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ORIGINAL ARTICLE

Spatial updating in virtual reality: the sufficiency of visual information

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Abstract Robust and effortless spatial orientation critically relies on ''automatic and obligatory spatial updating'', a largely automatized and reflex-like process that transforms our mental egocentric representation of the immediate surroundings during ego-motions. A rapid pointing paradigm was used to assess automatic/obligatory spatial updating after visually displayed upright rotations with or without concomitant physical rotations using a motion platform. Visual stimuli displaying a natural, subject-known scene proved sufficient for enabling automatic and obligatory spatial updating, irrespective of concurrent physical motions. This challenges the prevailing notion that visual cues alone are insufficient for enabling such spatial updating of rotations, and that vestibular/proprioceptive cues are both required and sufficient. Displaying optic flow devoid of landmarks during the motion and pointing phase was insufficient for enabling automatic spatial updating, but could not be entirely ignored either. Interestingly, additional physical motion cues hardly improved performance, and were insufficient for affording automatic spatial updating. The results are discussed in the context of the mental transformation hypothesis and the sensorimotor interference hypothesis, which associates difficulties in imagined perspective switches to interference between the sensorimotor and cognitive (to-be-imagined) perspective.

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Introduction

Humans and most animals share the ability to locomote through their immediate environment and interact with it quickly and effectively, seemingly without much cognitive effort or attention. This remarkable ability requires quick access to the spatial relationships between one's own body and relevant surrounding objects or object configurations. This suggests that the self-to-surroundings relationships might either be directly represented and/or stored in a body-centered (egocentric) reference frame for quick access or can at least be easily and quickly transformed into one. As keeping track of individual objects is inefficient for larger numbers of objects, it seems reasonable to assume an additional environmental reference frame stored in long-term memory that contains a hierarchical representation of object-to-object spatial relations independent of the current observer position (e.g., Hirtle & Jonides, 1985; McNamara, 1986; Stevens & Coupe, 1978; Wang & Brockmole, 2003).

Whenever we move through our surroundings, nontrivial perspective changes need to be continuously incorporated into our egocentric representation. *Explicit* mental perspective changes, like trying to imagine a viewpoint different from the actual one (''imaginal updating''), are typically found to be rather difficult and seem to require explicit attention and a cognitive effort, at least for shorter time intervals and/or distances traveled (e.g., Boer, 1991; Diwadkar & McNamara, 1997; Easton & Sholl, 1995; Hintzman, O'Dell, & Arndt, 1981; Rieser, 1989; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Shepard & Metzler, 1971; Wraga, Creem, & Proffitt, 2000). This is nicely illustrated by the increase in response time and error for increasing angular disparity between the current and the to-be-imagined perspective. When physically moving about, however, keeping track of where we are with respect to our immediate surroundings does not seem particularly challenging or effortful. This is even the case when useful visual cues are temporarily lacking, e.g., when walking in darkness. Rather, a number of studies demonstrated that our brain is capable of automatically updating our egocentric mental representation of our immediate surroundings when vestibular, kinesthetic, and/or motor-efferent signals indicate self-motion (e.g., Farrell & Thomson, 1998; Loomis, Da Silva, Philbeck, & Fukusima, 1996; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; May & Klatzky, 2000; Rieser, 1989; Sholl & Nolin, 1997; Wraga, Creem-Regehr, & Proffitt, 2004). When blindfolded participants are asked to point to previously-learned target locations after moving to a new location, response times can even be independent of the distance traveled or angle turned (e.g., Farrell & Robertson, 1998, 2000; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2004) (see, however, Wraga, 2003). This suggests that spatial updating can, under certain conditions, already occur automatically *during* the self-motion, not afterward. This remarkable capacity of our brain is referred to as ''**automatic spatial updating**'' 'or just ''spatial updating'', as it is thought to occur automatically during the motion, without the need for deliberate intention, explicit attention, or noticeable cognitive effort.

Minor changes in the experimental methodology can, however, lead to a slight increase in response time for increasing turning angles, especially when more cognitive processing is involved (e.g., Mou, McNamara, Valiquette, & Rump, 2004; Wraga, 2003). When verbal responses are employed instead of bodily responses like pointing, imagined spatial updating performance is typically improved and can even exceed spatial updating based on corresponding physical motions (see de Vega & Rodrigo, 2001; Wraga, 2003, for reviews on this issue). This suggests that the automaticity of spatial updating might be restricted to situations where observers are anchored to the coordinate system of their physical body. Such a first-order embodiment is tightly related to one's sensorimotor framework and is thus well suited for natural bodily responses. In more cognitive situations, observers are not necessarily anchored to the coordinate system of their physical body (second-order embodiments), and spatial updating can thus be more flexible and less tightly coupled to sensorimotor updating, thus allowing for easier changes in perspective (e.g., Avraamides & Ioannidou, 2005; Wraga, 2003).

In the remainder of this manuscript, we will restrict ourselves to pointing tasks and thus first-order embodiments. In this context, spatial updating is not only largely automated but often also reflex-like and hard-to-suppress to the extent that it is much harder *not* to update one's egocentric spatial representation according to a physical motion (i.e., ignoring the motion by keeping the initial mental representation and responding as if still being at the initial position and orientation) than to update it as usual (Farrell & Robertson, 1998, 2000; Farrell & Thomson, 1998; May & Klatzky, 2000; Riecke, von der Heyde, & Bülthoff, 2004). In an UPDATE task, participants in the studies by Farrell and Robertson (1998, 2000) had no difficulty pointing to previously seen targets after a blindfolded rotation to a new orientation, and response times were hardly affected by the turning angle. Furthermore, response times were comparable to a CONTROL task where participants moved back and forth to the initial orientation, which argues for automatic spatial updating. When participants were asked to ignore the next rotation and imagine that they still faced the initial orientation (IGNORE task), both pointing errors and response times were largely increased as compared to the UPDATE task, and response latencies increased with the to-be-ignored turning angle. This suggests that the physical motion somehow mandatorily triggered automatic spatial updating of the self-to-surroundings relationships such that participants experienced a conflict or interference between the automatically updated egocentric representation and the to-be-imagined (previous) representation. Farrell and Robertson (1998) suggested that participants subsequently had to ''undo'' the spatial updating to perform the IGNORE task.

Thus, it seems as if under certain circumstances the perceptually signaled motions mandatorily update one's egocentric representation. To refer explicitly to the reflex-like nature of spatial updating and the apparent lack of volitional control over our egocentric mental representation, we introduced the term ''**obligatory spatial updating**'' (Riecke, von der Heyde, & Bülthoff, 2001; Riecke et al., 2004). The obligatory spatial updating implies automatic spatial updating, but is more specific and can thus be hypothesized to be a subset of automatic spatial updating (Riecke et al., 2004). Note that our usage of the terms ''obligatory'' and ''automatic'' differ from the usage of the terms by Waller, Montello, Richardson, and Hegarty (2002).

Vestibular, proprioceptive, and tactile cues generated by physical motions (termed ''physical motion cues'' in this article) are generally considered to be essential and sufficient for obligatory and/or automatic spatial updating (e.g., Farrell & Robertson, 1998, May & Klatzky, 2000; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2004). Note, however, that participants in a study by Waller et al. (2002) failed to automatically and obligatorily update the layout of a previously seen path in an IGNORE task where they were asked to imagine the path rotating with them as they turned while wearing a HMD as a blindfold.

