

# Reference frames in learning from maps and navigation

Tobias Meilinger · Julia Frankenstein ·  
Katsumi Watanabe · Heinrich H. Bühlhoff ·  
Christoph Hölscher

Received: 26 September 2014 / Accepted: 10 November 2014 / Published online: 22 November 2014  
© Springer-Verlag Berlin Heidelberg 2014

**Abstract** In everyday life, navigators often consult a map before they navigate to a destination (e.g., a hotel, a room, etc.). However, not much is known about how humans gain spatial knowledge from seeing a map and direct navigation together. In the present experiments, participants learned a simple multiple corridor space either from a map only, only from walking through the virtual environment, first from the map and then from navigation, or first from navigation and then from the map. Afterwards, they conducted a pointing task from multiple body orientations to infer the underlying reference frames. We constructed the learning experiences in a way such that map-only learning and navigation-only learning triggered spatial memory organized along different reference frame orientations. When learning from maps

before and during navigation, participants employed a map-rather than a navigation-based reference frame in the subsequent pointing task. Consequently, maps caused the employment of a map-oriented reference frame found in memory for highly familiar urban environments ruling out explanations from environmental structure or north preference. When learning from navigation first and then from the map, the pattern of results reversed and participants employed a navigation-based reference frame. The priority of learning order suggests that despite considerable difference between map and navigation learning participants did not use the more salient or in general more useful information, but relied on the reference frame established first.

---

T. Meilinger (✉) · H. H. Bühlhoff (✉)  
Max Planck Institute for Biological Cybernetics, Tübingen,  
Spemannstr. 38, 72076 Tübingen, Germany  
e-mail: tobias.meilinger@tuebingen.mpg.de

H. H. Bühlhoff  
e-mail: heinrich.buelthoff@tuebingen.mpg.de

T. Meilinger · K. Watanabe  
Research Center for Advanced Science and Technology, The  
University of Tokyo, 4-6-1 Komaba, Meguro-ku,  
Tokyo 153-8904, Japan

J. Frankenstein · C. Hölscher  
Center for Cognitive Science, University of Freiburg,  
Friedrichstr. 50, 79098 Freiburg, Germany

J. Frankenstein · C. Hölscher  
ETH Zürich, Swiss Federal Institute of Technology, Clausiusstr.  
59, 8092 Zürich, Switzerland

H. H. Bühlhoff  
Department of Brain and Cognitive Engineering, Korea  
University, Anam-dong 5ga, Seongbuk-gu, Seoul 136-713,  
Republic of Korea

## Introduction

When searching for a hotel in an unfamiliar city or a location in a complex unfamiliar building (e.g., hospital, airport), navigators very often consult maps first—may they be displayed at a building's entrance, printed on paper, or displayed on a satnav or handheld. Only after consultation, navigators approach their goal with potentially revisiting their maps during navigating. Consequently, in real life, humans typically acquire environmental spatial information both from maps and navigation together. However, not much is known about this learning situation, as most studies examined spatial learning either from navigation only or from maps only. In the present work, we aim at examining the combined case.

In a seminal study, Thorndyke and Hayes-Roth (1982) compared the existing spatial knowledge of participants working in a building for 1–12 month to the newly acquired spatial knowledge of participants studying a building-map for up to roughly 1 h. Spatial knowledge

tested was differentiated between route knowledge (e.g., used to estimate route lengths) and survey knowledge (e.g., used to estimate straight line directions and distances). Navigation learners performed better in route knowledge tasks than map learners. Contrarily, map learners performed better in some, but not all survey knowledge tasks. Several other studies (Latini-Corazzini et al., 2010; Lloyd, 1989; Moeser, 1988; Richardson, Montello, & Hegarty, 1999; Rossano, West, Robertson, Wayne, & Chase, 1999; Taylor, Naylor, & Chechile, 1999) found similar results: survey knowledge typically is better after map than after navigation learning, and vice versa for route knowledge.

Differences in the acquired knowledge after learning from maps and navigation hint towards different processing. However, they do not tell much about how spatial knowledge is represented in memory. One key aspect for spatial memory is the underlying reference frame, i.e., the coordinate system relative to which spatial information is represented. For example, locations within a room are typically represented relative to a reference frame either defined by the perspective(s) in which participants experienced the room, or by the rooms' intrinsic geometry, i.e., aligned with the walls of the room (McNamara, Sluzenski, & Rump, 2008). If participants cannot access memory directly from a perspective aligned with a memory reference frame, additional processing is needed to compensate for misalignment, increasing latencies and errors. Therefore, testing participants' knowledge from different orientations allows examining the underlying memory reference frame.

