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Local and global reference frames for environmental spaces

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Two experiments examined how locations in environmental spaces, which cannot be overseen from one location, are represented in memory: by global reference frames, multiple local reference frames, or orientation-free representations. After learning an immersive virtual environment by repeatedly walking a closed multisegment route, participants pointed to seven previously learned targets from different locations. Contrary to many conceptions of survey knowledge, local reference frames played an important role: Participants performed better when their body or pointing targets were aligned with the local reference frame (corridor). Moreover, most participants turned their head to align it with local reference frames. However, indications for global reference frames were also found: Participants performed better when their body or current corridor was parallel/orthogonal to a global reference frame instead of oblique. Participants showing this pattern performed comparatively better. We conclude that survey tasks can be solved based on interconnected local reference frames. Participants who pointed more accurately or quickly additionally used global reference frames.

Keywords: Reference frame; Environmental space; Spatial memory; Reference direction; View-dependent; Orientation-free; Self-localization; Pointing; Survey knowledge; Virtual environment; Head-mounted display; Navigation; Spatial orientation.

Spatial memory is crucial for any mobile organism. Without spatial memory we would have to search for our bathroom every morning, would struggle to find the supermarket, and would get lost each time we turned a corner. Spatial memory is especially important in environments that cannot be overlooked from one vantage point, but have to be navigated through in order to be learned. According to Montello (1993) these spaces such as towns or buildings are called *environmental spaces* (see also Tversky, 2005). Conversely, *vista spaces* can be experienced from a single point of view—typical examples include most rooms, open squares, and even small valleys. Most research on spatial memory has focused on vista spaces or on figural spaces such as pictures, maps, or computer screens (e.g., Huttenlocher, Hedges, Corrigan, & Crawford, 2004; Kelly & McNamara, 2008, 2010; Waller & Hodgson, 2006; Wang & Spelke, 2000). However, everyday navigation

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often encompasses environmental spaces where navigators have to relate multiple views experienced during locomotion in order to grasp the whole environment. In this paper, we build upon prior work on memory for vista spaces and investigate how these results might generalize towards environmental spaces.

To ensure sufficient experimental control and repeatability, we used a tightly controlled virtual environment corridor navigation task that met two important prerequisites: First, in order to classify as an environmental space, it had to exclude all global landmarks that would be visible from most or all locations within the space. Otherwise, this space could be classified as a vista space, as all locations could be specified relative to this global landmark (for borderline examples see Iachini, Rutolo, & Ruggiero, 2009; McNamara, Rump, & Werner, 2003). Second, using a virtual environment allowed us to exclude potential interference from preknowledge or preconceptions about the environment and ensured that the environment was learned from navigation only, without any potential confounds from having access to representations of that space such as descriptions (Shelton & McNamara, 2004; Taylor & Tversky, 1992; Wilson, Tlauka, & Wildbur, 1999) or maps (Richardson, Montello, & Hegarty, 1999; Tlauka & Nairn, 2004).

To this end, we compared predictions of the three prevailing theories considered with representing environmental spaces. These theories have different predictions regarding which reference frames, also known as coordinate systems, are used to represent the space: Global reference frame theories assume that all representations of an environment are integrated within or subsumed under one global reference frame. Local reference frame theories propose that representations of local spaces and their connections are used for navigation purposes. Finally, orientation-free theories question the importance of reference frame orientation for navigation.

Global reference frames

Most theories concerning spatial memory for environmental spaces propose that locations are at some point represented within a single global reference frame (see Figure 1, left side; Kuipers, 2000; McNamara, Sluzenski, & Rump, 2008; O'Keefe, 1991; Poucet, 1993; Trullier, Wiener, Berthoz, & Meyer, 1997). Survey estimates such as pointing, distance estimation, or shortcutting between two mutually nonvisible locations typically rely on such global reference frames. Other spatial tasks such as route navigation might, however, be based on interconnected local representations.

When navigating an environmental space, it is by definition experienced piecewise, as only local vista spaces are visible during navigation, but never the whole environment. Most theories suggest that local surroundings are represented within local reference frames. Poucet (1993) as well as McNarama et al. (2008) proposed that these local reference frames are integrated into a higher level reference frame and are thus aligned with each other. As different individuals experience an environmental space often in very different ways, the orientation of a higher level reference frame might differ between individuals. Nevertheless, similar navigational experiences of a space may result in identical global reference frame orientations for most or all navigators. The orientation of local reference frames has been shown to originate from experienced egocentric view(s) (especially the first view experienced) or from the intrinsic allocentric structure of the space (Kelly & McNamara, 2008; McNamara et al., 2003; Mou & McNamara, 2002; O'Keefe, 1991; Shelton & McNamara, 2001). But how is the orientation of one's representation of an environmental space determined? As environmental spaces can by definition only be experienced by integrating information from travelling through local vista spaces, it is conceivable that the orientation of the local reference frames of vista spaces is somehow extended towards environmental spaces. Then the initial experience with that space (e.g., after entering a building), the main experienced orientation within this space, and its overall structure (e.g., the main orientation of the building) could jointly determine the orientation of the resulting global reference frame. The present study was designed to test whether prior results

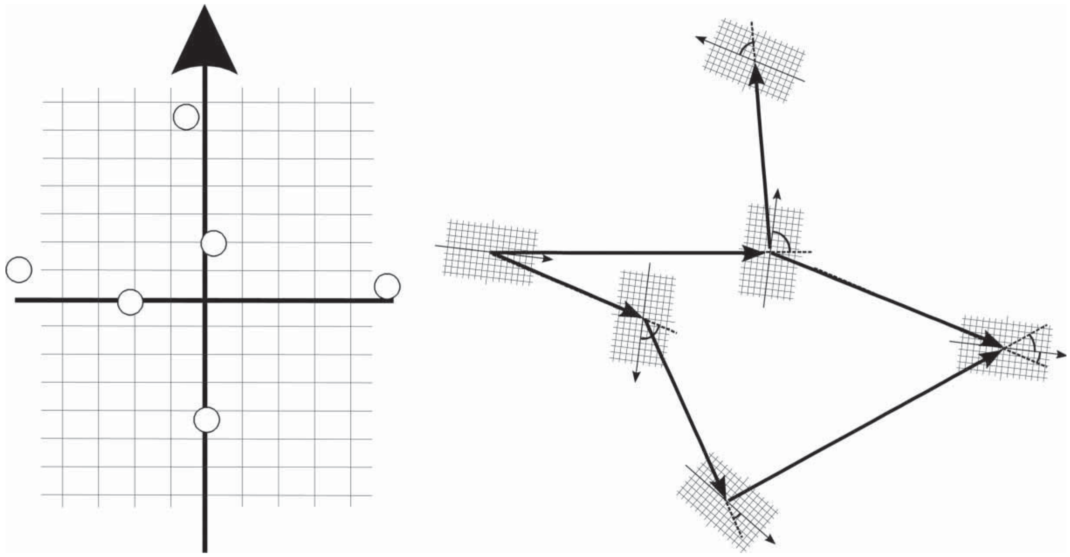

Figure 1. *Information about distances and relative orientations between locations within a space can be represented in a least two different ways, as sketched in the figure. Left: Locations are subsumed within a global reference frame (i.e., coordinate system). Right: Local reference frames are connected pairwisely within a graph representation. Edges represent the relative direction, distance, and orientation between two local reference frames.*

on reference frame selection within a vista space can be extended towards environmental spaces. In order to do so, the learning experience with an environmental space was standardized across participants in a way that all three factors yield the same global reference frame orientation. Then we tested whether this global reference frame was in fact used by participants within a survey (i.e., a pointing) task. This test used predictions for body, head, target, and location alignment effects.

Body alignment effect

The body alignment effect states that navigators should perform best (i.e., point most accurately or quickly) when their body orientation is aligned with the orientation of a reference frame representing this space (Iachini & Logie 2003; Levine, Marchon, & Hanley, 1984; McNamara et al., 2008). When being misaligned, costs for realignment (e.g., by mental rotation or perspective shift) may occur. This "strong claim" predicts that participants relying on a global reference frame will perform best when aligned with this global reference frame irrespective of their current location. However, it has also been shown that orthogonal body orientations and contra-alignment (i.e., 90°, 180°, and 270°) often yield better performance than oblique misalignments (i.e., 45°, 135°, 225°, and 315°; Kelly & McNamara, 2008; Mou & McNamara, 2002; Shelton & McNamara, 2001). This "weak claim" thus predicts better performance for orientations parallel or orthogonal to a global reference frame than for oblique orientations.

Head orientation effects

Mental rotation or perspective shifts have been proposed as compensation for (body) misalignment (Iachini & Logie, 2003; Kozhevnikov, Motes, Rasch, & Blajenkova, 2006; Shepard & Metzler, 1971). When navigators can turn their head they might at least partially compensate for body misalignment by aligning their head and looking into the direction of a reference frame. When relying on a global reference frame, participants are predicted to turn their head into the orientation of the global reference frame.

Target alignment effects

Just as an alignment between the body and a representation yields better performance in various orientation tasks, alignment between the target direction and a representation can also improve performance. In pointing tasks both effects are relevant: The angle to a target has to be computed relative to a reference frame in memory (unless the target direction was constantly updated). It has been shown that pointing to misaligned target directions can lead to decreased pointing performance (Rump & McNamara, 2013). Consequently, global reference frame utilization predicts improved pointing performance if the direction to the pointing target is aligned with the global reference frame, as compared to other directions.

Location alignment effects

Location alignment effects predict a potential performance benefit if the main reference axis of a local surrounding geometry (e.g., corridor or street orientation) is aligned with (or orthogonal to) the global reference frame. This prediction relates to prior work showing better pointing performance towards close-by streets or corridors that are parallel or orthogonal rather than oblique to the one currently located in (Montello, 1991; Werner & Schindler, 2004). A global reference frame common for a whole environmental space could yield the same effect.

The effects described are indicators of the reference frame within which environmental spatial information is encoded. They are based on the principle that orientation offset from an encoded reference frame orientation yields additional computation and thus increased error and/or latency as compared to merely accessing spatial information (McNamara et al., 2008). Head turning is a means of lowering the costs of body misalignment by physical instead of mental compensation. Prior research was mainly concerned with body alignment. Consequently, this is also the main indicator for the present study. However, in order to take all potential sources into account, we complemented this main indicator with additional ones that originate theoretically from the same underlying source—namely, reference frame orientation in memory. We also disentangled self-localization within an environment from pointing, which is often intermingled in the literature. Furthermore, we looked at error as well as latency measures. In accordance with prior research, our main measure will be pointing accuracy. However, as accuracy might be traded off with latency in pointing or prior self-localization, we included latency measures here.

