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Imaginal perspective switches in remembered environments: Transformation versus interference accounts[☆]

Mark May

Institute for Cognitive Research, University of the Armed Forces Hamburg, D-22039 Hamburg, Germany

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Abstract

Imaginal perspective switches are often considered to be difficult, because they call for additional cognitive transformations of object coordinates (transformation hypothesis). Recent research suggests that problems can also result from conflicts between incompatible sensorimotor and cognitive object location codes during response specification and selection (interference hypothesis). Three experiments tested contrasting predictions of both accounts. Volunteers had to point to unseen object locations after imagined self-rotations and self-translations. Results revealed larger pointing latencies and errors for rotations as compared to translations, and monotic latency and error increases for both tasks as a function of the disparity of object directions between real and imagined perspective. Provision of advance information about the to-be-imagined perspective left both effects unchanged. These results, together with those from a systematic error analysis, deliver clear support for an interference account of imaginal perspective switches in remembered surroundings.

Keywords: Spatial memory; Object localization; Perspective change; Cognitive transformation; Response selection conflict; Spatial interference effects

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E-mail address: mm@unibw-hamburg.de.

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1. Introduction

While moving in space humans and other intelligent mobile animals keep track of changes of directions and distances to object locations in their surrounding. Changes in spatial relations can result from bodily movements of the actor, but can also result from imaginal switches of perspective to other points in the environment. Especially in humans, a number of everyday problems are characterized by the need to perform imaginal perspective switches to other vantage points in space; for instance, taking the perspective of another person while giving instructions, planning one's own as well as anticipating other peoples movement trajectories while playing a ball game; tele-operation of vehicles, etc. Following a short review of previous research, the present studies tested different hypotheses with respect to the cognitive and sensorimotor mechanisms underlying imaginal perspective switches in remembered space.

1.1. Prior research

In developmental psychology there has been a long tradition of thinking of spatial perspective taking as a fundamental cognitive ability that is not fully developed before children reach the age of about ten years (Piaget & Inhelder, 1948/1967). The ability to imaginally switch perspectives is often described as a developmental progress from an exclusively egocentric—or self-centered—mode of spatial processing in the younger child, to a dominantly allocentric—or environment-centered—mode of processing in older children and adults (Millar, 1994). Recent research has made different corrections to Piaget's original position, demonstrating that the ability to take foreign perspectives depends, for instance, on the testing method used (e.g., Huttenlocher & Presson, 1979; Newcombe & Huttenlocher, 1992), on the locomotor status of the child (e.g., Acredolo, 1990; Bertenthal, 1996), or on geometrical aspects of the environment (e.g., Hermer & Spelke, 1996). An increasing number of researchers consider difficulties with imaginal perspective switches, and related spatial tasks, not so much as resulting from cognitive limitations in the younger child's construction of the spatial environment, but as resulting from problems to efficiently cope with conflicting spatial information in such situations (Millar, 1994; Newcombe & Huttenlocher, 2000; Thelen, Schöner, Scheier, & Smith, 2001).

While focusing on the ontogeny of spatial abilities, developmental research has almost exclusively relied on qualitative error analyses, limiting the possibilities to test hypotheses about time-critical processing demands of imaginal perspective taking tasks. Over the last years, research in adults has started to fill this gap by using response times in addition to error data. Various studies show that switches of spatial perspective are easy (i.e., comparable to baseline performances without switches), when blindfolded actors are allowed to bodily move into a second position before having to point to, or walked up to, an unseen object location; for distances of more than 10 m, and turns up to at least 360°, vestibular, kinesthetic, and maybe also motor-efferent signals seem to support an automatic updating of spatial relations to objects in the surround (Berthoz, 1997; Farrell & Thomson, 1998; Loomis, Klatzky, Golledge, & Philbeck, 1999; May & Klatzky, 2000; Rieser, 1999; Rieser, Guth, & Hill, 1986; Wang & Spelke, 2000).

Switches of spatial perspective turn out to be much more difficult when the actor has to imagine being located at a position different from the one he or she is actually bodily located at. When asked to point to unseen objects from such an imagined perspective, additional processing costs are reflected in increases in response times or errors using very different methodologies (Amorim & Stucchi, 1997; Boer, 1991; Bryant & Tversky, 1992; Easton & Sholl, 1995; Farrell & Robertson, 1998; Franklin, Tversky, & Coon, 1992; Hintzman, O'Dell, & Arndt, 1981; May, 1996; Rieser, 1989; Rieser, Garing, & Young, 1994; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998; Waller, Montello, Richardson, & Hegarty, 2002; Woodin & Allport, 1998; Wraga, Creem, & Proffitt, 2000).