Simple navigational spaces, for example, walking round a block, are typically memorized relative to a reference frame defined by the first leg this space was encountered (Shelton & McNamara, 2004; Tlauka, Carter, Mahlberg, & Wilson, 2011; Wilson, Wilson, Griffiths, & Fox, 2007). For more complex spaces, local reference frames defined by individual streets or corridors play a more prominent role than the initial orientation (Meilinger, Riecke, & Bühlhoff, 2014). Spaces with a central building visible from almost all locations may be memorized relative to a reference frame centered on this building, even if body orientations during the exploration of this space differ (Iachini, Ruotolo, & Ruggiero, 2009; Marchette, Yerramsetti, Burns, & Shelton, 2011; McNamara, Rump, & Werner, 2003). As a summary, simple orthogonally organized built spaces are memorized in a single reference frame either oriented along the orientation the space was first encountered, or along salient geometric cues.

Maps are represented within the orientation they were experienced (first), which corresponds to “upwards” in the map (Borella, Meneghetti, Muffato, & De Beni, 2014; Hinzman, O'Dell, & Arndt, 1981; Tlauka & Nairn, 2004).

Similarly, when accessing locations within a country, access is typically quicker and more accurate when participants are physically or mentally oriented northwards than when oriented in other orientations (Sholl, 1987; Werner & Schmidt, 1999). Locations within countries are usually learned from north-up maps rather than from navigation, and are thus consistent with memorizing map knowledge within a map-upwards reference frame.

Some studies compared reference frames after learning the same space from navigation only or from a map only (Richardson et al., 1999; Rossano et al., 1999; Sun, Chan, & Campos, 2004). All studies found advantages for recalling locations in a map orientation as compared to the opposite orientation. For navigation learning, the advantage for first leg orientation as compared to the opposite orientation was typically not found, or only when learners experienced the environment by virtual navigation, keeping a constant body orientation throughout learning in front of a computer screen (Richardson et al., 1999; Rossano et al., 1999; see also Shelton & McNamara, 2004; Tlauka et al., 2011).

To our knowledge, no study so far examined reference frames in learning from navigation and maps together under controlled experimental conditions. Some studies examined reference frames in memory for familiar spaces such as one's city of residency or university campus. In these spaces, navigators probably experienced maps in addition to months or years of navigational experience (Frankenstein, Mohler, Bühlhoff, & Meilinger, 2012; Marchette et al., 2011; Sholl, 1987; Werner & Schmidt, 1999). For example, when participants were visually placed into a virtual model of their city of residency, they pointed to distant city locations most accurately when facing north (Frankenstein et al., 2012). As city maps are typically displayed north-up, this suggests that participants might have used a map-based reference frame. This effect was specific for the pointing task as participants relied on a different knowledge source when conducting a route task (Meilinger, Frankenstein, & Bühlhoff, 2013). Other studies used pointing from imagined body positions and found a north-up advantage even when local maps typically were oriented westwards (Marchette et al., 2011), or they found that north-up was not prioritized over south-up, but both were better than facing eastwards or westwards (Werner & Schmidt, 1999). In Sholl (1987), participants were physically facing north or west and pointed to non-visible locations on the surrounding campus. Here, no differences between westwards or northwards body orientations were observed. However, in Sholl (1987), the campus map used to illustrate the campus was oriented east-up.

In summary, past studies suggest that map-based reference frames might be used in spatial memory for highly

familiar spaces. However, the learning situation was not controlled, especially one does not know which maps within which orientation(s) participants did indeed experience. Furthermore, memory reference frames might have originated not from a map, but from the intrinsic structure of the city or the campus itself, or participants might have shown a general north preference maybe based on a magnetic compass sense (Carrubba, Frilot, Chesson, & Marino, 2007). The first motivation for the current study was to rule out these alternative explanations and show that map experience indeed caused the employment of a map-based reference frame after learning from maps and navigation. Participants learned a simple virtual navigational space either from navigation only by actually walking through it, from map only, or from both sources together. We organized the geometric layout of the space and its initial contact view in a way to establish a consistent reference frame along the main axis of the environment. The map was not oriented along this orientation, but offset by 90°. Consequently, when learning from both sources, participants could choose either orientation. Subsequently collected pointing data thus indicated whether participants organized their spatial memory along a navigation-based or a map-based reference frame. If map contact in everyday navigation situation was indeed responsible for memory organization along a map-based reference frame, participants experiencing a map first and then learning from navigation while being able to view the map again any time during navigation should perform best when tested along the map orientation than along the navigation orientation.