Mental transformation versus interference hypothesis

The difficulty of imagining perspective changes seems to arise from the required mental transformation (*mental transformation hypothesis*, e.g., Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989) as well as from processing costs resulting from an interference between the sensorimotor and the to-be-imagined perspective (*sensorimotor interference hypothesis* for imagined perspective switches in remembered environments, Brockmole & Wang, 2003; May, 1996, 2000, 2001, 2004; Wang, 2005). Recent support for the interference hypothesis stems from two carefully designed studies by May (2004) and Wang (2005), which demonstrated that pointing performance (response times and pointing accuracy) decreased with increasing angular disparity between the actual and to-be-imagined perspective/egocentric object direction (''angular disparity effect''), even when participants were given extra time to imagine (i.e., pre-process) the new perspective. That is, angular disparity effects can occur even when participants are allowed sufficient time to perform the necessary mental spatial transformations. These findings differ from classic mental rotation studies where angular disparity effects disappeared if participants were given sufficient time to imagine the new orientation of the object (Cooper & Shepard, 1973). This suggests a fundamental difference between the processes underlying imagined self-motions and imagined object-motions—only the latter can be easily explained by the mental transformation hypothesis (see discussion in Wang, 2005).

We propose that the interference hypothesis can also account for the difficulty observed in the IGNORE tasks and the ease (automatic spatial updating) observed in many UPDATE tasks. In the IGNORE tasks, participants have to cope with an interference between the to-be-imagined (previous) perspective and the current (new) perspective resulting from obligatory spatial updating. This explanation is supported by the observed ease of spatial updating when there is no interference (UPDATE conditions) and the relative ease of adopting a new perspective when participants are completely disoriented (e.g., May, 1996). In this framework, we propose that *automatic* spatial updating refers to the relative ease of transforming one's -egocentric mental representation if there is no interference. Examples include cases where the to-be-imagined perspective coincides with the current, perceptually signaled one, or if participants are completely disoriented such that there is no (or only a weak) embodied egocentric representation of their surroundings left to produce interference. Furthermore, we propose that *obligatory* spatial updating specifies the mandatory, reflex-like and automatic updating of the sensorimotor representation (first-order embodiment), even when in conflict with the to-be-imagined, more cognitive representation (second-order embodiment). Note that if spatial updating would not be obligatory, participants in IGNORE tasks could easily suppress spatial updating and keep their previous perspective as instructed and thus would not experience any interference.

Relation between visual motion cues, self-motion sensation, and spatial updating

There is a large body of literature demonstrating that optic flow can induce a compelling illusion of self-motion (vection) (see Dichgans & Brandt, 1978; Hettinger, 2002; Riecke, Schulte-Pelkum, & Caniard, 2006; Warren & Wertheim, 1990, for reviews). Given that the perception of self-motion (real or illusory) seems to be closely related to, or even a prerequisite for, spatial updating as proposed by Riecke and von der Heyde (2002), it might be possible that optic flow is also sufficient for spatial updating. The high vection onset latency of typically 4–30 s and the possible drop-outs, however, jointly suggest that optic flow alone might not be sufficient to immediately and reliably induce *obligatory* spatial updating. Interestingly, even at this early stage of perception we see strong dependencies on display parameters like field of view (FOV), spatial frequency content, and even higher-level factors like the interpretation or meaning of the stimulus (e.g., Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005c).

In addition to the perception of self-motion, studies have shown that humans can also extract angles turned and distances traveled from pure optic flow information (e.g., Bremmer & Lappe, 1999; Loomis & Beall, 1998; Warren, Kay, Zosh, Duchon, & Sahuc, 2001; Warren & Wertheim, 1990). The ability to extract this kind of information is a prerequisite for visually-based spatial updating. Again, we see that performance is highly dependent on the display parameters and device used (see, e.g., discussion in Riecke, van Veen, & Bülthoff, 2002; Riecke, Schulte-Pelkum, & Bülthoff, 2005a).

Studies that directly address spatial updating from optic flow are rather sparse, and suggest that optic flow might be sufficient to enable automatic or even obligatory spatial updating for translations (May & Klatzky, 2000). For rotations, however, optic flow information, at least when presented via head-mounted display (HMD), seems to be insufficient for spatial updating, and physical rotations seem to be required (Chance, Gaunet, Beall, & Loomis, 1998; Klatzky et al., 1998; Wraga et al., 2004). Using an HMD with an FOV of 44° × 33°, Klatzky et al. (1998, p. 297) stated that "optic flow without proprioception, at least for the limited field of view of our virtual display system, appears not to be effective for the updating of heading". Similarly, Chance et al. (1998) found reduced spatial orientation ability when rotations were only displayed through an HMD, without concurrent physical motions.

Does this mean that the visual cues alone are not, in principle, sufficient for spatial updating of rotations? Perhaps where optic flow fails, a richer stimulus might succeed. Little research has been done on spatial updating using more realistic and highly structured environments, and the evidence so far is rather inconclusive: using highly structured and photorealistic stimuli of interior rooms presented on a computer monitor (34.5° FOV), Christou and colleagues demonstrated that visual information that indicated the current viewing position implicitly or explicitly improved response times and recognition of individual objects and object arrays from novel viewpoints (Christou & Bülthoff, 1999; Christou, Tjan, & Bülthoff, 1999, 2003). Object recognition performance remained, however, view-dependent for rotations that were only visually displayed (i.e., no automatic spatial updating), whereas physically moving to the new vantage point can, under certain conditions, enable view-independent recognition of objects and object arrays (Simons & Wang, 1998; Wang & Simons, 1999; Simons, Wang, & Roddenberry, 2002).

A similar lack of spatial updating automaticity has been reported by Wraga et al. (2004) using highly structured and slightly less realistic visual stimuli. Wraga et al. used an HMD (60° × 46.8° FOV) to display room-like simulated scenes containing alcoves with four or five target objects. After real or visually simulated self-rotations, participants were asked to indicate the direction of target objects either verbally or by pointing using a virtual, visually simulated pointer. Both response measures showed improved spatial updating performance when physical motion cues accompanied the visual motions. The data indicate that the visual cues provided through the HMD were not sufficient for enabling automatic spatial updating, even though the stimuli contained several landmarks and were continuously visible. The authors conclude that "self-movement plays a key role in spatial updating tasks involving rotation movement within a full perceptual context" (p. 413).

In apparent contrast, recent studies by Riecke and colleagues showed, using a rapid pointing task and highly structured photorealistic replica of familiar natural environments, that visual cues alone *can* be sufficient for both automatic and obligatory spatial updating (Riecke et al., 2001, 2004; Riecke, von der Heyde, & Bülthoff, 2005d). That is, participants were unable to successfully ignore or suppress the visual stimulus for all stimulus conditions tested. Reminiscent of the results for earlier perceptual processes, the difficulty in ignoring the visual stimulus was more pronounced for larger visual turns and when the FOV was increased (from 40° × 30° to 84° × 63°). Most noticeably, however, concurrent physical motion cues from passive motions showed little, if any, effect. This indicates that the visual stimuli alone were already quite powerful and sufficient for updating our egocentric mental representation in an almost reflex-like manner.