Local reference frames

Local reference frames as defined here correspond to surroundings usually visible from a single vantage point ("vista spaces") such as streets or places (Cartwright & Collett, 1983; Chown, Kaplan, & Kortenkamp, 1995; Christou & Bülthoff, 1999; Gillner, Weiß, & Mallot, 2008; McNaughton, Leonard, & Chen, 1989; Meilinger, 2008; Meilinger, Franz, & Bülthoff, 2012; Waller, Friedman, Hodgson, & Greenauer, 2009; Wang & Spelke, 2002). They can refer to individual views or to representations of the whole visible space. In the latter case not only the experienced perspective but also orientations intrinsic to the space (e.g., parallel to the longer walls) may determine reference frame orientation of this space (Kelly & McNamara, 2008; Mou & McNamara, 2002; Shelton & McNamara, 2001). Please note that the global–local distinction was also used for vista space and their subparts such as object arrays, strings, mats, and so on (Greenauer & Waller, 2010; McNamara, 1986). Within the present work, local reference frames always refer to a whole vista space, whereas global reference frames refer to the environmental space (cf. Steck & Mallot, 2000).

When representing multiple locations within an environmental space, local reference frames have to be connected with each other. Instead of subsuming local reference frames under a global reference frame, they might also be connected pairwisely forming, for example, a graph structure (Figure 1, right; e.g., Mallot, 1999; Mallot & Basten, 2009; Meilinger, 2008). These connections can represent mere topology, a behaviour whose execution brings a navigator towards the next reference frame (enabling route navigation), ordinal relations, or metric relations (e.g., in which direction and at which distance the next reference frame is located).

Within environmental spaces many tasks were shown to rely on interconnected local reference frames. In particular, local reference frames have been shown to contribute to self-localizing (Christou & Bülthoff, 1999; Meilinger et al., 2012), spatial updating (Wang & Brockmole, 2003a, 2003b), or route navigation (Mallot & Gillner, 2000). However, survey tasks such as pointing require the integration of memory about immediate and remote locations into one reference frame to allow for the assessment of relative direction, orientation, or distance. As mentioned, one solution to this problem is integrating all spatial locations within one global reference frame. Alternatively, the required integration could (a) happen within a navigator's current local surrounding reference frame and (b) encompass not all, but mainly, those locations relevant for the current task (Meilinger, 2008). If pointing is indeed based on local reference frames, then various alignment effects are predicted that differ from the predictions of global reference frames, thus allowing us to disambiguate between the reference frames used.

Body alignment effects
Best performance should be obtained when navigators are aligned with the local reference frame they are currently located within. Performance may drop with further misalignment (strong claim), or be mainly worse for oblique misalignments relative to orthogonal or contra-alignment (weak claim).

Head orientation effects
Partial compensation may be obtained by aligning one's head with the local reference frame orientation.

Target alignment effects
Targets located in the direction of the local reference frame may be pointed towards more easily and accurately than targets located in other directions.

Location alignment effects
No location alignment effects as with the global reference frames are expected, as the local geometry will always be aligned with a local wall.

Orientation-free theories

Orientation-free theories posit that performance is independent of one's orientation within an environment—at least for highly familiar environments, but sometimes also on shorter time scales (Byrne, Becker, & Burgess, 2007; Evans & Pezdek, 1980; Gallistel, 1990; Sholl, 1987). Representing locations within a reference frame requires representing an orientation with the reference frame. Otherwise no relative direction can be specified. Orientation-free theories, therefore, state that these orientations do not play a role. This might be accomplished in at least four ways: First, the reference frame is used for computing distances and angles, but this does not trigger behavioural consequences in terms of an alignment effect (Byrne et al., 2007). Second, many pairwise relations between local objects are encoded that rely on differently oriented local reference frames (Sholl, 1987). If many frames with differing orientations have to be taken into account, then one might conclude that the overall influence of the different orientations cancel each other out and thus yield no overall orientation bias. Third, one might argue that a single location is represented multiple times within multiple oriented reference frames. Thus navigators will always be able to rely on a reference frame that they are (almost) aligned with. Fourth, navigators might use actual orientation-free representations (Gallistel, 1990). If so, these representations could not rely on any coordinate system, as this always has an orientation. Structural descriptions can be orientation free, like in this example: given three locations A, B, and C, distance(AB) = distance(BC); angle(ABC) = 90°. However, these spatial descriptions often have multiple solutions (Grush, 2000), and transforming them into a format usable for actions seems quite difficult. We do not argue about which conception of orientation-free behaviour seems most suitable, but only consider it as a potentially observed outcome;

all of them predict no body, head, or location alignment effects, neither locally nor globally.

Summary and preview of experiments

The aforementioned theories have different predictions that will be tested in the two experiments: (a) A representation within a global reference frame predicts the same global alignment effects for all of its locations; (b) local reference frame theories predict multiple, locally defined alignment effects; (c) orientation-free theories predict no systematic alignment effect, neither locally nor globally.

To test these predictions, we conducted two experiments in which participants learned a virtual environment presented via a head-mounted display (HMD) by repeatedly walking through it. In the testing phase, participants were teleported to different previously learned locations in the environment. They were then asked to identify their location and heading and afterwards point towards particular instructed targets. We systematically varied body orientation in order to test body alignment effects relative to the local corridor or global reference frame. In Experiment 1, participants could freely turn their head during testing. They thus were able to at least partially compensate for body misalignments, which allowed us to test for head alignment effects. In Experiment 2, head and body orientations were aligned during testing, such that participants could only mentally compensate for potential misalignments. This situation is sometimes termed *perspective alignment effect*.

EXPERIMENT 1

Method

Participants

Nine females and nine males between the ages of 18 and 31 years ($M = 25$ years, $SD = 3.7$ years) participated in the experiment. Fourteen of them participated as part of a seminar, most of them studying psychology or biology; four were recruited via a participant database and were paid for their participation. Their self-described sense of direction as measured with the German version of the Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) ranged from medium low to medium high (3.0, 5.6 points; $M = 4.4$; $SD = 0.8$; average on 15 questions on a 1–7 Likert scale).

Material

In the learning phase, participants were asked to learn the layout of the virtual environment and seven target objects located therein by walking through it several times. Participants' head position was tracked by 16 high-speed motion capture cameras at 120 Hz (Vicon® MX 13) while they walked freely in a large tracking space 15 × 12 m (see Figure 2). The participants' head coordinates were transmitted wirelessly (using wireless local area network, WLAN) to a high-end notebook computer (Dell XPS M170), which was mounted on a backpack worn by the participant. This notebook rendered an egocentric view of a virtual environment in real time. Participants viewed the scene in stereo using a head-mounted display (eMagin Z800 3D Visor) that provided a field of view of 32 × 24 degrees at a resolution of 800 × 600 pixels for each eye. While this HMD was lightweight and provided comfortable ergonomics without any occurrence of motion sickness, it only provided a rather small field of view, which might have reduced participants' sense of presence as well as walking speed and accuracy and might thus have slowed down the learning of the environment somewhat, which was one reason to apply a learning criterion as described below (e.g., Alfano & Michel, 1990; Arthur, 2000; Toet, Jansen, & Delleman, 2007). Moreover, participants had to turn their head in order to acquire information from their left or right side. Nevertheless, the overall set-up provided important depth cues such as stereo vision and motion parallax, as well as all bodily cues important for orientation such as efference copies and vestibular and proprioceptive information.

Using this set-up, the participants walked through a virtual environment that consisted of seven connected straight corridors, each with a different wall colour (see Figure 3). The corridors

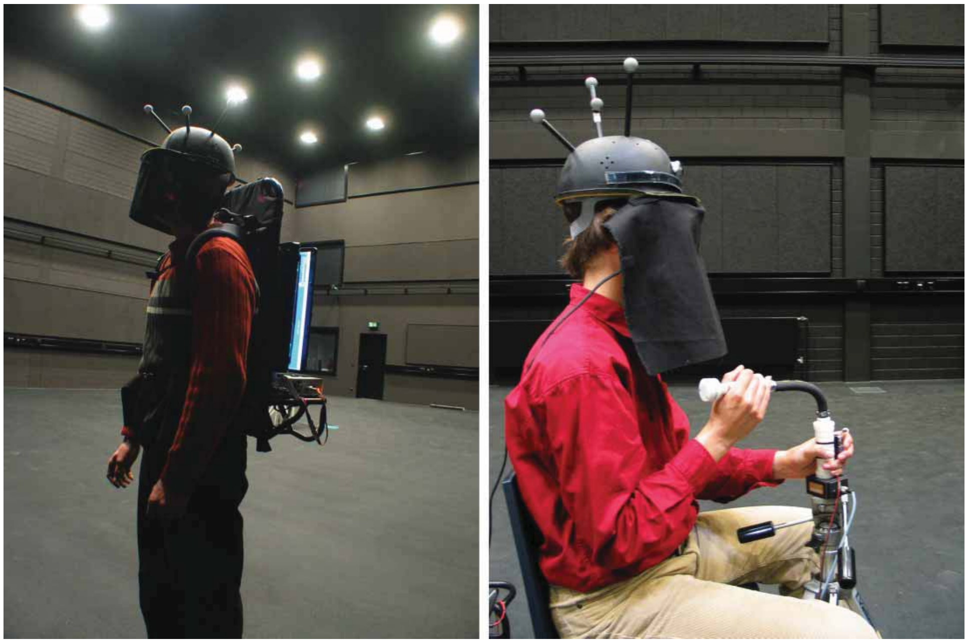

Figure 2. *The virtual reality set-up. The left image depicts a participant during the learning phase, equipped with a tracking helmet, a head-mounted display (HMD), and a notebook mounted on a backpack. The right image shows a participant pointing to a target during the testing phase. To view a colour version of this figure, please see the online issue of the Journal.*

formed one closed loop without any junctions. Seven distinct target objects were placed at a height of 1.3 m, one in each corridor. The seven target objects were selected to be similar to the objects used in earlier studies investigating spatial memory (e.g., Mou & McNamara, 2002). To ensure that participants experienced the corridors only from one direction, they always walked through the corridor in a clockwise direction, without ever turning around. Note that the current experiments were not designed to test for the influence of global versus local landmarks. Instead, the experiment was purposefully designed to exclude all global landmarks to be able to investigate how we build up a representation from exposure to individual connected vista points without any potential confounds of global orientation cues, similar to exploring a building or local neighbourhood in the absence of global orientation cues. The structure of the environment and its initial exposure was, however, arranged to establish a unique global reference frame in order to extend results found within vista spaces towards the environmental space at hand (see map in Figure 3): first experience, main orientation during exploration, and overall elongation of the environment coincided to suggest the same global reference frame orientation. Initial experience and main orientation of the physical lab space result in an identical reference frame in order to prevent interference from multiple reference frames of the physical hall and the virtual environment (e.g., May, 2004; Riecke & McNamara, 2007). This environment also allowed for comparisons of corridors oblique versus parallel/orthogonal to this global reference direction. Pointing accuracy and time was measured using a custom-built pointing device (see Figure 2, right).