Of special interest for the present research are studies comparing different geometrical types of movements in imagined surroundings. Movements in the horizontal plane can be described as rotations, i.e., changes of facing direction while staying in the same location (e.g., 90°-turn in place), as translations, i.e., changes of location while keeping the facing direction constant (e.g., making three steps in one direction), or as a combination of both, i.e., changing location and facing direction at the same time. Different studies show that pointing judgments are slower and more inaccurate after imaginal rotations than after imaginal translations (Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989), and that response times and errors increase as a function of the self-rotation angle the actor has to imagine being turned around to (Easton & Sholl, 1995; Farrell & Robertson, 1998; Hintzman et al., 1981; May, 1996; May & Wartenberg, 1995; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2000). These effects seem to be invariant over different procedural variations (e.g., verbal indication of object direction vs. pointing with the extended arm vs. pointing with a joystick), as well as stable for different environments and spatial scales (e.g., from confined experimental rooms up to knowledge about the university campus).

Up to now, debate continues about the nature of the mechanisms underlying imaginal repositionings in remembered surroundings. Memory-based perspective switches constitute a complex cognitive task including processes of stimulus identification, spatial memory retrieval, transformation of position and object coordinates, as well as response planning and execution. Extra costs observed in repositioning tasks have been mainly discussed in terms of mental transformation requirements (e.g., Boer, 1991; Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2000); in the last years, specific processing problems resulting from spatial response conflicts have also been discussed (May, 1996, 2000, 2001). The studies reported in this article aimed at contrasting predictions formulated on the basis of both hypotheses. Although both accounts do not exclude each other on logical grounds, experimental evidence that would support or weaken—or maybe even confirm or discredit—the one or the other account seem useful for advancing and further stimulating research in the field.

1.2. Mental transformation hypothesis

The *mental transformation hypothesis* states that imaginal perspective switches are difficult, because they require additional cognitive transformations of object coordinates when switching to a new position in an imagined environment. The account can be considered as an extension of the idea of mental object transformations (Cooper & Shepard, 1978) to spatial imagery of viewer perspectives; very different versions of the more general idea of perspective switches as mental transformations can be found in the literature (e.g., Boer, 1991; Easton & Sholl, 1995; Huttenlocher & Presson, 1973, 1979; Mou, McNamara, Valiquette, & Rump, in press; Presson & Montello, 1994; Rieser, 1989; Wraga et al., 2000).

The most elaborate formulation of the transformation idea was developed in the context of a body-centered memory retrieval model by Easton and Sholl (1995). Easton and Sholl's model distinguishes between an environment-centered system of object-to-object relations (serving as knowledge basis for allocentric coding of locations in memory) and a body-centered system of self-to-object relations (serving as structure for egocentric retrieval of locations from memory). It assumes that both systems operate in concert, and that body-centered retrieval of object coordinates functions as an imaginal superposition of the self-to-object system onto a portion of the object-to-object representational system. Thus, imaginal repositionings are assumed to be an analog process of mental rotation or translation, leading to processual extra costs the larger the rotation angle or translation distance to superimpose the self-to-object system onto the object-to-object system becomes (for a detailed description of the model see Easton & Sholl, 1995, pp. 483–487; for further treatments and extensions see Sholl, 1995, 2000, 2001).

Evidence in favor of the mental transformation account, in general, and the imaginal superpositioning model, in particular, comes from studies revealing increases in pointing latency and/or pointing error as a function of increases of the imagined self-rotation angle (Easton and Sholl, 1995, Exp. 1; Presson & Montello, 1994; Rieser, 1989, Exp. 3), as well as from experiments showing increases of pointing latency and/or error as a function of the imagined self-displacement distance (Easton and Sholl, 1995, Exps. 1–4). Some authors take the fact that actors need more time and commit larger errors after imaginal self-rotations than after imaginal self-displacements as evidence that the underlying transformation processes are more simple in the case of mental translations (e.g., Rieser, 1989, argued for a direct access to spatial knowledge after translations, but not rotations), or conversely, more complex in the case of mental rotations (e.g., Presson & Montello, 1994, argued for a higher degree of computational complexity in rotations, under the assumption that a Cartesian coordinate representation is used).