This apparent conflict might be due to any of the many differences between the different experiments. These differences include experimental procedures, display device (HMD vs. projection setup or monitor), FOV, and properties of the visual stimulus itself (mainly familiarity, structuredness, and realism). The fact that stimuli of Riecke et al. were highly structured and photorealistic cannot alone explain why they found obligatory spatial updating, since Christou et al. used visual stimuli of similar quality but failed to observe automatic spatial updating. Display parameters, on the other hand, have been found to affect spatial updating performance (Riecke et al., 2005d), just as they affect earlier perceptual processes. More specifically, both reducing the FOV and switching from a projection system to an HMD (40° × 30° FOV) decreased spatial updating performance. It is important to note, however, that the spatial updating remained automatic and obligatory, demonstrating that the visual cues presented via an HMD are, under some circumstances, sufficient to enable the automatic and obligatory spatial updating of rotations.

Main idea and preview of experiment

The optic flow stimuli devoid of any landmarks have been widely used in the literature for a number of research questions and tasks, and have been shown to be sufficient for solving a number of spatial orientation tasks. They have, however, never been shown to be sufficient for enabling automatic or obligatory spatial updating of rotations. Here, we tested if the efficacy of pure optic flow for spatial updating can be increased if we use the display setup that has maximized spatial updating performance in the study by Riecke et al. (2005d). As a baseline, we replicated two conditions that yielded optimal spatial updating performance (Riecke et al., 2005d). Those "Full Scene" conditions used a highly structured, photorealistic replica of the Tübingen market place projected onto a curved, 84° × 63° projection screen. These baselines were then compared to two novel conditions, where the visual stimulus was reduced to an unstructured optic flow pattern devoid of any landmarks ("Pure Optic Flow" conditions). Apart from the change in visual stimulus condition, the procedures closely matched those of Riecke et al. (2005d). We were interested in two main questions:

1. Does pure optic flow have any obligatory influence on spatial updating of rotations at all? (This would be indicated by Ignore performance being inferior to Update and/or Control performance.) Might pure optic flow even be sufficient for inducing automatic and/or obligatory spatial updating if we take a display device that has previously been shown to be highly effective in triggering spatial updating? [This would be indicated by Update performance being similar to Control performance (automatic spatial updating), and exceeding Ignore performance (obligatory spatial updating), respectively.]
2. The literature suggests that spatial updating should be rendered automatic when physical motion cues are provided, even when the visual cues alone are not sufficient (e.g., Chance et al., 1998; Klatzky et al., 1998; Wang & Simons, 1999; Wraga et al., 2004). To test this hypothesis, the two visual conditions (Full Scene vs. Pure Optic Flow) were crossed with two physical motion cue conditions (Platform On vs. Platform Off).

Methods

Participants

A group of 13 female and 4 male naive participants took part in this study[1]. Ages ranged from 15 to 45 years (mean: 25 years, SD: 7.4 years). All participants had normal or corrected-to-normal vision and no signs of vestibular dysfunction. Participation was voluntary and paid at standard rates.

Stimuli and apparatus

The participants were seated on a 6DOF Stewart motion platform (Motionbase Maxcue) at a distance of about 1.14 m from a curved projection screen (2 m curvature radius) that was mounted on the platform (see Fig. 1a). The computer-generated visual stimuli were projected non-stereoscopically at a resolution of 1,024 × 768 pixels using an LCD video projector (Sony VPL-PX 21 with wide angle lens VPL-FM 21). The simulated FOV was 84° × 63° and matched the physical FOV. The whole projection setup was surrounded by black curtain. During the experiment, instructions were provided using a computergenerated voice and active noise canceling headphones (Sennheiser HMEC 300) that participants wore throughout the experiment. Pointings were performed using a purpose-built pointing wand that participants held with both hands (see Fig. 1a). The pointer was position-tracked in all six degrees of freedom using an Intersense IS600-mk2 tracker. A more detailed description of the experimental stimuli and apparatus can be found in Riecke et al. (2005d).

The visual stimuli consisted of the same photorealistic replica of the Tübingen market place that has been used by Riecke et al. (2005d; see Fig. 1b, c). In a landmark pretest, the participants were able to name between 6 and 22 landmarks on the Tübingen market place (mean: 13.3), indicating that they were already quite familiar with the environment used. To disambiguate the influence of landmark information from optic flow, the market place stimulus was replaced by a simple optic flow pattern during the motion and

[1] Gender is known to correlate, under certain circumstances, with spatial abilities like imagined perspective changes and spatial updating of path layouts (Mou et al., 2004; Sholl & Bartels, 2002). Studies using a methodology comparable to the current study did, however, not show any gender effects. Hence, the female bias in the current participant population does not seem critical. Moreover, only withinsubject analyzes were used in the current study.

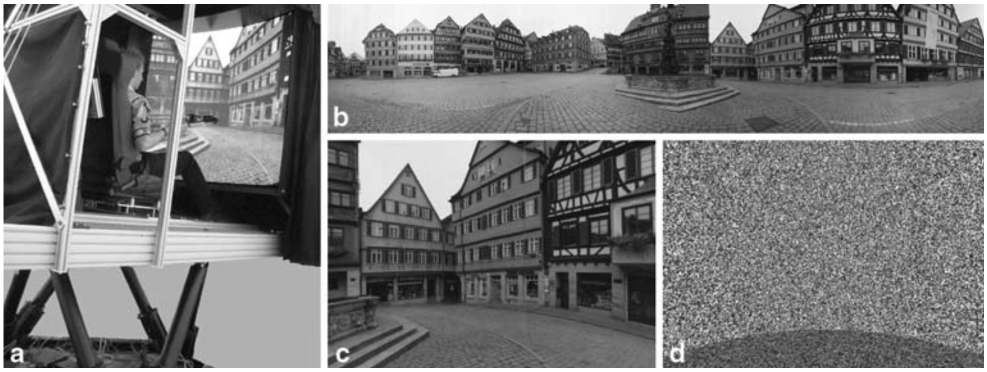

Fig. 1 **a** Participant seated in front of a curved projection screen displaying a view of the Tübingen market place. The whole setup is mounted on a motion platform. **b** Visual stimuli used in the FULL SCENE condition were generated by wrapping a 360° panoramic image (4,096 × 1,024 pixel) of a natural scene (the market place of the town Tübingen in southern Germany) onto a cylinder. **c** The rendering viewpoint was centered in the cylinder, such that observers saw an undistorted, photorealistic view onto the scene, as if looking through a window (FULL SCENE condition). **d** For half of the trials, the market stimulus was replaced by an optic flow pattern (grayscale fractal texture) during the motion and pointing phase (PURE OPTIC FLOW condition)

pointing phase of half of the trials (PURE OPTIC FLOW condition, see Fig. 1d).

The current study is among the first to directly compare the potency of different visual stimuli to induce spatial updating as assessed by rapid pointing, and was designed to compare two extreme cases: A naturalistic scene that affords spatial orientation and presence (Riecke et al., 2005a; Riecke, Schulte-Pelkum, Caniard, & Bülthoff, 2005b) versus an artificial-looking grayscale texture devoid of any reference objects. We are aware that the PURE OPTIC FLOW and FULL SCENE stimuli differed not only in terms of higher-level features (e.g., presence or absence of landmarks embedded in a familiar natural scene) but also in terms of lower-level features like spatial frequency content and motion energy, which are known to affect illusory self-motion perception (vection) (Dichgans & Brandt, 1978; Hettinger, 2002). In the current study, it is, however, highly unlikely that participants experienced vection in any condition, as presentation times of the moving visual stimulus never exceeded 6 s, which is still well below the typical vection onset times of 10–20 s that were observed using a similar setup and stimulus (Riecke et al., 2005d). Nevertheless, it is feasible that lower-level stimulus parameters like spatial frequency content might affect visually induced spatial updating, and future studies are needed to disambiguate the individual contributions.