Procedure

Learning phase. In the learning phase, participants were asked to walk five times clockwise through the corridors. Their task was to learn in which corridor and where in the whole layout an object was

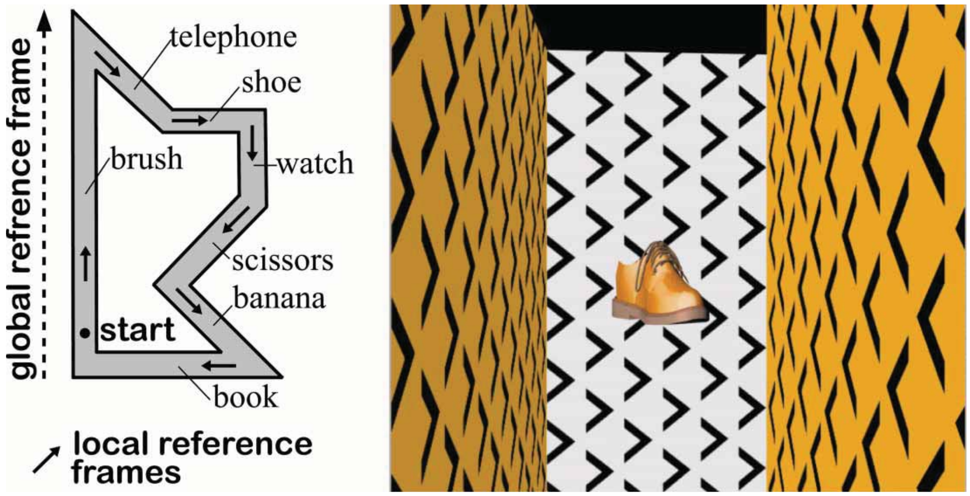

Figure 3. *Left: A map of the virtual environment. Participants always walked around the environment clockwise. At each object location, participants were tested in eight different visually simulated body orientations (–135°, –90°, –45°, 0°, 45°, 90°, 135°, and 180°), which includes the orientations aligned with the global reference frame (0°) and aligned with the local reference frame (e.g., –90° when positioned at the "shoe"). Right: A perspective screenshot of the environment during the learning phase. During the test phase, the target objects were removed. To view a colour version of this figure, please see the online issue of the Journal.*

located. Participants were asked not to turn around or look back into the corridor they were coming from. They could take as much time as they wanted. A learning criterion where the objects were removed from the environment ensured comparable knowledge levels for all participants: During two additional rounds through the environment participants were asked at every second place which object had been located at this location. Participants who did not name all seven objects correctly could walk an extra round through the corridors with objects before being asked again. In addition to errors in the learning test, we recorded navigation time and head orientation during learning.

Test phase. In the following test phase, all target objects were removed, and participants were seated on a chair in front of the pointing device (see Figure 2, right). Through the HMD, they were presented with a view of one of the seven corridors exactly from the location where target objects had been situated during the learning phase, but in different visually simulated orientations for different trials. Multiple geometric and texture cues were available for participants to orient themselves and determine their original walking direction through the corridors, including an asymmetric wall texture and the colour, relative orientation, and texture of the adjacent corridor that was visible when looking towards the end of the current corridor. Participants thus used the cues visible from the corridor to determine their simulated body orientation within a trial. In Experiment 1, we allowed participants to freely move their head to look around, as such head rotations naturally occur during human spatial orientation tasks. However, participants were instructed to not stand up and therefore kept a constant body orientation with respect to their surroundings.

Each participant performed 56 trials, consisting of a factorial combination of seven locations (one for each corridor) by eight different visually simulated body orientations (–135°, –90°, –45°, 0°, 45°, 90°, 135°, and 180°). Trial order was randomized for each participant. These test directions included directions aligned with local (i.e., along the corridor) and global reference frames (see Figure 3). For each trial, participants were asked to first identify their location and heading and afterwards point towards a randomly chosen target object. The time for self-localization was recorded as the time between the initial presentation of a new view and the time when participants indicated via button press that they had localized themselves in the environment (i.e., when they knew the depicted corridor and their orientation in the corridor; note that we did not ask participants to imagine the direction of any potential target object, as this was not announced until they had completed self-localization). Immediately afterwards, participants were asked to point as accurately and quickly as possible to a goal target (one of the seven learned target objects), which was indicated by text on the screen. Targets were chosen randomly from one of the other six corridors and were always occluded by the corridor walls. We measured both pointing error and latency. However, pointing error was the central measure, as it was the predominant measure in prior research.

Global reference frame orientation was predicted by the common experience history and the global layout structure. However, individual participants might still come up with a different global reference frame. As validity check we used a postexperimental map-drawing task. Upwards in this map was estimated as the orientation of a potential individual global reference frame orientation, because in order to draw this orientation no mental rotation would be necessary. Participants were provided with a blank DINA4 sheet of paper and were asked to draw a map of the environment that included the locations and names of the objects. Two raters independently rated the orientations of the map—that is, whether participants drew it as displayed in Figure 3 or in another orientation (e.g., with the book at the top). The raters chose between eight possible orientation categories (i.e., north, north-east, east, south-east, etc.). In case of disagreement they eventually reached consensus.

Data analysis

Body alignment. For analysing body alignment effects eight different body orientations (i.e., –135°, –90°, –45°, 0°, 45°, 90°, 135°, and 180°) relative to a global or local reference frame were compared. The 0° condition corresponded to the local or global reference frame orientation as predicted by the theories (i.e., the orientation a corridor was walked through and upwards in Figure 3). If body orientations differed significantly as indicated by a main effect of an analysis of variance (ANOVA), we proceed by testing whether this difference originated from the strong claim by comparing 0° with the mean of the remaining orientations. For the weak claim we compared parallel and orthogonal orientations (0°, ±90°, and 180°) with oblique orientations (±45° and ±135°), but only in case the strong claim was not significant.

Head alignment. For head alignment during self-localization and pointing, we computed relative head orientation frequencies in the eight above-mentioned categories.

Target alignment. For target alignment effects during pointing we compared trials with targets located in the direction of a global or local reference frame with targets located in other directions. Target directions were classified as aligned when deviating not more than ±30° from a global or local reference frame and were classified as misaligned otherwise. Due to the structure of the environment, smaller angular deviations or using eight categories would have resulted in cells with no or only very few observations. The strong claim in location alignment effects would compare performance in the brush corridor with performance in other corridors (see Figure 3). In order to establish a global reference direction, the brush corridor was by design also the corridor experienced first, such that a primacy effect (i.e., better memory of elements experienced first) would have further emphasized this orientation (Postman & Philips, 1965). The strong claim was thus necessarily confounded with a primacy effect, and results could not be disambiguated. We only examined the weak claim for which an alternative explanation by a primacy effect is unlikely as orthogonal and oblique corridors were spread over the whole course: We compared performance in brush, shoe, clock, and book corridors with performance in telephone, scissors, and banana corridors.

The different alignment effects are independent predictions. Therefore, we did not adjust alpha levels for the different effects. As a control for individual global reference frame orientations differing from the predicted one, we also tested alignment effects relative to the map orientation. As 16 out of 18 participants drew their maps aligned with the global reference frame direction, these analyses did not yield different results and were thus not reported separately.

Individual differences. We also examined individual differences for effects found. This was done to examine whether usage of a certain reference frame increased performance. For each participant we computed the numerical difference for a significant contrast between an aligned and a misaligned condition (e.g., the difference between 0° and the remaining orientations or between parallel/orthogonal and oblique orientations). These differences were correlated with each other and with average performance. Only parameters that showed a significant alignment effect were correlated.

In order to have a reliable and parameter-free control of outliers, we computed median values per condition and participant (i.e., across repetitions). This aggregated data were then submitted to either paired t test or within-subject ANOVAs. In the latter case we additionally applied t tests according to predictions of the strong and weak claim if the ANOVA was significant.

Results

Learning

Five of the 18 participants (27%) made errors during the learning test and thus had to walk three more times through the labyrinth. On average, participants walked 7.8 times ($SD = 1.4$) through the labyrinth and spent 17 min ($SD =$ 5.6 min) doing so. Neither learning time nor the number of learning trials (i.e., errors during learning) correlated with the performance in self-localization or pointing ($n = 18$, six rs $< .37$, ps $> .14$). Performance was thus unaffected by the amount of prior time spent on learning the environment. We thus conclude that the learning criteria was effective, and all participants acquired a comparable level of knowledge during the learning phase.

While walking through the environment, 32% of the time participants faced the global reference frame orientation (see Figure 3). This is more often than the average of any other orientation, $t(19) = 10.9$, $p < .001$, $d = 2.57$. Not only the initial orientation and the geometric layout but also orientation during learning coincided, thus predicting a common global reference frame orientation.

Pointing accuracy (defined as the absolute pointing error) was significantly better than the chance level of 90°, $t(17) = 24.8$, $p < .001$. That is, participants did indeed acquire survey knowledge of the layout. We did not observe any *gender* difference: errors during learning test, $t(16) = 1.11$, $p = .284$, $d = 0.53$; time for self-localization, $t(16) = 1.04$, $p = .313$, $d = 0.50$; pointing error, pointing time, and overall learning time, $t(16) < 1$. The data were collapsed for further analysis.

In the following, we provide statistical analyses of the different alignment effects for the main experiment. A summary is provided in Table 1.

Body alignment

As indicated in Figure 4 (left), participants' pointing accuracy and self-localization time varied as a function of local orientation, $F(7, 119) = 7.0$, $p < .001$, $\eta_p^2 = .29$, and $F(7, 119) = 2.58$, $p = .017$, $\eta_p^2 = .13$, respectively. As predicted by the local reference frames theories, participants pointed more accurately, $t(17) = 2.54$, $p = .021$, $d = 0.60$, and self-localized faster, $t(17) = 4.42$, $p < .001$, $d = 1.04$, when oriented in the direction in which they had experienced the corridor (0°) than when oriented otherwise [pointing latency: $F(7, 119) = 2.05$, $p = .054$, $\eta_p^2 = .11$].