1.3. Sensorimotor interference hypothesis

The *sensorimotor interference hypothesis*, on the other hand, states that imaginal perspective switches are difficult, because actors have to deal with spatial information conflicts when acting from an imagined perspective in the environment. The account does not dispute that additional cognitive computations are necessary when people perform imaginal perspectives switches, but locates the main source of difficulties in an interference conflict between real and imagined perspective; different formulations of the general idea can be found in the literature (e.g., Angyal, 1930;

Brockmole & Wang, 2003; May, 1996; Newcombe & Huttenlocher, 2000; Presson, 1987).

A specific version of the idea has recently been worked out by May (2000, 2001). May's model assumes that imaginal repositionings lead to conflicts between sensorimotor object location codes, as defined by the actor's real (i.e., bodily taken) perspective, and cognitive codes of the same object locations, as defined by the to-be-imagined perspective in space. Conflicts between the two representations are assumed to lead to interference effects during response selection as a function of the degree and type of spatial incompatibility between the competing codes of the surrounding (for discussions of incompatibility effects in different spatial tasks see Castiello, 1996; Fitts & Seeger, 1953; Logan & Zbrodoff, 1982; Lu & Proctor, 1995; Tipper, 1992).

Assuming that a pointing task is used to examine imaginal perspective switches the model makes a distinction between two independent sources of interference effects: The first source is referred to as *object direction disparity*, and can be described in terms of the angular difference between body- and task-defined egocentric object directions (which can vary in the range between 0° and 180°). For rotations, the amount of object direction disparity is equivalent to the angle of imagined self-rotation; e.g., a rotation of 90° leads to a object direction disparity of 90° between real and imagined perspective for all objects in the surrounding. For translations, the situation is more complex, since the amount of disparity depends on the relation between the actor's actual position and the critical object location, as well as on the distance and direction of the imagined self-displacement in space; e.g., for an object 5 m in front of an actor, a self-displacement of 1 m to the right leads to a disparity of about 12°, a displacement of 5 m to the right to a disparity of 45°, and so on. It is postulated that object direction disparity leads to a selection problem between incompatible action vectors during response specification, and that the magnitude of the conflict depends on the degree of angular difference between the competing vectors. More specifically, pointing responses from the imagined perspective are considered to be the final output of a conflict resolution between the incompatible response direction codes from real and the imagined perspectives; increases in interference effects as a function of the amount of object direction disparity are expected for both repositioning tasks (i.e., no conflict at 0° angular disparity, maximal conflict at 180° angular disparity).

It is important to note that there are hardly any experiments comparing rotations and translations while controlling for the amount of object direction disparity (see discussion in next section); the only published data available indicate significant performance differences between imaginal rotations and translations when the amount of object direction disparity was held constant for both (Presson & Montello, 1994).[1]

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[1] Presson and Montello (1994) reported a study with single-trial testing that examined rotations and translations while avoiding confounds with object direction disparity by testing only two different rotation and translation tasks. The authors used different floor plans with the first (A) inducing a 30°, and the second (B) inducing a 90° object direction disparity for rotation and translation tasks; results revealed significant differences in pointing accuracy and latency with participants performing better on floor plan A as on floor plan B. Unfortunately, the performance differences were not discussed in terms of object direction disparity, probably because floor plan was treated as a random variable in the experiment.

The interference model accounts for these differences by postulating a second source of interference effects, referred to as *head-direction disparity*. Head-direction disparity is assumed to be responsible for the performance differences between rotations and translations, as changes of heading between actual and tested perspective are found in rotation tasks only. Independent from the problem of deciding between the two incompatible action vectors (first interference source), the problem is one of specifying the action vector from the imagined perspective when the spatial reference system defined by the actor's current body position leads to a rotational conflict. More specifically, it is postulated that the specification of the response direction becomes more difficult because the reference system underlying the to-be-imagined facing direction is continually interfered with by misleading head-direction signals from the reference system associated with the actor's actual position in space (for a recent discussion of the neural basis of head-direction signals see Wilson, 2000).[2]