Design and procedure

An extended training phase preceded the main experiment to familiarize participants with the rapid pointing procedure, the different spatial updating tasks, the VR setup, and the landmarks using a pictorial landmarks recognition test. Rapid pointing was trained in the real world with a laser pointer attached to the pointing wand until participants were able to point with accuracy of roughly 4°. After the training, each participant completed three sessions that were identical apart from the quasi-randomization of turning angles and cue combinations. All three sessions were performed on the same day, with intermittent breaks to avoid fatigue effects and obviate the influence of declining alertness.

The experiment used a repeated-measures, within-subject design (see Table 1), with two visual conditions (FULL SCENE vs. PURE OPTIC FLOW) crossed with two physical motion cue conditions (PLATFORM ON vs. PLATFORM OFF). The two FULL SCENE conditions were designed to replicate condition F and H of the control experiment by Riecke et al. (2005d), whereas the two PURE OPTIC FLOW conditions were novel. Four different spatial updating tasks (CONTROL, UPDATE, IGNORE, and IGNORE BACKMOTION) were used for each condition as described below.

- **CONTROL**: This is a baseline task in which participants are turned to a new orientation and immediately back to the initial one before being asked to point consecutively to four targets announced via headphones. The CONTROL task is expected to yield optimal performance, as the required spatial updating can be considered as rather trivial.
- **UPDATE**: This is the standard spatial updating situation in which participants are rotated to a new orientation before being probed. If the available cues are sufficient for enabling automatic

Table 1 Summary of the four different spatial updating tasks used

Spatial updating task	Visual turning angle α	Trials per cue combination (A, B, C, and D) and session	Trials per session	Trials altogether
1. Update	80°≤|α|≤456°	4	16	48
2. Control	80°≤|α|≤114°	2	8	24
3. Ignore	80°≤|α|≤228°	2	8	24
4. Ignore Backmotion	80°≤|α|≤228°	2	8	24

spatial updating, Update performance should be (almost) as good as Control performance (‘‘**automatic spatial updating**’’).

- **Ignore**: Participants are instructed via headphones to ignore the following rotation to a new orientation and respond as if they had not moved. If the presented spatial cues are powerful enough to trigger spatial updating of their mental egocentric representation (even against their conscious will), those turns should be harder to Ignore than to Update. The induced spatial updating would then be considered ‘‘obligatory’’ or ‘‘reflex-like’’ in the sense of being largely beyond conscious control and consciously hard-to-suppress (‘‘**obligatory spatial updating**’’).
- **Ignore Backmotion**: To avoid disorientation and confusion that might be elicited by the Ignore task, participants are rotated back to the previous orientation after each Ignore trial.

Each trial consisted of the following three phases:

1. **Auditory announcement** indicating whether the upcoming trial was an Ignore trial, an Ignore Backmotion trial, or a ‘‘normal’’ trial (Update or Control trial).
2. **Motion phase**, in which a rotation was presented on the projection screen. A Gaussian velocity profile was used, with a peak velocity of twice the mean velocity (80°/s). In half of the trials (Platform On conditions) the visual motion was accompanied by a physical rotation of the platform. As the motion range of the platform was limited to ±57° for yaw rotations, but we wanted to investigate rotations larger than that (larger rotations are often assumed to be more difficult to update/ignore), we decided to use a gain factor $g_{vestibular/visual} = 1/4$ between the physical and visual motion. That is, the platform moved only with 1/4 of the visual rotational velocity. Pre-experiments and the Control experiment of Riecke et al. (2005d) had shown that vestibular/visual gain factors down to 1/4 do not change spatial updating performance consistently, are easily accepted by the participants, and typically pass unnoticed, especially when being involved in an engaging task like rapid pointing (see below). This is in agreement with earlier findings that visuo-vestibular mismatches in VR are typically not noticed, even though they can lead to recalibration of turn perception (Ivanenko, ViaudDelmon, Siegler, Israël, & Berthoz, 1998). Nevertheless, further studies would be needed to test if the finding that gain factors down to 1/4 do not affect spatial updating performance also extends to more impoverished, pure optic flow stimuli.
3. **Pointing phase**, consisting of four repetitions of

- *Auditory announcement* of the next target object to point to. The pointing targets were selected randomly within a comfortable pointing range but outside of the current FOV $|\alpha_{pointer} - \alpha_{straight\text{-}ahead}| \in [42^{\circ}, 110^{\circ}]$.
- *Subsequent pointing*: Participants were instructed to always point ‘‘as accurately and quickly as possible’’.
- *Raising the pointer to the upright (default) position*, indicating to the computer that the experiment can go on. This upright default position ensured similar pointing motions (and thus response times) for all target directions independent of the previous pointing direction, an issue that is often not accounted for in studies using compasslike pointers (e.g., Wraga et al., 2004).

To allow participants after the Pure Optic Flow trials to re-anchor to the correct orientation before the next trial, the corresponding view of the Tübingen market place was presented after each pointing phase for several seconds until the next trial started.

Each session lasted about 18 min and consisted of 40 trials, which were split up into 16 Update trials, and 8 trials for each of the other spatial updating tasks. All four cue combinations (A–D) were used within each session. The order of Pure Optic Flow and Full Scene conditions was randomized.

Dependent measures

Five different dependent variables were employed. As pointing data are inherently directional (circular) data, circular statistics were used for computing the dependent variables (Batschelet, 1981).

The **response time**, defined as the time between the mean end of the pronunciation of the first two syllables (1.43 s) and the subsequent pointing, was used to indicate how easily participants could access their spatial knowledge. To correct for between-subject response time differences without affecting the overall mean response times, the *relative* response time was computed, which was defined as the response time for a given participant and condition, divided by the ratio between his/her mean CONTROL response time in that condition and the mean CONTROL response time across all participants in that condition. The **configuration error**, defined as the mean angular deviation of the signed pointing error of the 4 pointings per trial, was used to quantify the consistency of participants' spatial knowledge of the target configuration. The configuration error will be zero if the relative angles between the four target objects are reported correctly. The **absolute pointing error** was used to assess how accurately participants knew where they were with respect to their surroundings. It was computed by taking the absolute value of the angular deviation between the actual and correct pointing direction. A part of their absolute pointing error might, however, be caused by a general misperception of their current ego-orientation. If, for example, participants misperceive their ego-orientation by 30°, this might already explain up to 30° of their absolute pointing error. To estimate this overall error in participants' perceived ego-orientation per trial, the **absolute ego-orientation error per trial** was computed by taking the absolute value of the circular mean of the four signed pointing errors per trial (Batschelet, 1981, Chap. 1.3). Finally, the **ego-orientation error in turning direction** (defined as the circular mean of the four signed pointing errors per trial) was computed to investigate if participants' ego-orientation error might be related to the direction of motion.