No differences in participants' performance due to the global reference frame orientation could be found [self-localization time, pointing time, and pointing accuracy, all $F(7, 119) < 1$ (see right column in Figure 4)]. That is, the current data provide no support for the strong claim of single reference frames stating that best performance is

Table 1. *Summary of results of Experiments 1 and 2 in comparison with the predictions of the three theories*

		Alignment effects			
		Body	Head	Target	Location
Experiment 1:	Global reference frame	✓ Self-localization	×	×	✓
	Local reference frames	✔	✔	×	N/A
	Orientation-free theories	×	×	×	×
Experiment 2:	Global reference frame	×	×	×	✓ Self-localization
	Local reference frames	✔	×	✔	N/A
	Orientation-free theories	×	✓	×	×

Note: A big check indicates support for the strong claim (i.e., better performance when aligned with the predicted orientation than when aligned with other orientations). A small check indicates support for the weak claim (i.e., better performance when parallel or orthogonal to a reference orientation than when oblique), or a lack of any significant alignment in case of orientation-free theories. If the effect was not found in the main parameter accuracy, but only in pointing latency or self-localization latency, the parameter is mentioned. Body alignment was the main indicator. The weak claim was tested in location alignment only. In Experiment 2, head alignment was only possible during self-localization, not during pointing.

observed when participants are aligned with a global reference frame. There was, however, support for the weak claim: Participants self-localized faster in orientations parallel or orthogonal to a global reference frame than in oblique orientations: 9.1 s versus 10 s, $t(17) = 2.59$, $p = .019$; $d = 0.61$; pointing error and time, both $t(17) < 1$.

Head orientation

The relative frequencies of head orientations indicated where participants looked during the experiment to acquire information (especially during self-localization) and to at least partially compensate for their body misalignment (especially during pointing). We found very strong effects of local head orientation during self-localization (see Figure 5 top left), $F(7, 119) = 195$, $p < .001$, $\eta_p^2 = .92$, and during pointing (Figure 5 bottom left), $F(7, 119) = 24.1$, $p < .001$, $\eta_p^2 = .59$. Participants mainly looked into the direction of a location reference frame (i.e., 0°)—even more so than in the opposite 180° direction: during self-localization, $t(17) = 3.27$, $p = .005$, $d = 0.77$; during pointing, $t(17) = 2.41$, $p = .028$, $d = 0.57$.

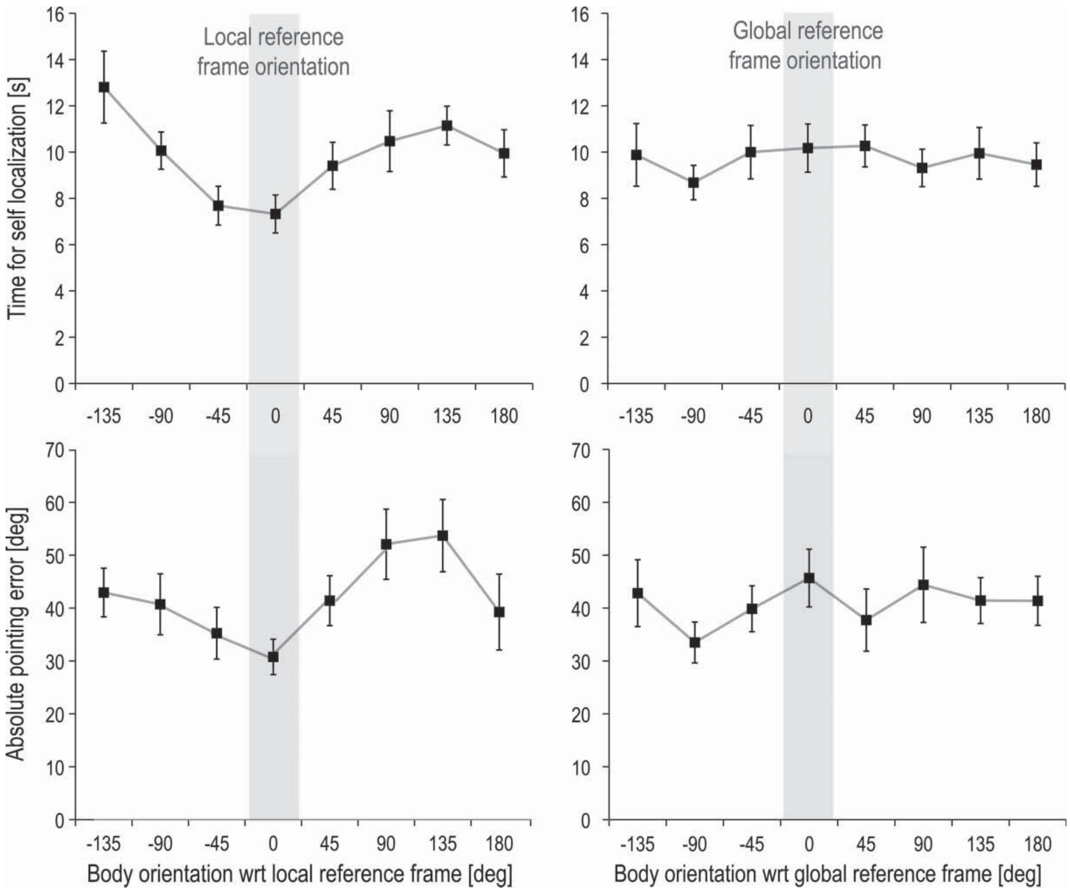

Figure 4. *Pointing errors and self-localization time for Experiment 1 as a function of body orientation relative to local reference frames (left plots) and the global reference frame (right plots). Means and standard errors for the time for self-localization (top row) and for pointing accuracy (bottom row) are displayed.*

We also found effects of global orientation during self-localization (Figure 5 top right). $F(7, 119) = 11.9$, $p < .001$, $\eta_p^2 = .41$, and during pointing (Figure 5 bottom right), $F(7, 119) = 5.85$, $p < .001$, $\eta_p^2 = .26$. However, contrary to the strong claim, participants did *not* look most often into the global reference frame orientation. They least often faced the −45° orientation, which might be caused by the fact that they never walked through a corridor in this orientation during learning. There was no effect of the weak claim either [self-localization, $t(17) = 1.91$, $p = .071$, $d = 0.45$; pointing, $t(17) = 2.01$, $p = .060$, $d = 0.48$].

Please note that this averaged pattern was not prevalent in every participant. It differed especially during the moment of pointing (i.e., when deflecting the pointing stick). Four participants almost always looked straight ahead in this moment. Eight participants almost always looked down a corridor, preferably in the orientation they experienced it during learning (one participant even tried to turn around when oriented 180° to the experienced orientation). The remaining six participants showed a mixture between these two strategies (e.g., by looking down a corridor when they only had to turn their head by 45° and looking straight when a 90° head turn would have been

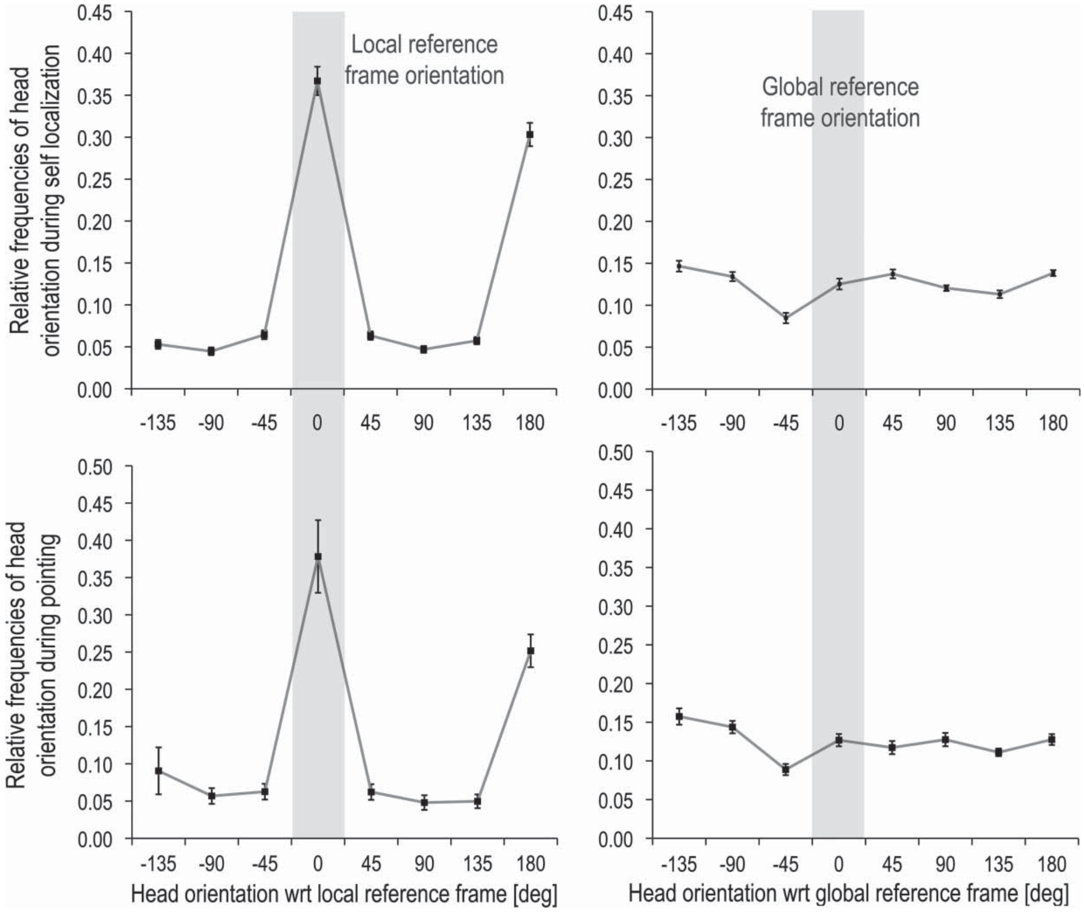

Figure 5. *Relative frequencies of head orientation during self-localization (top row) and pointing (bottom row) as a function of participant's head orientation relative to a local (left side) or the global reference frame (right side) in Experiment 1.*

required). Not a single participant showed a pattern of aligning the head preferably with a global orientation.

Target alignment

The target alignment effect examines the direction of the pointing target relative to the orientation of global or local reference frames independent from body orientation. Participants' pointing did not differ between targets aligned and misaligned with a local reference frame, neither for pointing error, $t(17) < 1$, nor for response time, $t(17) = 1.96$, $p = .067$, $d = 0.46$. We found an effect in pointing time relative to the global reference frame orientation: $t(17) = 2.17$, $p = .045$, $d = 0.51$; pointing error: $t(17) < 1$. However, contrary to the predictions, participants pointed faster towards targets not aligned with a global reference frame than to aligned targets.