The second motivation for this study was to find out *why* participants would organize their everyday memory along a map-based reference frame. Prior research on spatial learning showed that participants experiencing a room environment from two viewpoints either relied on a reference frame originating from the perspective experienced first, or used the second perspective experienced if this view matched a salient orientation, for example, was aligned with the walls of the room and/or the intrinsic object layout (Kelly & McNamara, 2010; Shelton & McNamara, 2001). By the terminology of Piaget (Piaget & Inhelder, 1969), this could either be described as an assimilation of later information into an existing reference frame, or an accommodation of information learned towards the salient orientation of a later reference frame. However, participants typically use the reference frame established first, and only adjust it if latter experiences are very salient. Applying this approach to learning from navigation and maps, participants might only rely on map-based reference frames, because they typically experience the map first. Alternatively, navigators employ a map-based reference frame because maps are more salient and/or useful than navigation-acquired knowledge. As

explained above, maps are more useful for survey tasks like the pointing task used here (Lloyd, 1989; Moeser, 1988; Richardson et al., 1999; Rossano et al., 1999; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). Furthermore, maps are usually experienced within one single orientation, whereas navigators experience multiple different orientations of an environment making individual orientations less prominent.

To test whether map-based reference frames are used because they are typically experienced first or because they are more salient or useful than navigation, we ran another condition asking participants to first learn from navigation only before consulting the map. If the map is more salient or useful, participants are expected to rely on a map-based reference frame and perform best in map orientation irrespective of the order of learning. However, if participants rely on the first established reference frame and assimilate later information within this reference frame, their performance should be better when they are aligned with the navigation-based reference frame, i.e., the first view experienced or the intrinsic organization of the environment.

## Methods

The data examined here were collected within two independent experiments, however, both are reported together here as the methods are very similar, and hypotheses tested are strongly related.

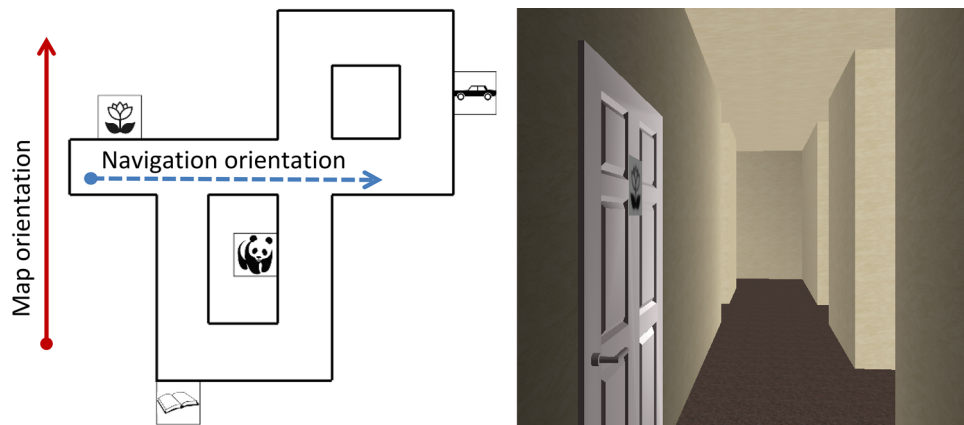
In the Experiment 1, participants learned the environment either from map only, from navigation only, or from the map first and from navigation afterwards. In the Experiment 2, participants learned the environment from navigation first and then from a map.

### Participants

For Experiment 1 (i.e., the first three conditions), thirty-six participants (16 female; age  $M = 28.2$ ,  $SD = 8.1$ ) were recruited via a subject database, gave informed consent and were paid for their participation. Participants were randomly assigned to the three learning conditions, resulting in 12 participants per learning condition. For Experiment 2 (i.e., the last condition), another fifteen participants (eight female; age  $M = 26.3$ ,  $SD = 6.7$ ) were recruited likewise. This research was approved by the ethical committee of the university hospital of Tübingen.

### Materials

Figure 1 shows the virtual environment participants experienced and which consisted of several corridors including



**Fig. 1** *Left panel* the map participants learned from the map-learning conditions with arrows for map and navigation orientation added which were not shown to the participants. *Icons* reflect the position of doors. *Right panel* the initial view that participants first saw the

environment for the navigation learning conditions. This view was from the dead end at the left side of the map. The initial orientation in the navigation was eastward and, therefore, offset by  $90^\circ$  from the north-up orientation of the map

four doors. Each door was marked with a different pictogram and faced a different global direction. No other door was visible when standing in front of a door, but participants had visual access to all doors when walking along the main corridor, which was about 11 meters long. When learning from navigation, participants started to encounter the environment facing the view displayed on the right panel of Fig. 1 (the dotted arrow indicating participants initial viewing and starting direction). This *navigation orientation* was aligned with the main geometric axis of the environment. Both factors—main layout orientation and initial view—were known to influence reference frame selection for an environment (McNamara et al., 2008). The map was always displayed in the orientation depicted in Fig. 1 (*map orientation*). Please note that participants did not see the arrows or their labels when learning from the map. The map orientation and the navigation orientation were offset by  $90^\circ$ .