Results and discussion

The data are presented in three subsections: the first subsection will investigate baseline (CONTROL) performance, followed by an analysis of automatic and obligatory spatial updating. The full data set is presented in Fig. 2.

Fig. 2 Compilation of all dependent variables, plotted for the four different stimulus combinations (*Block A–D*, represented at different *gray levels*) and the four different spatial updating tasks UPDATE ("U"), CONTROL ("C"), IGNORE ("I"), and IGNORE BACKMOTION ("IB"). Note that only the FULL SCENE conditions show the typical response pattern for obligatory and automatic spatial updating: UPDATE performance is almost as good as baseline CONTROL performance (implying automatic spatial updating), whereas IGNORE performance is considerably worse (implying obligatory spatial updating). IGNORE BACKMOTION performance was comparable to or better than UPDATE performance, suggesting that participants were properly reanchored to the surround and no longer disoriented by the preceding IGNORE trial ▶

Baseline (CONTROL) performance

The simple back-and-forth rotation of the CONTROL task always ended in the initial orientation. The required spatial updating should therefore be rather trivial and not depend much on the available *dynamic* motion cues. Differences in the CONTROL task performance, then, indicate differences in the usability of the available *static* spatial information. Thus, the PURE OPTIC FLOW condition should yield reduced performance if the static visibility of the FULL SCENE is essential.

Pointing results were quantified using two-factorial analysis of variances (ANOVAs) for the factor's visual information and physical motion information for each of the five dependent variables. The results are summarized in Table 2. The ANOVAs revealed significant main effects of visual information on response time, configuration error, absolute pointing error, and absolute ego-orientation error. Physical motion information showed a significant main effect only in terms of the configuration error. The interaction reached significance only for the ego-orientation error in turn direction.

FULL SCENE cues allowed for good baseline performance, whereas PURE OPTIC FLOW performance was consistently lower (see Fig. 2). This decrease suggests that it is not so much the knowledge about the correct orientation (participants knew that CONTROL motions ended exactly at the initial orientation), but the static visibility of the visual scene that aligns the mental representation properly and allows for optimal pointing performance. Optic flow information, however, still allowed for decent baseline performance far from chance. Additional passive physical motion cues proved irrelevant for the FULL SCENE condition, and even decreased pointing consistency slightly in the PURE OPTIC FLOW condition ($t(16) = 2.71$, $P = 0.015$* using paired two-tailed t-tests).

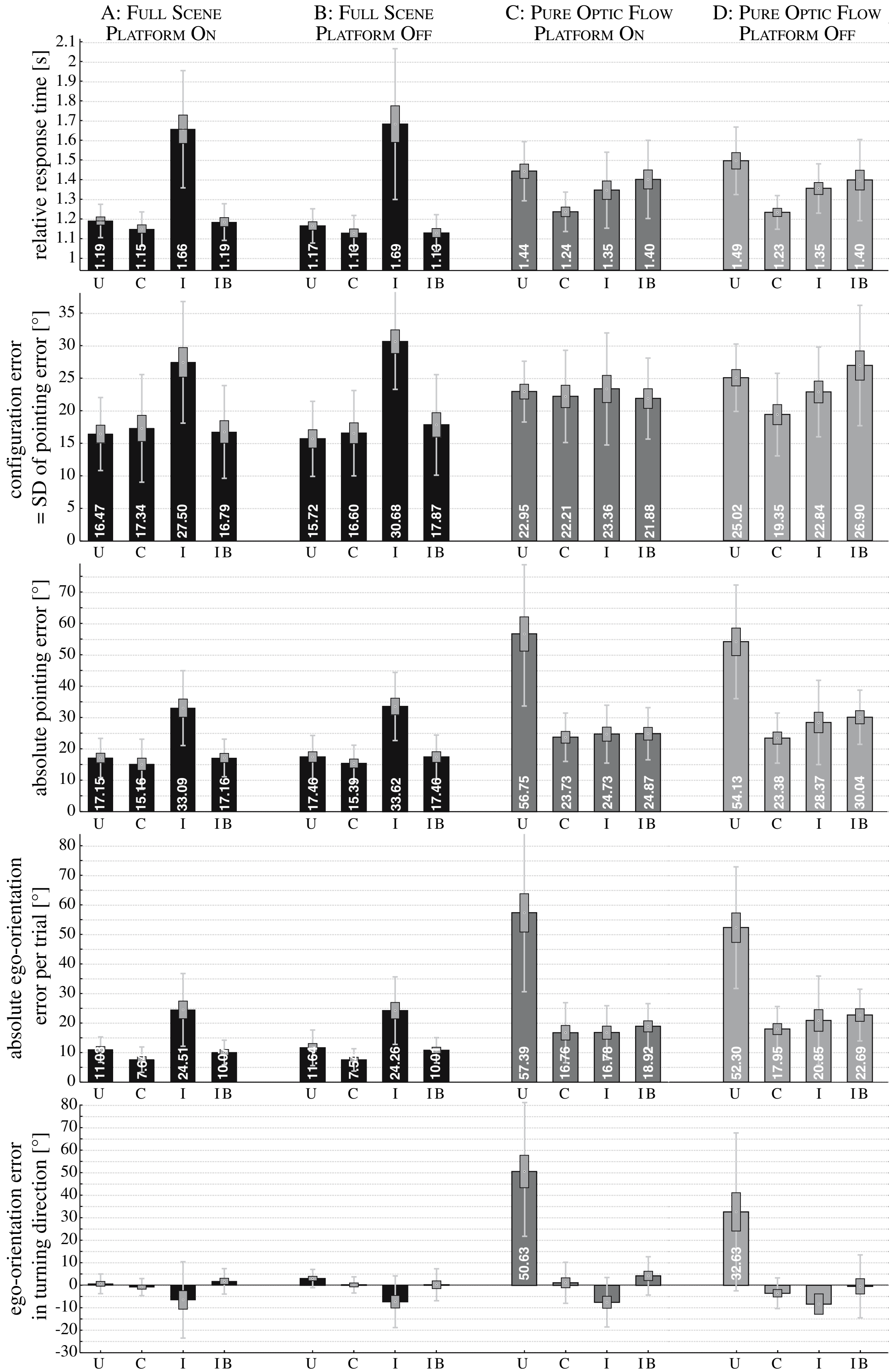
A: Full Scene
Platform On
B: Full Scene
Platform Off
C: Pure Optic Flow
Platform On
D: Pure Optic Flow
Platform Off
relative response time [s]
1.19 1.15 1.66 1.19
1.17 1.69
1.44 1.24 1.35 1.40
1.49 1.23 1.35 1.40
configuration error
= SD of pointing error [°]
16.47 17.34 27.50 16.79
15.72 16.60 30.68 17.87
22.95 22.21 23.36 21.88
25.02 19.35 22.84 26.90
absolute pointing error [°]
17.15 15.16 33.09 17.16
17.40 15.39 33.62 17.40
56.75 23.73 24.73 24.87
54.13 23.38 28.37 30.04
absolute ego-orientation
error per trial [°]
24.51
24.26
57.39 16.76 16.78 18.92
52.30 17.95 20.85 22.69
ego-orientation error
in turning direction [°]
50.63
32.63
U C I IB

Table 2 Analysis of variance results for the CONTROL task (top), the difference between UPDATE and CONTROL performance, which serves as a measure of automatic spatial updating (middle), and the difference between IGNORE and UPDATE performance, which serves as a measure of obligatory spatial updating (bottom)