The present experiments were the first to investigate performance differences between imaginal rotations and translations when object direction disparity was under experimental control and independently varied. Of special interest was whether differences between both movement types would still be found after object direction disparity was under experimental control and of what type the differences would turn out to be (e.g., constant differences or monotonically increasing differences as a function of self-rotation angle). Prior empirical support for a sensorimotor interference account comes from experiments showing that imaginal rotations and translations are affected by object direction disparity in a similar manner (i.e., monotonic latency increases), while bodily performed rotations and translations into the same positions revealed no latency increases compared to baseline conditions without switches (May & Wartenberg, 1995). Further evidence comes from experiments showing that disorientation—actors were turned around in circles until losing track of their orientation to the surrounding—led to significantly more accurate and faster pointing responses as compared to performances of actors remaining oriented to the spatial surrounding (May, 1996); such a facilitation effect

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[2] Head-direction conflicts are conceptually related to effects found in the use of misaligned maps (e.g., Levine, Jankovic, & Palij, 1982; May, Péruch, & Savoyant, 1995), or in the use of misaligned memory representations resulting from orientation specific learning experiences (e.g., Presson & Hazelrigg, 1984; Shelton & McNamara, 1997; Sholl & Nolin, 1997). After some controversy, recent research shows that orientation specific learning episodes lead to orientation specific spatial memory representations under most circumstances (Waller et al., 2002; for exceptions see Sholl & Bartels, 2002). We prefer to draw a distinction between head-direction and misalignment effects, since misalignment disparity is usually treated as a spatial difference between a person's heading during learning and the person's heading during testing, while the concept of head-direction disparity concentrates on spatial differences between the person's real and imagined heading in the actual testing situation. Mou et al. (in press) have recently demonstrated that head-direction and misalignment conflicts can have independent detrimental effects on pointing errors and latencies. The present account leaves open how conflicts with the head direction during learning exerts influences on the retrieval and response generation processes during testing. I thank an anonymous reviewer for bringing the distinction between both kinds of heading differences to my attention.

agrees well with the assumption that disorientation relieves actors from sensorimotor interferences resulting from directionally incompatible location codes and head-direction signals when responding from an imagined spatial perspective. A recent series of experiments extended on this finding by showing that imaginal repositionings in the actual environment (bodily presence) exerted stronger detrimental effects on pointing performances as compared to imaginal switches in a remote environment the actor was not bodily attending while being tested (May, Rieser, & Young, in preparation).

1.4. Experimental comparisons of rotations and translations

Different methods have been used to test the assumptions of both theoretical accounts. Tests of transformation assumptions have generally used methods of single-trial imaginal switches. Participants are instructed to point to a target location A, as if facing towards (rotation) or standing at (translation) a reference location B; single-trial testing means that target and reference locations switch from trial to trial. In contrast, tests of interference assumptions have generally used blocked testing of multiple target locations per to-be-imagined perspective. The present studies used the method of single-trial switches, because it seems best suited to ensure that transformation processes are an effectual part of the repositioning task requirements examined, as has been shown in earlier work using this method (e.g., Easton & Sholl, 1995; Rieser, 1989). Conversely, blocked testing was not used, because it could lead to an underestimation of the role of transformational mechanisms in imaginal repositionings, since spatial transformations might be partially or completely executed at the beginning of a testing block, not revealing themselves proper anymore in the latencies and errors measured.

With the exception of a study by Presson and Montello (1994, cf. Footnote 1) experiments using single-trial testing methods have generally neglected the potential influence of disparity of egocentric object directions in imaginal perspective switching tasks. Controlling for object direction disparity does not seem critical when testing rotations, because rotation angle and object direction disparity increase proportionally. Control, however, becomes important when testing imaginal translations, or tasks that have a translational as well as a rotational component. A closer inspection of spatial tasks used in previous studies helps to illustrate the point: A reanalysis of the translation tasks examined by Rieser (1989, Exp. 3) revealed constant amounts of 38° object direction disparity for all eight, equally distant, reference locations. Finding no performance differences between the different translation conditions is therefore in agreement with a transformation account (constant distances), as well as with an interference account (constant amounts of disparity). In a similar vein, a reanalysis of Easton and Sholl's (1995) studies, in which translation distance was varied, revealed a confounding of repositioning distance and object direction disparity; for example, in their Experiment 1 distances (in feet) and corresponding disparity amounts (in °) were: 2′: 13°; 3′: 21°; 4′: 28°; 5′: 37°; 6′: 48°; 7′: 50°; 8′: 55°; 9′: 56°. Again, it is not possible to tell, whether the observed performance decreases went back to imagined self-displacement distance (transformation hypothesis), or whether they resulted from movement-induced disparities of egocentric object directions (interference hypothesis).[3]