Participants saw the map and the environment through a head-mounted display (HMD). For navigation learning, participants' head coordinates were tracked by 16 high-speed motion capture cameras with 120 Hz (Vicon<sup>®</sup> MX 13) to render an egocentric view of the virtual environment in the HMD in real-time. We used a NVIDIA Quadro FX 4600 graphics card with 768 MB RAM and a nVisor SX60 HMD with a field of view of  $44^\circ$  (horizontal)  $\times$   $35^\circ$  (vertical), a resolution of  $1,280 \times 1,024$  pixels for each eye with 100 % overlap. The inter-pupillary distance was fixed at 6 cm. We adjusted the HMD fit and screen position for each participant. The overall setup provided important depth cues such as stereo vision, texture gradients, and motion parallax. The experiment was programmed in Virtools<sup>®</sup> 5.0 (Dassault Systemes).

## Procedure

Participants learned the environment from a map, from physically walking through the environment, or from both sources until passing learning criteria ensuring comparable spatial knowledge for all participants. In the following test phase, participants conducted a pointing task in different body orientations. From the performance pattern in the pointing task, we inferred the reference frame underlying participants' spatial representation of the environment.

## Map learning

Participants put on the HMD displaying a black screen. The map was displayed for at least 1.5 min, but participants were free to look at the map longer. Afterwards, participants removed the HMD and conducted a map knowledge test. For this, they saw the map in Fig. 1 with the pictograms removed, i.e., only the corridors, on a computer screen. The pictograms were placed below the map. Participants were asked to replicate the map by dragging the pictograms in their correct positions using a mouse. Only if participants placed all pictograms correctly, they proceeded to the pointing task. Otherwise map learning with the HMD continued until participants passed the map-learning test.

## Navigation learning

Participants put on the HMD displaying a black screen. After leading participants round a circle once to diminish interference from the physical laboratory room, participants were led to the start position. Next, they faced the

environment's initial orientation as indicated in Fig. 1, and freely explored the environment by physical walking as long as they wanted before proceeding to the navigation learning test. Remaining within the virtual environment, participants were asked to approach a target location along the shortest path possible. For example, when standing at the panda, the shortest path to the flower was to directly go to the main corridor and then to the flower and not to pass by the book. Participants were tested for all 12 possible starting–target pairs of pictograms in a fixed order. In case they made an error, this pair was repeated after a self-determined additional navigation time in the environment.

#### *Navigation after map learning*

The procedure was the same as navigation learning except for the following. At the start location (before seeing the virtual environment), participants watched the map for at least 1.5 min just as in the map-learning condition. During navigation, they could consult the map as often as they wanted by pressing a button on a joystick that they held in their hand. By pressing the button again, the map vanished and they faced the environment again. Participants conducted the map-learning test after passing the navigation learning criterion.

#### *Map after navigation learning*

Participants learned the environment just as in the navigation condition. They walked through the environment until passing the learning criteria. Only then they were presented with the map displayed within the HMD just as in the map-learning condition, i.e., they were required to look at the map for at least 1.5 min. After indicating themselves that they looked at the map sufficiently long participants directly continued with the map-learning test.

#### *Pointing task*

After finishing learning in the different conditions described above, participants proceeded to the pointing task. For that, participants stood at a table with a mounted joystick, facing the virtual environment through the HMD. First, participants were teleported to a starting location in front of one of the doors. The facing direction was one of the four global orientations (i.e., differed by 90°); participants either faced the door, the empty wall or one of the two corridors. Participants were allowed to look around, but could not walk around as they held the joystick and thus also kept a constant body orientation. In each trial, they first confirmed successful self-localization (i.e., recognition of their location and orientation) by pressing a joystick button. For the pointing task, the pictogram of a target was

displayed in the middle of the HMD-screen. Participants were instructed to point as quickly and accurately as possible to the target displayed by deflecting the joystick and confirming their choice with the trigger button. During pointing, they were required to look straight ahead. Therefore, they were not able to look into the direction of the target and point into that direction with the joystick at the same time. They had to align their viewing direction and body orientation and point into a (mainly) different target direction using the joystick. In case of misalignment of body and head orientation, the pointing response was not accepted. Immediately after pointing to the first target, the pictogram was replaced by the pictogram of the second target and the pointing procedure was repeated, before commencing to the third target. The order of target locations was determined randomly for each sequence. After pointing to the third target finishing a block, the HMD display turned black. Participants could take a break and started the next block by pressing the button on the joystick. The pointing task consisted of 16 blocks in 4 orientations at each of the 4 locations resulting in 48 pointing trials. The order of these 16 blocks was determined randomly for each participant. Participants did not receive feedback about their pointing performance.