	Response time		Configuration error		Absolute pointing error		Absolute ego-orientation error		Ego-orientation error in turn direction	
	$F(1,16)$	P	$F(1,16)$	P	$F(1,16)$	P	$F(1,16)$	P	$F(1,16)$	P
CONTROL										
FULL SCENE/PURE OPTIC FLOW	**10.1**	**0.006****	**5.31**	**0.035**	**30.3**	**0.000*****	**58.0**	**0.000*****	0.202	0.659
PLATFORM ON/OFF	1.04	0.323	**7.70**	**0.014***	0.005	0.944	0.124	0.73	2.56	0.129
Interaction	0.578	0.458	1.85	0.193	0.089	0.769	0.167	0.69	**5.35**	**0.034***
UPDATE–CONTROL										
FULL SCENE/PURE OPTIC FLOW	**23.0**	**0.000*****	**5.70**	**0.030***	**54.7**	**0.000*****	**54.1**	**0.000*****	**29.1**	**0.000*****
PLATFORM ON/OFF	1.38	0.257	**8.49**	**0.010***	0.292	0.596	0.734	0.404	*3.58*	*0.077m*
Interaction	0.982	0.337	**5.30**	**0.035***	0.229	0.639	1.09	0.312	**5.35**	**0.034***
IGNORE–UPDATE										
FULL SCENE/PURE OPTIC FLOW	**30.6**	**0.000*****	**45.9**	**0.000*****	**53.0**	**0.000*****	**45.0**	**0.000*****	**23.7**	**0.000*****
PLATFORM ON/OFF	0.001	0.979	0.125	0.729	2.50	0.133	1.88	0.189	*3.66*	*0.074m*
Interaction	2.93	0.106	**4.98**	**0.040***	1.13	0.304	2.45	0.137	*3.92*	*0.065m*

The asterisks indicate the significance level (5, 0.5 or 0.05%). Marginal significance (10% level) is indicated by an 'm'

Automatic spatial updating

In this subsection, we investigate the automaticity of spatial updating by comparing spatial updating performance for turns to different orientations (UPDATE trials) with the CONTROL trials.

Hypotheses

If the available cues are sufficient for automatic spatial updating, UPDATE performance should be almost as good as CONTROL performance. Other studies where automatic spatial updating was observed report response time increases by about 100 ms for UPDATE trials when participants are physically moving while being blindfolded (Farrell & Robertson, 1998; May, 2000) and 50–60 ms when participants could see the surrounding room or a virtual replica thereof (Riecke et al., 2004). Absolute pointing errors showed a clear increase only if participants were blindfolded (Farrell & Robertson, 1998; Riecke et al., 2004), but not if participants had visual information from a surrounding (real or simulated) scene (Riecke et al., 2004). Hence, for the current experiment we would predict an increase in pointing error only for the PURE OPTIC FLOW condition, and not for the FULL SCENE condition.

FULL SCENE conditions

As can be seen in Fig. 3, both FULL SCENE conditions show virtually the same excellent updating performance, irrespective of physical motion cues: response times were increased by less than 40 ms between CONTROL and UPDATE trials, indicating that spatial updating to new orientations was automatic and almost as easy as baseline performance. The configuration error remained unchanged, indicating that the consistency of the mental spatial representation did not suffer from the turns. The small increase in absolute pointing error of roughly 2° was probably caused by the increase in absolute egoorientation error of roughly 4°.

PURE OPTIC FLOW conditions

Here, the response pattern changes drastically (see Table 2): First, response times increased by more than 200 ms, indicating that automatic spatial updating was impaired without visibility of the FULL SCENE. Second, both absolute pointing error and ego-orientation error were increased by more than 30°: due to the lack of landmarks, participants were most likely forced to use path integration to estimate the angle turned (see absolute ego-orientation error plot in Fig. 2). Finally, there was a general overestimation of the angle turned, indicated by the considerable ego-orientation error. This overestimation was substantially more pronounced for condition C (50.6°, see Fig. 2) than for condition D (32.6°; a paired *t*-test shows a significant difference in turning direction ($t(16) = -3.09$, $P = 0.0071$*). The direction of this effect was unexpected, as one might rather predict that additional physical motion cues (condition C) should have improved the ego-motion perception. The additional physical motion cues