Location alignment

A shown in Figure 6, performance varied between locations for self-localization time, $F(6, 102) = 5.16$, $p < .001$, $\eta_p^2 = .23$, and pointing error, $F(6, 102) = 2.79$, $p = .015$, $\eta_p^2 = .14$, but not for pointing time, $F(6, 102) = 1.93$, $p = .084$, $\eta_p^2 = .10$, or the number of errors observed during the learning test, $F(6, 102) = 2.01$, $p = .072$, $\eta_p^2 = .11$. The

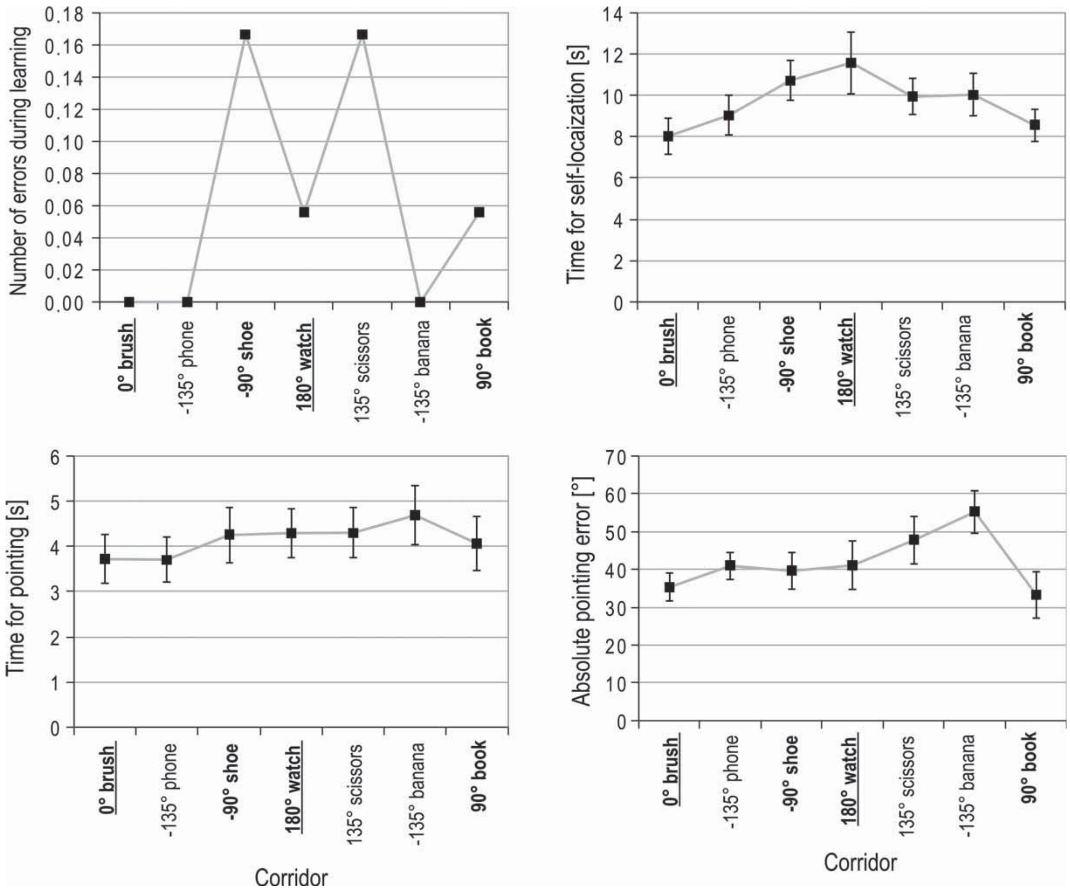

Figure 6. *Performance in Experiment 1 as a function of location in the environment. Corridors written in bold letters were parallel/orthogonal to a global reference direction; parallel corridors are additionally underlined.*

weak claim of location alignment was supported for pointing error, $t(17) = 2.62$, $p = .018$, $d = 0.61$, but not self-localization time ($t < 1$): Participants pointed more accurately in corridors parallel or orthogonal to the global reference frame orientation (i.e., the corridors with the brush, the shoe, the watch, and the book) than in oblique corridors (i.e., the telephone, the scissors, and the banana).

Individual differences

The weak claim of global reference frames was supported for body and location alignment. "Global" participants showing this location alignment more strongly (i.e., those who showed a higher difference in pointing error between oblique and orthogonal corridors) pointed faster in general ($n = 18$, $r = .62$, $p = .006$). "Local" participants here showed a higher difference between being aligned versus not aligned with a local reference frame in body or head alignment. Participants who more often aligned their head with a local reference frame pointed slower ($r = .67$, $p = .003$), but not significantly less accurately ($r = .44$, $p = .065$). Higher differences in body alignment were unrelated to average performance (six rs = [–.09; .12], ps > .628). Being more "global" was not correlated with being "local" (six rs = [–.38; .01], ps > .116). Participants thus do not seem to rely on either local or global reference frames alone, but might use both at the same time.

Discussion

Local reference frames

As predicted by local reference frame theories, participants performed better when they were aligned with the local reference frame and looked more often into the orientation of a local reference frame (see Table 1 for a summary of the results).

So far local reference frames (e.g., views) have mainly been supported in the context of self-localization, route following, or recombining familiar routes (Christou & Bülthoff, 1999; Gillner et al., 2008; Iachini & Logie, 2003; Mallot & Gillner, 2000; Meilinger et al., 2012; Waller et al., 2009). For survey tasks, however, the predominant focus has been on global reference frame theories. The present experiment supports accounts stating that interconnected local reference frames can also be used for survey tasks (e.g., Meilinger, 2008).

Body alignment predicts best performance when a navigator is aligned with a reference frame. In misaligned situations, additional processes must compensate for the discrepancy between one's current orientation in the environment and the reference frame in which it was encoded. This compensation could be accomplished, for example, by mentally rotating the environment or one's position in the environment (Iachini & Logie, 2003; Kozhevnikov et al., 2006; Shepard & Metzler, 1971). As participants were allowed to turn their head they could also compensate for the misalignment simply by turning their head into the experienced orientation. Indeed many participants did just that. Such compensation, however, could only be partial, as the trunk orientation and with it the orientation of the pointing stick was fixed. Participants who turned their head still had to compensate for the offset between head orientation and body orientation. Indeed, participants who more often turned their head also pointed slower. Maybe these participants had reduced abilities to mentally compensate for misalignments, so they more often used a compensation strategy by turning their heads. The physical awkwardness of the posture especially during extreme head turning might also as such account for the larger pointing error. Despite this awkwardness, participants aligned their head with local reference frames. Alternatively to compensating for misalignments, it is conceivable that participants only turned their head to look down the corridors because this provided them with more information than did facing a wall. Indeed the rather small field of view of the HMD forced them to turn their heads in order to obtain new information. However, merely acquiring information does not explain why they more often looked down a corridor in the direction of walking than in the opposite direction. These orientations should not have differed in the information provided. Such a preference of facing the experienced walking direction does, however, make sense if participants tried to align with their local reference frame, for example, in the form of an experienced view. In addition, during pointing, participants knew where they were located and should not have needed to obtain more information about their surroundings. We thus propose that especially during pointing, participants turned their head also to compensate for misalignment with their internal representation of the environment.

One limitation of our self-localization data is that we only recorded time and not accuracy. However, if participants self-localized faster in body orientations aligned with the local reference frame only by the cost of a higher error, such an erroneous self-localization should have yielded higher errors during pointing and not the smaller errors observed. It is thus unlikely that errors in self-localizations were responsible for the observed effects. Similarly, participants might have imagined distant locations already during self-localization and thus speeded up their pointing latencies—despite being instructed to press the joystick button as soon as they knew where they were. Even if they did so, this should not have affected the alignment effects, which were observed both in self-localization and in pointing.

Global reference frames

Global reference frame theories predict that a global reference frame is used for survey tasks such as pointing (Kuipers, 2000; McNamara et al., 2008; O'Keefe, 1991; Poucet, 1993;

Trullier et al., 1997). The strong claim of global reference frame theory predicts that performance should be best when body orientation, head orientation, or target direction are aligned with the global reference frame. This was, however, not found. In fact, performance was best when head or targets were aligned with an orientation different from the one predicted by global reference frame theories. The strong claim of global reference frame theories was not supported by the present data.

The support for the weak claim looks more promising. Participants performed better in body orientations and in corridors parallel or orthogonal to the global reference frame orientation than in oblique orientations. This extends findings showing better pointing performance towards close-by streets or corridors that were parallel or orthogonal rather than oblique to the one currently located in (Montello, 1991; Werner & Schindler, 2004). In the present experiment, however, aligned versus misaligned contrast was not between the current and the target corridor, but between the current corridor and a mental global reference frame used to represent the whole environment.

Overall, the conclusions we can draw about global reference frames in Experiment 1 are somewhat limited. Whereas pointing errors regarding body alignment (which was the central measure in prior studies) showed clear effects for local reference frames, there was no such support for global reference frames. In addition, the location alignment effect was mainly driven by higher accuracy in the first and last corridor as indicated in Figure 6. If the first corridor profited from a primacy effect (Postman & Philips, 1965), corridors adjacent to the first corridor could be seen during learning and test, so their orientation relative to the first corridor might have been inferred more easily. As the last corridor was an aligned corridor as well, this might have further contributed to location alignment, in addition to potential recency effects. Although this does not explain the effect in body alignment, it indicates that our tentative conclusions on global reference frames should be taken with caution and should be tested in future experimentation that uses different layouts to disambiguate global alignment effects from potential primacy/recency effects.

Global reference frame orientation was determined by the initial experience and the geometric orientation of the whole environment. This prediction is a generalization of results obtained from experiments within vista spaces (Kelly & McNamara, 2008; McNamara et al., 2003; Mou & McNamara, 2002; O'Keefe, 1991; Shelton & McNamara, 2001). Results from the weak claim suggest that this generalization might in fact have been valid. Similar to many of these experiments, participants performed better in parallel and orthogonal orientations than in oblique orientations. Head orientation during learning was also most frequently oriented along the predicted orientation. This factor might have mediated the selection of a global reference frame. Future experimentation may examine which of conflicting predictions from geometric layout and initial and main experience drive the selection of a global reference frame.

The common global reference orientation was obtained by standardizing the learning experience for all participants. In everyday navigation, experiences often are not standardized in the same way. Consequently, any global reference frames are likely to differ between navigators. Results from map drawing show that only two out of out of 18 participants drew their maps in another orientation than the predicted one, suggesting only limited variation. When analysing the data relative to the drawn map orientation instead of the predicted global reference orientation, results were also very similar.