We recorded pointing latency (i.e., the time between the onset of the pictogram presentation and the button press) as well as pointing error (i.e., the absolute deviation of the indicated direction from correct direction). During learning, we also recorded duration of navigation, duration of map viewing and the number of times participants looked at the map when learning from map and navigation. Due to an error in the program, we only recorded the duration of map viewing of the first three participants who learned from maps only. For participants in the combined conditions, both, navigation and map viewing times were recorded correctly. Also pointing performance was collected correctly from all participants.

#### *Analyses*

To control for outliers, we excluded values deviating more than 3 SD from the overall mean (<4 %). Data were submitted to a mixed model analysis with the factors of learning condition (4 levels) and testing orientation (4 levels). In case of a significant interaction, we conducted planned pairwise comparisons between map orientation and initial orientation within each learning condition. We did not compare performance in map and navigation orientation with the remaining two test orientations, as these comparisons were not meaningful for employment of map-versus navigation-based reference frames. However, the other orientations were tested to cover all possible cardinal directions and not bias participants towards certain

orientations during the pointing task. Compared to an ANOVA, a mixed model analysis is less restrictive with regard to distribution assumptions (Snijders & Bosker, 1999). Commonly accepted effect sizes for linear mixed models are not yet available. Thus, we report partial eta square ( $\eta_p^2$ ) derived from data aggregated per participant and the respective condition. We expected an interaction between body orientation and learning condition. Specifically, we expected navigation learners to perform better along the navigation orientation, while map learners were expected to perform better along the map orientation.

## Results

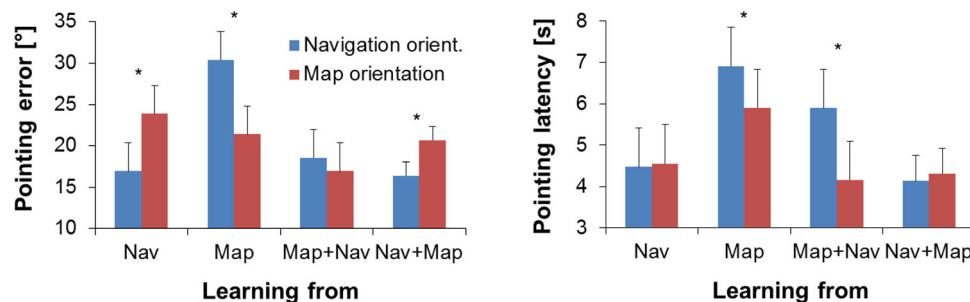
### Pointing performance

We observed a main effect of body orientation for pointing latencies,  $F(3, 2,341.7) = 5.00$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.06$ , but not pointing errors,  $F(3, 2,302.4) = 1.65$ ;  $p = 0.175$ ,  $\eta_p^2 = 0.03$ . The interaction between body orientation and learning condition was significant for pointing errors,  $F(9, 2302.4) = 5.94$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.21$ , and latency,  $F(6, 2,341.7) = 3.70$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.11$ . Consequently, participants in the different learning conditions differed with respect to in which body orientation they pointed more accurately or quickly. Figure 2 shows these differences for the critical map and navigation orientations. As expected, navigation learners pointed more accurately when oriented along the navigation orientation compared to the map orientation,  $F(1, 264) = 7.97$ ;  $p = 0.005$ ,  $\eta_p^2 = 0.25$ . Also as expected, map learners behaved the other way round: they pointed more accurately,  $F(1, 261.1) = 12.88$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.40$ , and quickly,  $F(1, 263.0) = 7.06$ ;  $p = 0.008$ ,  $\eta_p^2 = 0.23$ , when oriented along the map orientation. These patterns replicated results from earlier studies and showed that the representation after learning from one source was indeed oriented along the predicted orientation.

Participants learning from map first and then from navigation relied on the map-based reference frame: they pointed more quickly in the map orientation than in the initial orientation,  $F(1, 273.0) = 19.3$ ;  $p < 0.001$ ,  $\eta_p^2 = 0.49$ , suggesting that map contact and no other factors caused the employment of a map-based reference frame. Finally, we compared this result to the condition of learning from navigation first and from the map afterwards. Here, the pattern reversed; participants pointed more accurately when oriented along the navigation orientation than when oriented along the map orientation,  $F(1, 334.3) = 7.98$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.42$ . This pattern suggests that participants relied on a navigation-based reference frame. When learning from both sources, participants did not generally rely on the potentially more useful or salient map-based reference frame, but the first experienced source determined the reference frame employed.