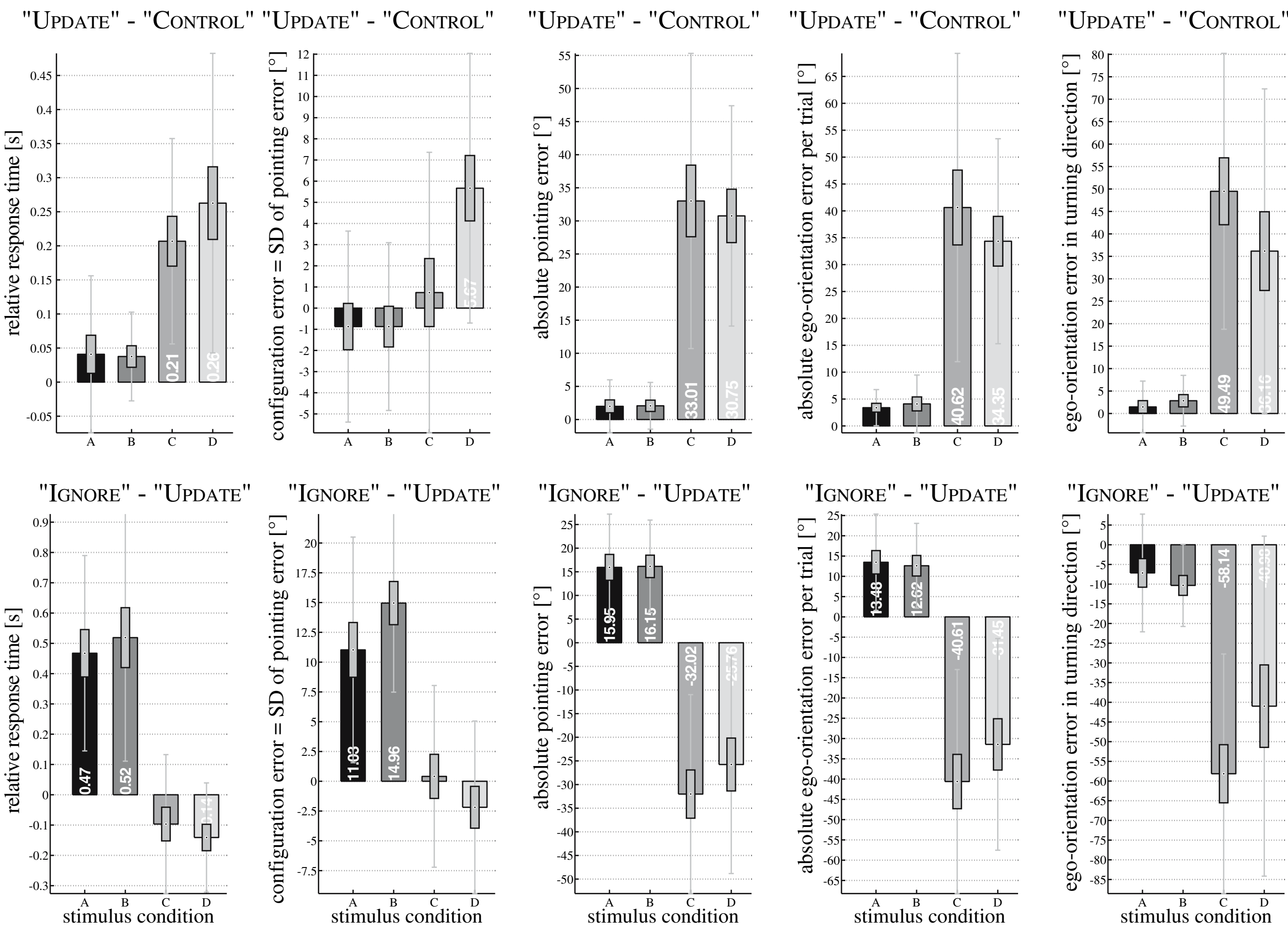

Fig. 3 *Top* Automatic spatial updating performance, quantified as the difference between Update and Control performance for the four different stimulus conditions *A* (Full Scene, Platform On), *B* (Full Scene, Platform Off), *C* (Pure Optic Flow, Platform On), and *D* (Pure Optic Flow, Platform Off). In the Full Scene conditions (*A* and *B*), the difference between Update and Control performance was only minimally above zero, indicating that automatic spatial updating was rather easy and accurate. In the Pure Optic Flow conditions (*C* and *D*), however, automatic spatial updating was considerably impaired, indicated by the clear offset from zero. *Bottom* Obligatory spatial updating performance, quantified as the difference between Ignore and Update performance. For the Full Scene conditions, the differences between Ignore and Update performance measures were positive for all but for the right plot. That is, ignoring a turn was considerably harder than updating it as usual, implying obligatory spatial updating. For the Pure Optic Flow conditions, however, the offsets from zero were negative, indicating that ignoring a turn was actually easier and more accurate than updating it. Hence, pure optic flow information proved insufficient for inducing obligatory spatial updating

apparently increased the perceived turning angle, even though the physical turning angles were only 1/4 of the corresponding visual turning angles.

The consistent overestimation of turning angles in both Pure Optic Flow conditions was rather surprising, as participants received feedback about their current orientation from the market place scene that became visible after each Pure Optic Flow trial. Nevertheless, most participants were apparently unable to use this feedback to re-calibrate their turn perception. This was corroborated by the lack of any learning effect—correlations between trial number and both ego-orientation error measures did not reach significance ($P > 0.05$). We presume that participants were so involved and challenged by the rapid pointing task that they had no cognitive or other resources left to successfully re-calibrate their turn perception.

Benefit of physical motion cues in the Pure Optic Flow conditions

The Platform Off condition showed a substantially larger configuration error in the Update task than in the Control task, whereas the Platform On condition showed no such effect. This interaction reached significance (see Table 2). This benefit from physical rotations was also apparent when comparing the UPDATE tasks themselves (see Fig. 2; $t(16) = 2.28$, $P = 0.036^*$). This suggests that the mental spatial representation of the surroundings was slightly less consistent when physical motion cues were missing. Even under those conditions, however, the configuration error of 25° was far from chance. As an increase in configuration error has earlier been observed for participants that were previously disoriented (Wang & Spelke, 2000) (although Holmes and Sholl (2005) were unable to replicate the effect), one might argue that the presence of concurrent physical turn cues prevented the slight disorientation observed in the PLATFORM OFF condition. While this is still speculative, if true it means that a vestibulo-visual gain factor of $g = ¼$ was sufficient to prevent this apparent disorientation, and that the full physical motion cues ($g = 1$) were not needed. Further studies are needed, however, to yield more definite answers about the potential influence of gain factors on spatial updating based on pure optic flow.

In summary, photorealistic landmarks embedded in a consistent scene proved sufficient for enabling automatic spatial updating, irrespective of concurrent physical motion cues from passive motions. This corroborates earlier findings that showed no effect of physical motion cues for a variety of gain factors (0, 0.25, 0.5, and 1) between physical motions and visual motions (Riecke et al., 2005d). The current study extends those findings by showing that spatial updating was no longer automatic when visual cues were reduced to a mere optic flow pattern. Under these conditions, concurrent physical turns improved performance slightly by preventing the configuration error from increasing. In contrast to predictions from the literature (e.g., Wraga et al., 2004), however, nonvisual turn cues were insufficient for enabling automatic spatial updating.

Obligatory spatial updating

In this subsection, the difference between IGNORE and UPDATE performance was used to investigate the reflex-like (obligatory) component of spatial updating. Only if spatial updating is obligatory should ignoring a motion be harder than updating a motion. This would be reflected in a difference between IGNORE and UPDATE trials well above zero.

FULL SCENE conditions

As expected from previous studies (Riecke et al., 2005d), the IGNORE performance was considerably worse than UPDATE performance for all measures whenever the FULL SCENE was visible. Especially the large increase of approximately 500 ms in terms of response time indicates that spatial updating was for both FULL SCENE conditions obligatory. Consistent with Riecke et al. (2005d), physical motion cues were completely irrelevant for the task, and visual FULL SCENE cues alone proved sufficient to render spatial updating obligatory.

PURE OPTIC FLOW conditions

In contrast to the FULL SCENE conditions, The PURE OPTIC FLOW conditions showed no signs for obligatory spatial updating whatsoever. Response times in the IGNORE tasks were even *smaller* (>100 ms) than in the UPDATE tasks. Furthermore, absolute pointing error and the ego-orientation errors were significantly *reduced* in the IGNORE trials. Taken together, this suggests that ignoring PURE OPTIC FLOW turns was actually much easier and more accurate than updating them. Only the configuration error showed virtually no effect, suggesting that it did not matter for the consistency of participants' spatial representation whether they were instructed to IGNORE a turn stimulus or use it to UPDATE to the new orientation. This suggests that the natural scene used was accepted as one consistent reference frame, similar to the room geometry that remained consistent despite participants being disoriented (Wang, 1999; Wang & Spelke, 2000, 2002).

Do physical motion cues enable automatic spatial updating in the PURE OPTIC FLOW conditions?

The literature suggests that physical motion cues should enable automatic spatial updating, even when the visual cues alone are not sufficient (e.g., Chance et al., 1998; Klatzky et al., 1998; Wang & Simons, 1999; Wraga et al., 2004). The passive physical motion cues used here, however, clearly did not enable obligatory or automatic spatial updating, not even when all visual information was reduced to mere velocity information from PURE OPTIC FLOW. The only marginally significant effect of the additional physical motions was an increase in the ego-orientation error in turning direction by about 18°.

Can PURE OPTIC FLOW be ignored completely?

