

May, M. (2000). *Kognition im Umraum [Cognition in spatial surroundings]*. Studien zur Kognitionswissenschaft. Wiesbaden: DUV: Kognitionswissenschaft.

May, M. (2004). Imaginal perspective switches in remembered environments: Transformation versus interference accounts. *Cognitive Psychology, 48*(2), 163–206.

May, M. (2007). Imaginal repositioning in everyday environments: Effects of testing method and setting. *Psychological Research Psychologische Forschung, 71*(3), 277–287. http://dx.doi.org/10.1007/s00426-006-0083-1.

May, M., & Wartenberg, F. (1995). Rotationen und translationen in umraeumen: Modelle und experimente rotations and translations in body-centered space: Models and experiments. *Kognitionswissenschaft, 4*(4), 142–153.

McNamara, T. P. (2003). How are the locations of objects in the environment represented in memory? In C. Freksa, W. Brauer, C. Habel, & K. F. Wender (Eds.), *Spatial cognition III. Lecture notes in computer science* (2685, pp. 174–191). http://dx.doi.org/10.1007/3-540-45004-1_11.

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory and Cognition, 28*(1), 162–170. http://dx.doi.org/10.1037/0278-7393.28.1.162.

Mou, W. M., McNamara, T. P., Rump, B., & Xiao, C. L. (2006). Roles of egocentric and allocentric spatial representations in locomotion and reorientation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 32*(6), 1274–1290.

Mou, W., McNamara, T. P., Valiquette, C. M., & Rump, B. (2004). Allocentric and egocentric updating of spatial memories. *Journal of Experimental Psychology: Learning, Memory and Cognition, 30*(1), 142–157.

Presson, C. C. (1987). The development of spatial cognition: Secondary uses of spatial information. In N. Eisenberg (Ed.), *Contemporary topics in developmental psychology* (pp. 77–112). New York: Wiley.

Presson, C. C., & Montello, D. R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception, 23*(12), 1447–1455. http://dx.doi.org/10.1068/p231447.

Riecke, B. E. (2003). *How far can we get with just visual information? Path integration and spatial updating studies in virtual reality*. MPI Series in Biological Cybernetics (Vol. 8). Berlin: Logos.

Riecke, B. E., & Hastings, L. (2011). *Do virtual and real environments influence spatial cognition similarly?* Poster 1031 presented at the 52th annual meeting of the psychonomic society (Psychonomics), Seattle, USA.

Riecke, B. E., Cunningham, D. W., & Bülthoff, H. H. (2007). Spatial updating in virtual reality: The sufficiency of visual information. *Psychological Research, 71*(3), 298–313. http://dx.doi.org/10.1007/s00426-006-0085-z.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 15*(6), 1157–1165. http://dx.doi.org/10.1037/0278-7393.15.6.1157.

Shelton, A. L., & Marchette, S. A. (2010). Where do you think you are? Effects of conceptual current position on spatial memory performance. *Journal of Experimental Psychology: Learning, Memory and Cognition, 36*(3), 686–698. 37/a0018713.

Shelton, A. L., & McNamara, T. P. (1997). Multiple views of spatial memory. *Psychonomic Bulletin & Review, 4*(1), 102–106.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology, 43*(4), 274–310. http://dx.doi.org/10.1006/cogp.2001.0758.

Sholl, M. J. (2001). The role of a self-reference system in spatial navigation. In D. R. Montello (Ed.), *Spatial information theory* (2205, pp. 217–232). COSIT. http://dx.doi.org/10.1007/3-540-45424-1_15.

Valiquette, C. M., & McNamara, T. P. (2007). Different mental representations for place recognition and goal localization. *Psychonomic Bulletin & Review, 14*(4), 676–680.

von der Heyde, M., & Riecke, B. E. (2002). Embedding presence-related terminology in a logical and functional model. *Presented at the 5th Annual International Workshop on Presence (PRESENCE 2002), Porto, Portugal*, 37–52.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 32*(4), 867–882.

Waller, D., Lippa, Y., & Richardson, A. (2008). Isolating observer-based reference directions in human spatial memory: Head, body, and the self-to-array axis. *Cognition, 106*(1), 157–183. http://dx.doi.org/10.1016/j.cognition.2007.01.002.

Waller, D., Montello, D. R., Richardson, A. E., & Hegarty, M. (2002). Orientation specificity and spatial updating of memories for layouts. *Journal of Experimental Psychology: Learning, Memory and Cognition, 28*(6), 1051–1063.

Wang, R. F. (2004). Between reality and imagination: When is spatial updating automatic? *Perception & Psychophysics, 66*(1), 68–76. http://dx.doi.org/10.3758/BF03194862.

Wang, R. F. (2005). Beyond imagination: Perspective change problems revisited. *Psicologica, 26*(1), 25–38.

Wang, R. F. (2003). Spatial representations and spatial updating. In D. E. I. & B. H. Ross (Eds.), *The psychology of learning and motivation. Advances in research and theory: Cognitive vision* (pp. 109–156). San Diego, CA: Academic Press.

Wang, R. F., & Spelke, E. S. (2000). Updating egocentric representations in human navigation. *Cognition, 77*(3), 215–250.

Wang, R. F., & Spelke, E. S. (2002). Human spatial representation: Insights from animals. *Trends in Cognitive Sciences, 6*(9), 376–382.

Werner, S., & Schmidt, K. (1999). Environmental reference systems for large-scale spaces. *Spatial Cognition and Computation, 1*(4), 447–473. http://dx.doi.org/10.1023/A:1010095831166. Spatial reference systems.