### Map-learning times

All participants who learned from maps passed the map-learning criteria before continuing to the pointing test. Comparing learning times between conditions, we found an overall difference,  $F(1, 27) = 27.3$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.69$ . Participants learning from navigation and then map ( $M = 1.6$  min,  $SD = 0.43$  min) or from map and then navigation ( $M = 2.3$  min,  $SD = 0.60$  min) looked at maps for shorter times than participants learning from map only ( $M = 4.0$  min,  $SD = 0.58$  min),  $F$ 's  $> 19.7$ ,  $p$ 's  $< 0.002$ ,  $\eta_p^2 > 0.60$ . When looking at the map only after navigating, the map-learning time was shorter than when looking at the map before and during navigation,  $F(1, 25) = 11.0$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.30$ . When looking at the map after navigation only participants barely extended the minimum time of 1.5 min. However, map first learners could also look at the map during navigation which resulted in 11 times ( $SD = 8.2$ ) looking at the map in average. These additional looking times during navigation might have



**Fig. 2** Absolute pointing error and pointing latency as a function of learning condition and body orientation during pointing (navigation orientation vs. map orientation). The first three learning conditions

were from Experiment 1 and the last learning condition was from Experiment 2. Means and standard errors as estimated from the marginal means are shown

caused the longer overall map looking times in map first learners as compared to navigation first learners.

### Navigation learning times

All participants who learned the environment from navigation passed the navigation learning criterion before continuing to the pointing test. Overall navigation times differed between learning conditions,  $F(1, 34) = 3.46$ ,  $p = 0.043$ ,  $\eta_p^2 = 0.17$ ). Participants who learned from navigation only ( $M = 5.7$  min,  $SD = 1.9$  min) spent shorter times in the environment than participants who learned from the maps before ( $M = 7.5$  min,  $SD = 1.9$  min) or after navigation ( $M = 6.9$  min,  $SD = 1.1$  min),  $F$ 's  $> 4.2$ ,  $p$ 's  $< 0.047$ ,  $\eta_p^2 > 0.15$ . However, this is not surprising as time for (additional) instructions how to handle the electronic map was recorded as navigation time.

### Discussion

Much is known about the organization of spatial memory acquired from maps or from navigation only (Hinzman et al., 1981; Iachini et al., 2009; Marchette et al., 2011; McNamara et al., 2003; Meilinger et al., 2014; Richardson et al., 1999; Rossano et al., 1999; Shelton & McNamara, 2004; Sholl, 1987; Sun et al., 2004; Tlauka et al., 2011; Tlauka & Nairn, 2004; Werner & Schmidt, 1999; Wilson et al., 2007). We replicated prior results showing memory organization along the initial view/main environmental axis after navigation learning, and along the map orientation after map learning. However, in everyday life, navigators often first consult a map to guide subsequent navigation to a destination. The present experiments are the first to directly examine spatial memory organization after learning from navigation and maps together.

When learning from maps before and during navigation, participants employed a map-based reference frame which was different from the reference frame used by navigation-only learners. Consequently, map experience caused the employment of a map-based reference frame. Our results suggest that advantages for testing along the potentially map-based north orientation as compared to other testing orientations found in studies examining memory of familiar campuses or urban environments (Frankenstein et al., 2012; Marchette et al., 2011; Sholl, 1987; Werner & Schmidt, 1999) root in prior map experience. Contrary to these studies, we controlled for the environment and the learning and, therefore, we could rule out alternative explanations for the observed North preferences originating from the intrinsic organization of the environments, naming (e.g., north-quarter), global landmarks, or maybe even a

magnetic compass sense (Carrubba et al., 2007). Our results suggest that map experience before and during navigation is enough to cause the organization of spatial memory along that reference frame rather than along a navigation-based one.

With the present study, we also wanted to answer the question of why map-based reference frames are used at all. We question whether maps are more salient or useful for survey tasks than navigation-based knowledge as shown in several studies (Lloyd, 1989; Moeser, 1988; Richardson et al., 1999; Rossano et al., 1999; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982) or whether maps are experienced first and the map-based reference frames are used to assimilate later navigation experiences within this reference frame (Kelly & McNamara, 2010; Shelton & McNamara, 2001)? Our results clearly point to the later explanation: Participants relied on the reference frame experienced first. When learning from the map first, participants used a map-based reference frame; when learning from navigation first, they used a navigation-based reference frame. Consequently, also learning from different sources like maps and navigation seems to follow the more general rule in spatial learning that established reference frames form the basis to integrate later experienced information (unless highly salient later information overrides earlier experiences). This result is in so far surprising, as map learning substantially differs from navigational learning with respect to learning time, the experienced perspectives (survey vs. route), the number of views to integrate (one vs. multiple), the involved sensory modalities (vision vs. vision and bodily cues), the richness of experience (abstract vs. rich), and the constancy of the experienced reference frame (constant during map learning continuously changing during navigation). It can easily be imagined that one of these factors would have prioritized one kind of learning and thus the employment of this reference frame, but this was not the case.