1.5. Overview of the studies

The present studies tested imaginal rotations and translations by choosing an environmental layout that allowed to control for and independently vary the amount of object direction disparity in both repositioning tasks. The overall goal was to generate experimental results that would help to elucidate the potential contributions of transformation and interference processes to imaginal perspective switches in space.

Experiment 1 replicated Rieser's pioneering study (1989, Exp. 3) with single-trial switches, while introducing object direction disparity as an additional experimental factor. The experiment aimed at contrasting transformation and interference hypotheses with respect to the causes of extra costs in imaginal repositionings (i.e., movement type and amount versus object direction disparity and head-direction disparity). In order to reach comparable amounts of object direction disparity for rotation and translation tasks a spatial layout with separate sets of objects markers on an inner circle, and position markers on an outer circle was used (instead of a single set objects and positions arranged as a circle in previous studies). This type of layout of objects and positions provided for translation trials with large amounts of object direction disparity (i.e., by enforcing imaginal traversals of objects), that had been missing in earlier single-trial experiments. Rotations and translations were compared on the basis of a reclassification of object-position combinations into four increasing classes of disparity (0–45°, 46–90°, 91–135°, and 136–180°).

Experiment 2 changed the presentation order of position and object information used in Experiment 1, as well as in most earlier studies, from object-position to position-object; also was a variation of the time-interval between presentation of position and object information introduced (SOA of 1 s, 3 s, and 5 s). The experiment tested contradictory predictions transformation and interference hypotheses make about the possibility to process a to-be-imagined perspective in advance, that is before the target object is presented. More specifically, an account postulating cognitive transformations during imaginal self-relocation should allow for pre-processing,

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[3] Separating effects of repositioning distance and object direction disparity is not easy to accomplish. Testing random sets of objects and positions almost definitely leads to confounds between both variables as illustrated by the following considerations: Assuming random distributions of objects and positions, as well as random imaginal self-displacements and self-rotations in the testing space, random responses after translational switches lead to a positively skewed distribution of disparity values with an average amount of 40° to 50° disparity depending on the geometrical shape of the local environment, compared to an equal distribution of disparity amounts after rotational switches with an average amount of 90° disparity per object location independent of distribution of objects and positions and shape of the local environment. Thus, without further measures object direction disparity will statistically tend to be double as high in rotation as compared to translations trials. The positively skewed distribution for translations results from the comparatively low probability of complete or near traversals of objects (i.e., jumping over object locations), when performing perspective switches in random or unconstrained spatial settings.

while an account postulating interferences during response specification and selection should not allow for pre-processing.

Experiment 3 used the same experimental design, but had participants learn the environment from a topographic map instead of having them learn it by directly exploring the real-world layout. Map learning was used to ensure that actors would have to use an allocentric representation of the environment as considered important by the retrieval model of Easton and Sholl (1995; see also Sholl, 1995). In addition to the three experiments, an analysis of pointing errors is reported; the aim was to test potential distractor influences of the irrelevant (body-defined) object directions on the observed (task-defined) pointing responses.

2. Experiment 1

The first experiment was a replication of Rieser's (1989) Experiment 3 with an additional factorial variation of object direction disparity. *Disparity* was introduced as a new variable and defined in terms of angular amount of egocentric object direction difference between real and imagined perspective (0–180°). According to the mental transformation hypothesis, disparity—defined as an independent variable—should have detrimental effects on the different rotation conditions, as disparity increases proportionally to the imagined self-rotation angle. On the other hand, no effects of disparity on the different translation tasks were expected, because the self- displacement distance to all positions was held constant and the self-rotation angle was zero. Thus, monotonic increases in pointing latency and/or error as a function of disparity should be observed after rotations, but no such increases should be found after translations.[4]

According to the sensorimotor interference hypothesis, similar detrimental effects of disparity were expected for rotation and translation tasks as disparity of egocentric object directions was varied between 0° and 180° for both tasks. Thus, monotonic increases in pointing error and/or latency as a function of disparity should be observed after imaginal rotations and translations. Rotation trials were expected to show additional pointing error and/or latency increases, because of head-direction differences between the actor's real and imagined spatial perspective that are not to be found in translation trials. From an interference view, it was of special interest to see, what form the performance differences between rotation and translation tasks would take: would constant differences indicating all-or-none head-direction interference effects be found, or would the differences between both tasks hint at gradually increasing head-direction effects as a function of self-rotation angle?