Orientation-free theories

Orientation-free theories do not predict any alignment effects (Byrne et al., 2007; Evans & Pezdek, 1980; Gallistel, 1990; Sholl, 1987). The current data showed, however, various clear alignment effects (see Table 1 for a summary). This is inconsistent with orientation-free representations for environmental spaces. The amount of exposure to the environment might, however, not have been sufficiently long to form a perspective-free memory of the environment as suggested by most of these positions. Using much longer learning times might eventually have led to different results. Similarly, the pattern of results might have been different if participants were allowed to freely explore, thus experiencing the corridors in multiple orientations. Nevertheless, the current data provide no support for orientation-free theories for the circumstances tested.

Individual differences

Our results support local reference frames and to a lesser degree global reference frames. However, participants who did use a global reference frame (i.e., showing a larger global effect than other participants) also performed better. Interestingly, these participants did not seem to trade off global with local reference frames—the sizes of local and global effects were not correlated between participants. Instead, they seemed to employ global reference frames in addition to local reference frames and by this achieved a better performance—maybe by integrating local reference frames within a global reference frame focusing on cardinal directions, without necessarily aligning local reference frames. Or they could have assigned a cardinal direction to each local corridor and thus eased integration.

Please note that in the present environment the influence of local versus global reference frames could not be disambiguated for individual corridors, as one corridor was aligned with the global reference direction, three were contra-aligned or orthogonal, and three were oblique. That is, if participants preferred local reference frames, these frames would be aligned to the global reference direction in the strong sense in one out of seven corridors and aligned in the weak sense (i.e., parallel or orthogonal) in four out of seven corridors. When averaged over the seven corridors, a preference for local reference frames would not be reflected in an overall preference for a global reference frame. That is, the influence of local versus global reference frames could be disambiguated when averaging over the seven corridors, although they cannot be disambiguated for each of the individual corridors.

In summary, while good navigators seemed to effectively combine local and global reference frames, many participants did not show evidence for global reference frames and thus presumably solved the pointing task based on local reference frames.

EXPERIMENT 2

In Experiment 1, participants were allowed turn their head in order to compensate for misalignment between body orientation and reference frame orientation. Experiment 2 was designed to investigate whether the observed results could be reproduced in the absence of such compensatory head turning. To this end, we instructed participants to look straight ahead during pointing. Here we expected a linear decrease in performance for increasing misalignments (Iachini & Logie, 2003; Shepard & Metzler, 1971). We also equalized visibility in all orientations during testing. As can be seen in Figure 7, the target objects were now placed in the centre of cylindrical rooms with entrance and exit doors that were closed throughout the test phase. Participants could thus no longer acquire additional information from looking down a corridor and seeing a part of the adjacent corridor as compared to facing a wall. They also could no

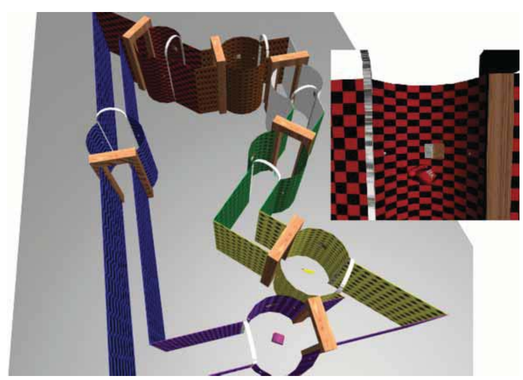

Figure 7. *Perspective view of the virtual environment used in Experiment 2 and of the interior of one room in detail (top right inset). Participants always walked around the environment clockwise, starting with the blue corridor. For the test phase, the doors were closed, and the seven target objects were removed. To view a colour version of this figure, please see the online issue of the Journal.*

longer infer the orientation of an adjacent corridor from visual input, but instead had to rely on their memory. As global alignment did not relate to head orientation during pointing, we expected similar results to those in Experiment 1. Last, we were interested in the way participants drew their maps and thus additionally recoded the order in which participants drew the corridors in their maps. This gave us hints about whether participants might abstract from the order in which they experienced the environment.

Method

Participants

Ten females and 10 males between the ages of 19 and 36 years ($M = 25$ years, $SD = 3.8$ years) participated in the experiment. They were recruited via a participant database and were paid for their participation. The database consists mainly of students from a large variety of academic disciplines. Their self-described sense of direction in the German version of the Santa Barbara Sense of Direction Scale (Hegarty et al., 2002) again ranged from medium low to medium high (2.9; 5.7 points; $M = 4.3$, $SD = 0.8$).

Material

The layout of the labyrinth was exactly the same as that in Experiment 1 except for cylindrical rooms that were introduced around each target object in order to avoid directional biases. We also altered the textures of the corridors such that each corridor could now be identified based on both their colour and texture. The new textures had no intrinsic orientation (see Figure 7). To ensure that participants had sufficient visual information to be able to determine their current location and heading for each of the eight orientations tested even without having to turn their heads (which they were only allowed during self-localization, but not during pointing), the entrance doors had a wooden texture, and the exit door on the opposite side had a metallic texture. Additional local orientation cues were positioned in every circular room at $\pm 45°$, $\pm 90°$, and $\pm 135°$.

Procedure

The procedure was identical to the one in Experiment 1 except for the following changes. In the learning phase, participants were asked to walk eight (instead of five) times clockwise through the corridors. At the end of the eighth passage, participants were shown the wall texture of a corridor and were then asked to name the object that is in the corridor of that texture. Participants who did not name all objects correctly could walk two extra rounds through the corridors before being asked again. During pointing, but not during self-localization, participants were asked not to turn their heads. If they did so during pointing against the instructions, the display turned black. They could thus not compensate for body-misalignment by turning their head. While drawing the map the experimenter recorded the order in which participants drew the corridors for 18 of the 20 participants. Fifteen out of the 18 maps were drawn in the orientation of the global reference frame. When comparing performance relative to the observed map orientation instead of the theoretically predicted global reference frame orientation, we obtained similar results, which are not shown here.

Results

Learning

Only one participant made an error during the learning test. On average participants walked 8.1 times ($SD = 0.4$) through the labyrinth and spent 16 minutes ($SD = 4.9$ min) doing so. Neither learning time nor the number of learning trials (i.e., errors during learning) correlated significantly with the performance in self-localization or pointing ($n = 20$, six rs $< .42$, ps $> .071$). Participants acquired thus a comparable level of knowledge.

While learning the environment, participants faced the predicted reference direction of single global reference frame theories in 28% of the time. This is more often than the average of any other orientation, $t(19) = 15.8$, $p < .001$, $d = 3.54$.

Pointing accuracy differed significantly from the chance level of 90°, $t(19) = 8.10$, $p < .001$. That is, participants did indeed acquire survey knowledge of the layout. Females and males did not differ in terms of their pointing time, $t(18) = 0.88$, $p = .388$, $d = 0.40$, or the time required for self-localization, $t(18) = 1.56$, $p = .137$, $d = 0.70$. Men pointed, however, more accurately, $t(18) = 4.34$, $p < .001$, $d = 1.94$. Including gender in any analysis of pointing accuracy did not produce different results (i.e., no interaction between gender and another factor that would limit the interpretation of the main effect of the other factor) and is thus not reported. In the following, we compare observed and predicted alignment effects for the local versus global reference theories. Results are summarized in Table 1.

Body alignment

Participants' pointing accuracy varied as a function of local orientation (see Figure 8 left side), $F(7, 133) = 3.11$, $p = .005$, $\eta_p^2 = .14$. They pointed more accurately when oriented along the local reference frame (0°) than when oriented in another direction, $t(19) = 3.99$, $p = .001$, $d = 0.89$. They pointed also more accurately when they were aligned (0°) than when they were contra-aligned (180°) with the local reference frame, $t(19) = 2.17$, $p = .043$, $d = 0.48$. An alternative explanation based on a speed–accuracy effect is unlikely, as there was no effect of local orientation on pointing time, $F(7, 133) = 1.02$, $p = .419$, $\eta_p^2 = .05$ [self-localization time $F(7, 133) < 1$]. We also tested whether the error increased linearly the more the body orientation deviated from the local reference frame orientation (i.e., the 0° condition; see Figure 8). Mentally rotating one's perspective to align it with the memory reference frame would predict such an increase. Indeed the pointing error increased linearly with the amount of misalignment: linear trend, $F(1, 19) = 5.54$, $p = .030$, $\eta_p^2 = .05$; time, $F < 1$.

Participants' performance did not vary as a function of global reference frame orientation, neither in terms of the absolute pointing error (see Figure 8 right side), $F(7, 133) = 1.43$, $p = .199$, $\eta_p^2 = .07$, nor for the pointing time, $F(7, 133) = 1.01$, $p = .430$, $\eta_p^2 = .05$, or for the time for self-localization ($F < 1$). We also found no support for the weak claim suggesting a difference between being oriented parallel or orthogonal versus oblique relative to the global reference frame: time for pointing, self-localization, and pointing error, all $t(19) < 1$.

Head alignment

During self-localization, participants could turn their head to look around. The relative frequencies of head orientation did not differ, neither relative to the local reference frame orientation, $F(7, 133) < 1$, nor relative to the global reference frame orientation, $F(7, 133) = 1.20$, $p = .306$, $\eta_p^2 = .06$ [orthogonal vs. oblique $t(19) < 1$]. In fact, participants mainly looked straight ahead while self-localizing.

Target alignment

Participants pointed more accurately to targets located along the direction of the local reference frame (42° vs. 57°), $t(19) = 2.52$, $p = .021$, $d = 0.56$ [pointing time, $t(19) < 1$]. This result was irrespective of body orientation. We found no effect of target alignment with the global reference frame orientation (pointing error and time $t(19) < 1$.

Location alignment

As shown in Figure 9, performance varied between locations for self-localization time, $F(6, 114) = 4.87$, $p < .001$, $\eta_p^2 = .20$, and pointing time, $F(6, 114) = 3.24$, $p = .006$, $\eta_p^2 = .15$ [pointing error, $F(6, 114) = 1.24$, $p = .293$, $\eta_p^2 = .06$]. Consistent with the weak claim, participants self-localized faster in corridors parallel or orthogonal to a global reference frame than in oblique corridors, $t(19) = 2.39$, $p = .028$, $d = 0.53$. Their pointing did not differ with respect to latency, $t(19) = 1.75$, $p = .096$, $d = 0.39$.