There are two plausible mechanisms of how the reference frames established are used and information is integrated. Participants could form two separate representations and only use the first one to solve the pointing task. Alternatively, they could use the already learned information to structure later experiences. An argument for employing separate representations comes from perspective switching costs. Map and navigation learning differ in perspective (i.e., vertical vs. horizontal). Learning from one perspective first and then transforming this information into another perspective results in perspective switching costs (Shelton & McNamara, 2004). Participants might have avoided these costs by keeping separate representations and relying on the first one for pointing. However, in accordance with Kelly and McNamara (2010), we think that the explanation based on

assimilating later experiences to established ones fits our data better at least for learning from map first. Participants used the opportunity to additionally consult the map during navigation for ten times in average. If they formed two independent memory traces, one would not expect them to consult the map at all. Retracing the map might have also been a way to facilitate switching from vertical map perspective to horizontal navigation perspective. Adopting a map-based reference frame for later navigation learning seems plausible, however, we do not know whether participants assimilated later map experience within an already established navigation-based reference frame. In this condition, participants learning the map could not look back to the corridor environment to facilitate perspective switching from horizontal navigation perspective to vertical map perspective. They also might have formed independent representations and relied on horizontal navigation-based knowledge for pointing which was conducted in the same horizontal perspective. Future experimentation is required to clarify this question.

Can differences in learning time be responsible for the observed results? We do not think this is a likely explanation. Navigation times were comparable between learning the map before or after navigation. The time difference in map view between map-only learning and learning from maps first was about 60 % and as such twice as large as the differences of 30 % between learning from maps before versus after navigation. But only the smaller time difference was associated with a change in reference frame, not the larger time difference. In addition, all participants passed a learning criterion for their map knowledge ensuring that comparable knowledge was acquired. It seems unlikely that different map viewing times led to differential use of reference frame structure while keeping the acquired knowledge comparable.

The primacy of the order of learning over usefulness or saliency was observed within a simple rectangular environment. Will our results also transfer to more complex environments? While this is an open empirical question it could very well be that maps might be more dominant in complex environments. The present environment was structured along a main corridor from which all relevant information could be perceived. Navigation learning yielded a single reference frame representation as within similar environments (Iachini et al., 2009; Marchette et al., 2011; Shelton & McNamara, 2004; Tlauka et al., 2011; Wilson et al., 2007). More complex environments such as cities or larger buildings rely more strongly on multiple local reference frames (Meilinger et al., 2014; Werner & Schmidt, 1999). In such spaces, the integration of multiple local views to solve a pointing task is much more demanding. Here, the utility of presenting integrated

information within a map may be larger. In complex environments, map-based and navigation-based knowledge might also more show the character of independent representations as indicated in memory of a highly familiar city (Meilinger et al., 2013).

The present experiments are the first to directly investigate memory organization after learning from navigation and maps together which is a typical case in everyday navigation. For the environment examined participants employed the first reference frame experienced and did not generally rely on the more salient or useful learning format.

**Acknowledgments** This work was supported by the DFG grants ME 3476/2-2 and in the SFB/TR8 Spatial Cognition project I6-NavTalk, by the Japanese Society for the Promotion of Science, Japan KAKENHI grant (23240034), the Humboldt Foundation, and by the Brain Korea 21 PLUS Program through the National Research Foundation of Korea funded by the Ministry of Education. We would like to thank Chantal Horeis and Nikola Bubalo for their help in data collection and analysis.