As can be clearly seen in Fig. 2, IGNORE performance for the PURE OPTIC FLOW conditions was typically between CONTROL and UPDATE performance, and for some dependent variables as good as CONTROL performance. This corroborates that having to UPDATE an optic flow-induced turn is considerably harder than having to IGNORE it. It is, however, noteworthy that response times for the IGNORE trials were considerably longer than for the CONTROL trials, both for condition C ($t(16) = 2.29$, $P = 0.036^*$) and for condition D ($t(16) = 3.16$, $P = 0.0061^*$). This was rather puzzling, as participants had essentially the same task in both the CONTROL and the IGNORE trials, namely having to point as if still being at the previous location, without any useful static visual cues. This effect is most peculiar in the PLATFORM OFF condition (D), where virtually the only difference between CONTROL and IGNORE trial was the optic flow displaying either a back-and-forth motion or just a forward motion, respectively. Nevertheless, the optic flow simulating a forward motion considerably impaired participants' performance in terms of response time and configuration error ($t(16) = 2.29$, $P = 0.036^*$). That is, the participants performed significantly better when the optic flow stimulus was *consistent* with their task of pointing as if being at the previous location (CONTROL trials). A conflicting optic flow motion, however, disrupted performance considerably (IGNORE trials). Hence, optic flow information *cannot* easily be ignored completely without noticeable performance decrease, and thus does seem to have at least some obligatory influence on our egocentric mental representation. It was, however, still much harder to use the optic flow information to UPDATE to new orientations than to IGNORE it and act as if still being at the same position, and optic flow information alone was clearly *not* sufficient to enable easy and automatic spatial updating to new orientations.

General discussion

The current study was designed to tackle two main questions, which will be examined in more detail in the following two subsections.

Question 1: Does pure optic flow have any influence on spatial updating of rotations?

The current experiment replicated and extended previous work by Riecke et al. (2005d), showing that visual cues from a consistent, well-known natural scene can be sufficient to induce automatic as well as obligatory spatial updating, irrespective of concurrent passive physical motions. PURE OPTIC FLOW information, however, proved clearly insufficient for enabling quick and accurate, automatic or obligatory spatial updating despite the use of a large FOV curved projection screen.

This finding is consistent with results from Klatzky et al. (1998) who used a different experimental paradigm: After being exposed to a two-segment path defined purely by optic flow, participants were asked to quickly turn physically to face the origin of locomotion, just as they would if they had physically walked the path and were at the end of the second segment. The participants responded as if they updated the translations for the two linear segments (s_1 and s_2) properly, but completely "forgot" to update the inbetween turn (α). Only if the turn was performed physically did they update their heading properly. The same behavior occurred when participants were asked to imagine walking the excursion or when watching another person walk. Klatzky et al. concluded that "simulated optic flow was not by itself sufficient to induce spatial updating that supported correct turn responses" (p. 293).

Nonetheless, the fact that IGNORE performance was not as good as CONTROL performance for the PURE OPTIC FLOW conditions indicates that the rotating optic flow stimulus did indeed have *some* specific influence on participants' egocentric mental spatial representation as assessed by rapid pointing. Even though the presentation times were too short to reliably induce a convincing perception of ego-motion (vection) (Riecke et al., 2005d), it was nevertheless not possible to simply ignore the optic flow rotation altogether and respond as if still being at the same initial orientation.

Question 2: Can additional physical motion cues enable automatic spatial updating when visual cues themselves are not sufficient?

In contrast to previous work, physical motion cues were clearly incapable of inducing automatic or obligatory spatial updating for the PURE OPTIC FLOW conditions. The reasons for this apparent conflict are not fully understood yet and might be caused by a number of differences in the experimental procedures. For example, in the study by Wraga et al. (2004) a swivel chair was used to execute rotations (actively or passively), whereas a motion platform and passive rotations were used in the current study. The smoothness of the computercontrolled motion as well as the gain factor of 1/4 might have reduced the effectiveness of the physical motion cues in the current study, even though the physical motions were clearly above the detection threshold. Vection studies have shown that initial jerks accompanying the motion onset can increase the selfmotion perception significantly (Schulte-Pelkum, Riecke, Caniard, & Bülthoff, 2006; Wong & Frost, 1981). This suggests that the more jerky rotations on the swivel chair might have enhanced the influence of the physical motions. The passive nature of the motions provided in the current study can probably be excluded as a potential reason, as previous studies have shown that actively executing a physical motion is not required for automatic spatial updating (Wang & Simons, 1999; Wraga et al., 2004; Yardley & Higgins, 1998). Differences in the pointing procedures might also be related to the apparent conflict: A rapid pointing paradigm using a two-handed pointing wand and 22 target objects was used in the current study, whereas a compass-like, visually displayed virtual pointer and four or five targets was used by Wraga et al. (2004). The latter paradigm yielded response times more than a factor of five above those found in the current study, suggesting that participants might have had enough time to employ more abstract or cognitive strategies like mental rotations, verbal strategies, counting targets, or exploiting symmetries in the target layout, which were not present in the current study. That is, it is unclear whether the experimental paradigm employed by Wraga et al. (2004) measured solely *automatic* spatial updating performance as intended or (also) some sort of cognitive, abstract mental spatial abilities. From the current data, it remains an open question under what exact conditions physical motion cues can reliably enable automatic/obligatory spatial updating of visually presented stimuli and enhance performance beyond visually induced spatial updating.

Mental transformation versus interference hypothesis revisited

The mental transformation hypothesis assumes that the difficulty in imagining a perspective different than the sensorimotor perspective stems mainly from the cognitive cost associated with the required mental transformation, and response times should thus increase with increasing angles of rotation (“angular disparity effect”, see the section called “Mental transformation versus interference hypothesis”). As the IGNORE tasks essentially require the participants to imagine still being in the original orientation despite sensorimotor cues indicating the new orientation, the transformation hypothesis would predict increased response times for larger rotations in the IGNORE trials for the conditions which yielded obligatory spatial updating (both FULL SCENE conditions). Correlation analyses revealed, however, no significant correlations between response time and turning angles, thus providing no support for the mental transformation hypothesis.

Furthermore, if the difficulty of IGNORE trials in the FULL SCENE conditions would be due to the associated mental perspective transformation, this should be reflected in larger response times for the first pointing. That is, the time to perform the mental transformation should be added to the response time of the first pointing. Later, pointings should accordingly show smaller response times, as the mental rotation process should be completed after the first pointing. The data showed, however, no significant correlations between response time and pointing number. Thus, it seems like the mental transformation hypothesis cannot easily account for the observed difficulty of the IGNORE tasks.

The data are, however, in agreement with the interference hypothesis, which associates the difficulty of imagined perspective switches to interference between the sensorimotor perspective and the cognitive (to-be-imagined) perspective and thus does not predict any angular disparity effect or pointing order effect (e.g., May, 2004; Wang, 2005). That is, we propose that the main cause for the observed difficulty of the IGNORE tasks in the FULL SCENE conditions is the conflict between two concurrent representations: The sensorimotor representation based on the visual cues and the to-be-imagined representation required to perform the pointing task. This is in agreement with participants stating that they had serious difficulties imagining their previous perspective because it conflicted with the visually presented view.

Note, however, that the current study was not explicitly designed to disambiguate between the transformation and interference hypothesis, and further, carefully designed studies would be needed to elucidate the underlying mental representations and transformations processes determining spatial updating performance.

Conclusions

These findings have important implications for our understanding of visuo-vestibular interactions and the sensory cues required and/or sufficient for enabling quick and robust spatial orientation as mediated by spatial updating. The possibility of enabling natural or close-to-natural spatial orientation in simulated environments with minimal physical motion requirements could also be of considerable interest from an applied perspective, as it might help to reduce overall simulation effort and cost. This is particularly true for the growing field of virtual reality applications and ego-motion simulations, where visual display hardware is becoming increasingly powerful and affordable, while physical motion platforms are still rather bulky, expensive, and require a considerable quantity of technical effort and expertise.

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