Order of corridors in map drawing task

In Experiment 2 we also recorded the order in which the corridors were drawn (e.g., first the

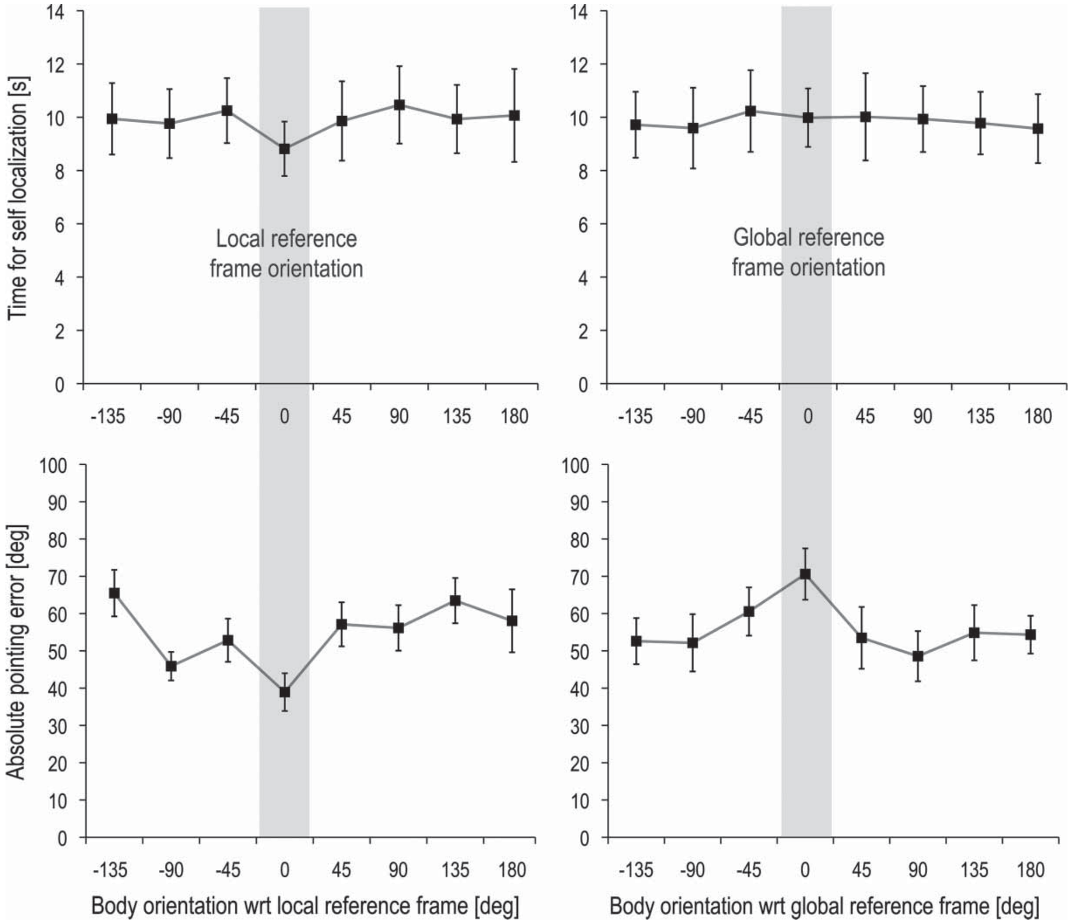

Figure 8. *Pointing error (bottom) and self-localization time (top) for Experiment 2, plotted with respect to local reference frames (left plots) and the global reference frame (right plots).*

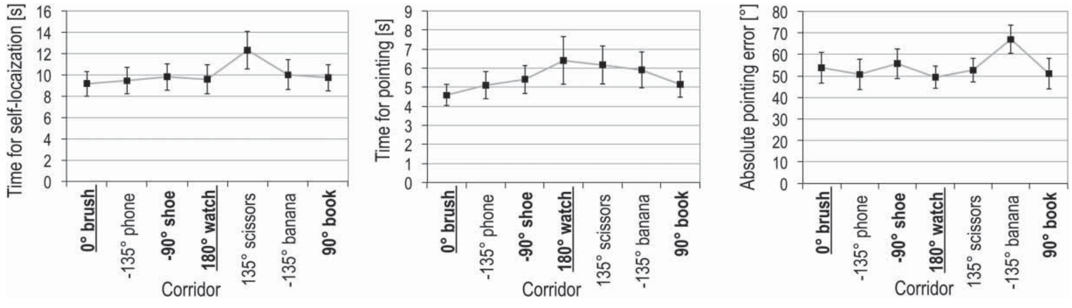

Figure 9. *Performance as a function of location in Experiment 2. Corridors parallel/orthogonal to the global reference frame direction are boldfaced. Parallel ones are also underlined.*

Table 2. *Mean rank order in which a corridor was drawn during drawing the map*

Corridors in the order of learning	*Mean rank of drawing this corridor*
Brush	1.33
Phone	2.22
Shoe	3.28
Watch	4.17
Scissors	5.17
Banana	5.89
Book	5.94

brush corridor, then the book corridor, etc.). Table 2 shows the mean rank number for each corridor. Most participants started with the brush-corridor that they also saw first when learning the environment. Twelve out of 18 participants (67%) drew the map exactly in the order of experiencing it during the learning phase, yielding a mean correlation between order of learning and drawing of $r = .82$ ($n = 7$). They did not abstract much from the learning order.

Individual differences

"Global" participants who oriented better in corridors parallel or orthogonal to the global reference frame (i.e., those who showed a higher difference in self-localization time between oblique and orthogonal corridors) pointed more accurately ($n = 20$, $r = .59$, $p = .006$) and were more likely male ($r = .54$, $p = .014$). "Local" participants who showed a stronger target alignment effect pointed less accurately ($r = -.68$, $p = .004$), were less likely "global" ($r = -.50$, $p = .024$), and by trend were more likely female ($r = .42$, $p = .064$). Maybe these participants used the corridor orientation as a proxy for the target and thus performed worse on average. "Local" participants as defined by body alignment (i.e., error difference between being aligned vs. not with a local reference frame) were not related with good or bad performance (three rs = [–20, 15], ps > .390) or with "global" participants ($r = -.06$, $p = .800$).

Discussion

As predicted by local reference frame theories, participants pointed more accurately when their body or their pointing target was aligned with the local reference frame. They also drew the map mainly in the order they first experienced the environment in (see Table 1 for a summary of results).

When their body was misaligned with a local reference frame, participants had to compensate for that misalignment, yielding higher pointing errors. Contrary to Experiment 1, this compensation could not be facilitated by head turning as this was prevented during pointing. Instead, participants had to mentally compensate for misalignments such as by mentally rotating the environment or their position within (Iachini & Logie, 2003; Kozhevnikov et al., 2006; Shepard & Metzler, 1971). Consistent with predictions from mental rotation, pointing errors increased roughly linearly with increased misalignment with the local reference frame. Note that the observed gender effects are also consistent with an underlying mental rotation, as the largest and most consistent gender effects in spatial cognition are found for mental rotation tasks (e.g., Voyer, Voyer, & Bryden, 1995). If participants used mental rotation for compensation, such gender differences are not surprising.

Just as smaller body misalignment relative to a reference frame can be an advantage, smaller target misalignments relative to a local reference frame were found advantageous as well. Such an advantage is expected when computing the target direction relative to a local reference frame. However, instead of a mere computational advantage the effect might also originate from the strategy of "when in doubt point along the local reference frame". While such a regression towards pointing in the direction of the local reference frame (or corridor) works reasonably well for targets aligned with this local reference frame, it will overall lead to considerable errors. Indeed, participants who showed target alignment effects also showed increased pointing errors.

Local reference frames theories typically assume that the individual reference frames are connected via pairwise directed relations (i.e., one reference frame is the reference for the other—the opposite way is not necessarily the case; e.g., Meilinger, 2008). When assuming that this directedness originates from how an environment was experienced, it should be along the direction of walking. Consistent with this assumption, maps were drawn in the order of walking. Relying only on a global reference frame that abstracts from the order of experience would not have predicted such a result. Only an additional representation preserving the order of walking working together with a global reference frame would explain the results.

Although participants were allowed to turn their head during self-localization in both Experiments 1 and 2, they only did so in Experiment 1, whereas in Experiment 2 they typically looked straight ahead during self-localization. This might be due to the fact that in Experiment 2, the corridor that was visible during training was hidden behind a door during testing. Thus, participants had to rely on the local cues presented on the walls and doors, which were visible in every body orientation.

Head alignment in self-localization in Experiment 2 is the only point where no alignment effects were observed at all as predicted by orientation-free theories. From our point of view, this null effect does not counter the alignment effects observed at all other occasions, which clearly speak against orientation-free theories. For the environment and procedure tested we conclude that no orientation-free representations were used.

Consistent with the weak claim of global reference frame theories, we found a location alignment effect. Participants self-localized more quickly in corridors parallel or orthogonal to the reference direction than in oblique corridors. Neither self-localization time nor location alignment was the central target of the present study. In addition, the apparent global location alignment effect on pointing errors might have been influenced by primacy in the case of the first corridor and a similar advantage for the adjacent corridors, including the last one, as discussed in Experiment 1. Consequently, this effect should not be overrated.

Global reference frame orientation was determined by the initial experience and the geometric orientation of the whole environment. Just as in Experiment 1, this generalization from vista spaces to an environmental space seems valid. During learning, participants' heads were oriented most frequently along the global reference frame orientation, which might have mediated reference frame selection.

In summary, our results support local reference frames and to some extent the weak claim of global reference frames, but rather not orientation-free representations. Participants who did use a global reference frame (i.e., showing a larger global effect than other participants) also performed better. These participants less often showed local target alignment (i.e., presumably a pointing strategy that does not take the exact locations of targets into account). No trade-off between local and global strategies was found for body alignment. In sum, the data suggest that most participants represented the recently learned environments mainly within local reference frames. Some participants in addition used a global reference, maybe in the form of cardinal directions. These participants also performed comparatively better.

GENERAL DISCUSSION

This study examined whether humans use local reference frames, global reference frames, and/or orientation-free representations to encode recently encountered environmental spaces explored via walking in a HMD-based virtual reality. As predicted by local reference frame theories (Cartwright & Collett, 1983; Chown et al., 1995; Christou & Bülthoff, 1999; Gillner et al., 2008; Mallot & Gillner, 2000; McNaughton et al., 1989; Meilinger, 2008; Waller et al., 2009; Wang & Spelke, 2002), participants performed better when their body or a pointing target was aligned with the local reference frame defined by the surrounding corridor. Most participants turned their head to align it with a local reference frame when allowed to do so. When head turning was restricted in Experiment 2, participants pointed better for smaller misalignments, suggesting compensatory mental rotation. These results indicate that participants represented the environment, at least in part, as local reference frames. Such results were not expected if participants exclusively relied on a global reference frame or on orientation-free representations, which were thought to exclusively account for survey tasks such as pointing. This is evidence that local reference frames play a role not only in recognition (Christou & Bülthoff, 1999; Meilinger et al., 2012), spatial updating (Wang & Brockmole, 2003a, 2003b), or route navigation (Mallot & Gillner, 2000), but also in survey tasks. Although further studies are needed to generalize these findings, they already challenge some of the current beliefs about survey knowledge and can help to gain a deeper understanding of the underlying representations.