## References

- Borella, E., Meneghetti, C., Muffato, V., & De Beni, R. (2014). Map learning and the alignment effect in young and older adults: how do they gain from having a map available while performing pointing tasks? *Psychological Research*, 1–16.
- Carrubba, S., Frilot, C., I. I., Chesson, A. L., Jr, & Marino, A. A. (2007). Evidence of a nonlinear human magnetic sense. *Neuroscience*, 144(1), 356–367.
- Frankenstein, J., Mohler, B. J., Bühlhoff, H. H., & Meilinger, T. (2012). Is the map in our head oriented north? *Psychological Science*, 23(2), 120–125. doi:10.1177/0956797611429467.
- Hinzman, D. L., O'Dell, C. S., & Arndt, D. R. (1981). Orientation in cognitive maps. *Cognitive Psychology*, 13, 149–206.
- Iachini, T., Ruotolo, F., & Ruggiero, G. (2009). The effects of familiarity and gender on spatial representation. *Journal of Environmental Psychology*, 29(2), 227–234. doi:10.1016/j.jenvp.2008.07.001.
- Kelly, J. W., & McNamara, T. P. (2010). Reference frames during the acquisition and development of spatial memories. *Cognition*, 116(3), 409–420. doi:10.1016/j.cognition.2010.06.002.
- Latini-Corazzini, L., Nesa, M. P., Ceccaldi, M., Guedj, E., Thinus-Blanc, C., Cauda, F., & Peruch, P. (2010). Route and survey processing of topographical memory during navigation. *Psychological Research*, 74(6), 545–559. doi:10.1007/s00426-010-0276-5.
- Lloyd, R. (1989). Cognitive maps—encoding and decoding information. *Annals of the Association of American Geographers*, 79(1), 101–124.
- Marchette, S. A., Yerramsetti, A., Burns, T. J., & Shelton, A. L. (2011). Spatial memory in the real world: long-term representations of everyday environments. *Memory & Cognition*, 39(8), 1401–1408. doi:10.3758/s13421-011-0108-x.
- McNamara, T. P., Rump, B., & Werner, S. (2003). Egocentric and geocentric frames of reference in memory of large-scale space. *Psychonomic Bulletin & Review*, 10, 589–595.
- McNamara, T. P., Sluzenski, J., & Rump, B. (2008). Human spatial memory and navigation. In H. L. Roediger (Ed.), *Cognitive psychology of memory. Learning and memory: A comprehensive reference* (vol. 2, pp. 157–178). Oxford: Elsevier.



- Meilinger, T., Frankenstein, J., & Bühlhoff, H. H. (2013). Learning to navigate: experience versus maps. *Cognition*, *129*(1), 24–30. doi:[10.1016/j.cognition.2013.05.013](https://doi.org/10.1016/j.cognition.2013.05.013).
- Meilinger, T., Riecke, B. E., & Bühlhoff, H. H. (2014). Local and global reference frames for environmental spaces. *Quarterly Journal of Experimental Psychology*, *67*, 542–569. doi:[10.1080/17470218.2013.821145](https://doi.org/10.1080/17470218.2013.821145).
- Moeser, S. D. (1988). Cognitive mapping in a complex building. *Environment and Behavior*, *20*(1), 21–49.
- Piaget, J., & Inhelder, B. (1969). *The psychology of the child*. New York: Basic Books.
- Richardson, A. E., Montello, D. R., & Hegarty, M. (1999). Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*, *27*(4), 741–750.
- Rossano, M. J., West, S. O., Robertson, T. J., Wayne, M. C., & Chase, R. B. (1999). The acquisition of route and survey knowledge from computer models. *Journal of Environmental Psychology*, *19*(2), 101–115.
- Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology*, *43*(4), 274–310. doi:[10.1006/cogp.2001.0758](https://doi.org/10.1006/cogp.2001.0758).
- Shelton, A. L., & McNamara, T. P. (2004). Orientation and perspective dependence in route and survey learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(1), 158–170. doi:[10.1037/0278-7393.30.1.158](https://doi.org/10.1037/0278-7393.30.1.158).
- Sholl, M. J. (1987). Cognitive maps as orienting schemata. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 615–628.
- Snijders, T., & Bosker, R. (1999). *Multilevel analysis*. Thousand Oaks: Sage.
- Sun, H.-J., Chan, G. S. W., & Campos, J. L. (2004). Active navigation and orientation-free spatial representations. *Memory & Cognition*, *32*(1), 51–71.
- Taylor, H. A., Naylor, S. J., & Chechile, N. A. (1999). Goal-specific influences on the representation of spatial perspective. *Memory & Cognition*, *27*(2), 309–319.
- Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, *14*, 560–589.
- Tlauka, M., Carter, P., Mahlberg, T., & Wilson, P. N. (2011). The first-perspective alignment effect: the role of environmental complexity and familiarity with surroundings. *The Quarterly Journal of Experimental Psychology*, *64*, 2236–2250. doi:[10.1080/17470218.2011.586710](https://doi.org/10.1080/17470218.2011.586710).
- Tlauka, M., & Nairn, M. J. (2004). Encoding of multiple map orientations. *Spatial Cognition & Computation*, *4*(4), 359–372. doi:[10.1207/s15427633scc0404\\_4](https://doi.org/10.1207/s15427633scc0404_4).
- Werner, S., & Schmidt, K. (1999). Environmental reference systems for large-scale spaces. *Spatial Cognition and Computation*, *1*, 447–473.
- Wilson, P. N., Wilson, Da, Griffiths, L., & Fox, S. (2007). First-perspective spatial alignment effects from real-world exploration. *Memory & Cognition*, *35*(6), 1432–1444.