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[4] The and/or-formulation of hypotheses means that effects are expected on one, or on both dependent measures. In case, an effect is only found on one variable (error or latency), an opposite effect on the other would lead to a rejection of the hypothesis. Note, that some of the earlier single-trial studies showed effects on both variables (Easton & Sholl, 1995; Presson & Montello, 1994), some only on response latencies (Rieser, 1989); furthermore, the observed pointing latencies and errors, as well as the strength of the effects observed varied considerably between different studies.

2.1. Method

2.1.1. Participants

Thirty-five male Hamburg University students with ages ranging from 20 to 34 years participated in the experiment in fulfillment of a research participation requirement in Introductory Psychology.

2.1.2. Apparatus

The experimental procedures as well as time and error measurement were controlled by a Personal Computer (80486-DX2-66 MHz). A headset for acoustical display of object and position information and a joystick for measurement of pointing responses were connected to the computer. The joystick was fixed to a tablet (40 × 30 cm), which participants wore at waist-heights stabilized by a neck and waist belt. Display of object and position names was achieved by running software-triggered sound-files standardized to 300 ms display time using a standard computer soundcard (Creative Labs Soundblaster ASP16). Measurement of pointing responses was achieved by using a self-centering analog precision joystick connected to a commercially available game card (Tandy-IBM).

Response time measurement started with the end of displaying the sound-file and ended with the initiation of the hand movement in the direction of the to-be-tested object location. Pointing latencies were measured with the help of a DOS-interrupt-routine allowing for a time resolution of about 6 ms. The computer clock was stopped when the joystick shaft was tilted approximately 5° from its vertical starting position. The direction of pointing responses was measured on the basis of the coordinates delivered by the joystick at two critical points along the hand movement trajectory. The spatial coordinates at an inner (5° tilting angle) and an outer circle (30° tilting angle) defined the starting and the endpoint of the to-be-measured hand movement trajectory (pointing direction). This setup allowed for an angular resolution of pointing responses of about 1.0° in all directions. A pair of tight-sitting skiing glasses covered with black tape was used to prevent participants from seeing the environment during testing (blindfold).

2.1.3. Experimental room and stimulus material

The experimental room (5.4 × 7.0 m) was unknown to all participants before entering the experiment. It was empty except for the stimuli, the table with the computer, and a chair for the experimenter (see Fig. 1).

Fig. 1 shows the configuration of position markers (circles labeled B, S, F, M, X, T, H, Z) and object markers (squares labeled 1–4). Positions were identified by letters printed on blue cardboard cylinders (80 cm high and 30 cm wide). Object locations were identified by numbers printed on red cardboard boxes (35 cm high and wide). Two black rectangular cardboard pieces were fixed to the floor indicating the participant's position during testing. The four object markers (squares) were placed at a distance of 150 cm, the eight position markers (circles) at a distance of 250 cm to the actor's standing position. In order to control for systematic effects of the object and position labels, as well as the position of the experimenter operating the com-

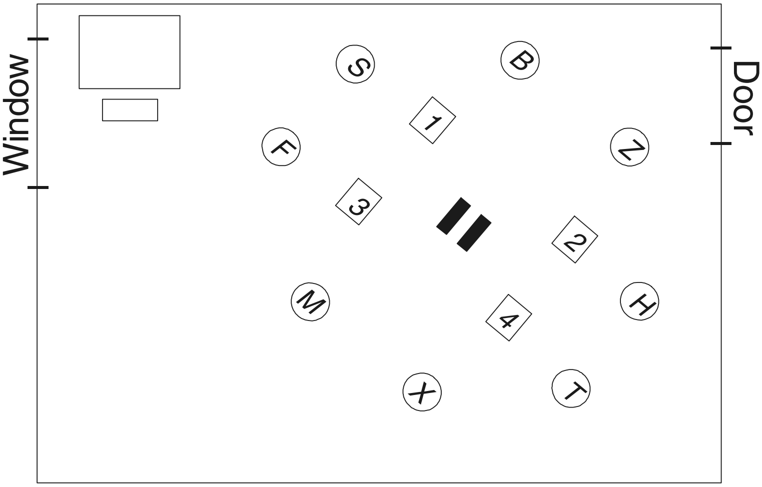


Fig. 1. Spatial layout of the testing room with object markers (squares) and position markers (circles). Actor position is indicated by the black rectangles in the middle of the configuration.