Global reference frame theories predict that one reference frame represents locations for a whole environmental space (Kuipers, 2000; McNamara et al., 2008; O'Keefe, 1991; Poucet, 1993; Trullier et al., 1997). We found support for the weak claim that orientations parallel or orthogonal relative to the predicted global reference frame yield better performance than oblique orientations. This was found for body orientations during self-localization in Experiment 1 and for location alignment in both experiments. Although these are not the central measures used in prior studies (i.e., not pointing accuracy in body alignment), these results provide some evidence that predictors for reference frame orientation known from vista spaces (i.e., initial experience and overall layout; Kelly & McNamara, 2008; Mou & McNamara, 2002; O'Keefe, 1991; Shelton & McNamara, 2001) can in fact be generalized to environmental spaces, at least for environments similar to the ones tested here. Other experiments found similar global body alignment effects relative to the first corridor experienced (Tlauka, Carter, Mahlberg, & Wilson, 2011; Wilson, Wilson, Griffiths, & Fox, 2007). In these experiments, the environment consisted of few rectangular corridors, and body orientations parallel and sometimes also orthogonal to a global reference frame were compared. Results from these as well as the present experiments suggest that with a standardized learning experience, participants tend to come up with the same global reference frame orientation. In everyday navigation situations, individual experiences and thus the selected reference frames might differ considerably.

With respect to pointing accuracy in body alignment, which was the central measure in prior studies, our results showed only effects for local reference frames. The additional measures used in the current study showed support for local as well as global reference frames. This suggests that local reference frames were used more intensively than global reference frames. However, participants who showed a stronger alignment effect for global reference frames also performed better. Presumably, only this subpopulation employed a global reference frame at all, but these people performed comparatively better. Using global reference frames for pointing within environmental spaces seems a successful strategy not shared by all navigators.

The self-described navigational abilities of participants ranged from mid-low to mid-high. Their background was mainly academic from various disciplines (i.e., not technically focused). The samples thus represented fairly average spatial abilities, but no extreme high- or low-spatial groups. Extrapolating from the present results it is conceivable that very high-spatial individuals might even more strongly employ global reference frames, whereas clearly low-spatial participants might more exclusively rely on local reference frames. Whether this is indeed the case and whether the latter case also applies to children and elderly navigators have to be subject to future research.

The present results extend prior results obtained from imagined self-placement at a city intersection (Werner & Schmidt, 1999). In this study, participants were shown to judge directions towards close-by locations quicker and more accurately when imagining looking down a street than facing a house corner at the intersection. The results from Werner and Schmidt (1999) can be interpreted as body alignment effects with respect to the local reference frame defined by the street. The present work extends these results, first, by standardizing the individual learning experiences. This showed that global reference frames defined by experience and/or main orientation may play a role as well. In addition, we extend the results to tests within a visually present environment rather than an imagined one, and we not only tested effects of body alignment, but also investigated potential effects of head, target, and location alignment.

Body alignment is the most important contributor to the present conclusion, as this factor was varied systematically for local and global reference frames, and it is most comparable to prior research on spatial memory structure where it was used almost exclusively. However, the current study showed significant alignment effects not only for body alignment, but also for head, target, and location alignment. We predicted all effects from one underlying source—namely, memory structure: Misalignment of body, target, or local environment with the encoded reference frame was predicted and was observed to yield an increase in error and/or latency as well as compensatory head alignment (McNamara et al., 2008), and this was exactly the data pattern we observed. Similarly, we examined pointing errors and latencies as sometimes (body) alignment effects were only observed in one of these measures (Iachini & Logie, 2003; Shelton & McNamara, 2004). Furthermore, pointing time might be traded off with time invested in self-localization. If reported at all, aggregated latency measures are usually reported (Tlauka et al., 2011; Wilson et al., 1999, 2007). We separated the two and indeed found that some effects in overall response time might rely more on the time needed for self-localization rather than pointing. Thus, by investigating multiple alignment effects and dependent measures and observing converging evidence, we could corroborate our findings and reduce the chance of Type I errors.

In order to be able to clearly disambiguate between the predictions of local, global, and orientation-free theories within one experimental paradigm, the current study used a highly constructed and rather unusual and sparse multicorridor virtual environment. While this severed the purpose of high experimental control and repeatability and allowed us to test the different hypotheses, it also necessarily limits the generalizability of the current results. In the future, it would be interesting to investigate whether/how the current findings might extend to different layout, size, type, and complexity of environments, as these are all factors that might affect the choice of strategy and reference frames. In addition, future research is needed to assess how specifics of the virtual reality technology and experimental methodology might have affected the results. It is, for example, conceivable that learning time might be reduced and the quality of the resulting spatial representation enhanced if the experiment was performed with a wider field of view HMD or in more naturalistic real-world environments (Alfano & Michel, 1990; Toet et al., 2007).

The current environment was specifically constructed to provide an environmental space, and caution was taken to exclude all global landmarks that could have provided a global orientation cue. Including such a global landmark that can be seen from many or all locations within the space would probably change the observed results significantly, as the environment's characteristics would approach those of a vista space. Consequently, one might expect the employment of a single reference frame for the whole space centred on this global landmark, as was observed before (Iachini et al., 2009; Marchette, Yerramsetti, Burns, & Shelton, 2011; McNamara et al., 2003). Another open question is the potential effect of global directional cues on reference frame selection. These cues encompass shadows, consistent slant throughout the environment, wind blowing from one direction, or faraway landmarks that do not provide reliably information about the distance to the landmark. Such global orientation cues have been shown to enhance navigation performance within virtual environments (Restat, Steck, Mochnatzki, & Mallot, 2004; Steck & Mallot, 2000). They can be used to estimate the relative orientation of local vista spaces, but not their relative position. Global reference frames require both directional and positional information. Providing part of this information might increase employment of global reference frames—however, this has yet to be shown.

Another constraint of the present results comprises the complexity of the environment. While an increase in corridor length as such might not matter so much, additional corridors will probably increase the difficulty of learning the environment and integrating it into one global reference frame. This might draw navigators towards stronger reliance on local reference frames. On the contrary, using fewer corridors and especially using only orthogonal turns will probably ease the task (Montello, 1991; Werner & Schindler, 2004). Here a stronger reliance on global reference frames seems plausible. This was indeed shown for judgements of relative direction within a simple rectangular four-leg environment learned from video presentation on a desktop screen (Shelton & McNamara, 2004; Tlauka et al., 2011) as well as learned from real navigation (Wilson et al., 2007). The complexity difference also reflects the typical difference between American grid-style cities and Asian/European style cities with more oblique street patterns. Again, future experimentation is needed to test these hypotheses.

Local and global reference frame orientations within the present experiments were defined by initial and prevalent experiences (which are egocentric in nature) as well as by the geometry of a local corridor and the overall environment (which are allocentric in nature). Consequently, the experiments are not suited to distinguish between these alternatives, and we cannot make any conclusions about the allocentric or egocentric nature of the reference frames used.

As the environment was learned via navigation and not from a single constant perspective, multiple factors along this experience may have contributed to the selection of the observed local reference frames. These include wall orientation, body orientation during learning, and experienced views. This may, in part, be mediated by anisotropy in the image statistics. For example, due to the experimental paradigm used, participants will see more images looking forward along the corridor than they do looking towards the walls. One way to separate view-related factors from geometry would be to have navigators not walk straight through corridors, but oblique to the corridor walls while always look straight. Follow-up testing would be indicative of whether participants perform better when aligned with their orientation walked or rather when aligned with the walls of a local corridor.

The average absolute pointing errors were 39.8° in Experiment 1 and 54° in Experiment 2 and thus larger than in most studies examining memory for vista spaces, where typical pointing errors range between 20° and 40° (e.g., Kelly & McNamara, 2008; Mou & McNamara, 2002; Shelton & McNamara, 2001). However, for pointing within environmental spaces, the observed errors are usually higher than in vista spaces, especially for the case of body misalignment. When participants where aligned with a local reference frame, the observed errors of 31° (Experiment 1) and 39° (Experiment 2) were even comparable to errors observed when learning a real environmental space (Montello, 1991; Richardson et al., 1999; Rossano, West, Robertson, Wayne, & Chase, 1999). Our participants indeed walked through the environment as we also do when exploring real environments. These biomechanical cues provided by walking have been shown to be important for spatial orientation (Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Ruddle, Volkova, & Bülthoff, 2011).

The present experiments were conducted in order to examine learning from environmental spaces, which by definition have to be navigated through to be fully apprehended. Several studies suggest that spatial knowledge acquired from maps or descriptions is represented within one reference frame common to the whole environment (Richardson et al., 1999; Shelton & McNamara, 2004; Tlauka & Nairn, 2004; Wilson et al., 1999). The orientation of this reference frame typically corresponds to the (initial) point of view of the description or the (initial) upward orientation of a map. Participants seem to construct a mental model of the whole environment usually from the initial perspective described. As a consequence, when learning from vista spaces, descriptions, or maps, *all* information is eventually present at one point in time during learning. This is different for environmental spaces where multiple local views are encountered successively. This difference in the spatiotemporal availability of information might, at least in part, explain why map-based, description-based, and vista space-based spatial information is preferably encoded within one common reference frame in long-term memory, whereas environmental spaces often are encoded using multiple local reference frames. Another interesting line for future research may involve interactions between multiple information sources such as learning from environmental spaces and descriptions or maps, which seems rather common for city environments. Recent results suggest that long-term residents of a city tend to self-localize on navigation-based cues, but nevertheless use map-based knowledge for a pointing task within the environment (Frankenstein, Mohler, Bülthoff, & Meilinger, 2012).

CONCLUSIONS

In conclusion, our participants did not exclusively rely on a global reference frame or an orientation-free representation for the survey task as might have been expected, but instead also used local reference frames. The strong influence of the current local surrounding is consistent with a line of research that considers cognition not as abstract, decontextualized processes, but rather emphasizes situational influences (Barsalou, 2008; Wilson, 2002). Reliance on local reference frames may also express a kind of cognitive idleness (Meilinger, 2008): Local surroundings are readily available in perception. Representing them within local reference frames instead of transferring them into a global reference frame thus saves computational effort during encoding. Local reference frames can be used for self-localization and route navigation when they are interconnected. This way, additional computations only take place when required—for example when integrating multiple local reference frames in order to accurately point to a distant goal. As shown here, these computations can still be strongly influenced by local reference frames. The nature of this integration process is still unknown. Multiple strategies seem possible with the employment of a global reference frame being a particularly successful one. Future research has to examine details of how local and global reference frames interact when navigating environmental spaces.

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