puter, half of the participants performed the task while physically facing in direction of the position markers B and Z, whereas the other half faced in direction of the position markers M and X. Since no effects of facing direction were found, both spatial tasks will be treated as if all participants had been physically facing B and Z.

In order to compare rotations and translations for equal amounts of disparity, all items for both tasks (object-position combinations) were classified as belonging to one of four classes of disparity amounts: 0–45°, 46–90°, 91–135°, or 136–180°. Mean changes in response direction corresponded to the midpoints of the categories for rotations as well for translations. For rotations, disparity depended on facing direction only (cf. Fig. 1): Facing position markers B or Z induced a change of 22.5° and was defined as small amount of disparity (0–45°); facing S or H induced a change of 67.5° and was defined as small-to-medium disparity (46–90°); facing F or T induced a change of 112.5° and was defined as medium-to-large disparity (91–135°); facing to M or X induced a change of 157.5° being classified as large amount of disparity (146–180°). For translations, disparity depended on the specific combination of object location and imagined observation point. The four classes of disparity were made up by the following sets of position-object combinations (cf. Fig. 1): small (0–45°): X1, T1, H1, F2, M2, S2, Z3, H3, T3, B4, S4, F4; small-to-medium (46–90°): M1, Z1, B2, X2, B3, X3, M4, Z4; medium-to-large (91–135°): B1, F1, T2, Z2, M3, S3, H4, X4; large (136–180°): S1, H2, F3, T4.

2.1.4. Procedure

Participants were tested individually in a session lasting 60–75 min. They were first guided to the starting position and asked to place their right and left foot onto the black cardboard markers. Here participants were given 5 min time to learn the names (i.e., numbers and letters), as well as the exact locations of the four object markers and eight position markers. Participants were asked to keep their feet on the shoe-size cardboard markers during the learning phase, but were allowed to turn their head as well as their upper body to inspect object or position markers in their surrounding. In order to secure stable knowledge they were pre-tested for objects and positions by having them point with their outstretched right arm into the direction of the requested position or object marker. In a first block, pre-testing was performed with the eyes open, in a second block, participants had to point to the markers while blindfolded. The experimenter corrected participants when their pointing judgment deviated significantly from the requested direction of an object or position. Each pre-testing block consisted of a random series of 24 trials (i.e., each position and object was tested twice).

Before starting with the experimental blocks all participants were given the chance to get comfortable with the use of the joystick as a device by pointing to different, arbitrarily chosen, objects in the testing space. They were then introduced to the rotation and translation tasks. In the rotation task, participants should point to one of the object markers as if facing towards one of the position markers; in the translation task, they should point to one of the object markers as if standing at one of the position markers while maintaining their actual facing direction in space. To make sure that they understood both instructions, they were given the chance to bodily move into one translation and one rotation perspective, and experience the consequences of both types of movements on the egocentric directions to objects in the surrounding. Participants were instructed to point as fast as possible without sacrificing pointing accuracy.

Participants then proceeded to the three experimental blocks. At the beginning of the first block, they were lead to the starting position, blindfolded and equipped with the headset as well as the joystick mounted to the tablet. Similar to Rieser (1989, Exp. 3), one experimental trial consisted of the following series of instructions realized as keywords displayed by computer-triggered sound files: (1) Object (i.e., one of the numbers “1,” “2,” “3,” or “4”), (2a) Task (i.e., either the German words “IN” for a translation, or the German word “NACH” for a rotation), and (2b) Position (i.e., one of the letters “B,” “S,” “F,” “M,” “X,” “T,” “H,” or “Z”). The time-interval between the onset of the acoustical display of the object name (1) and the onset of the display of the repositioning task (2a) was set to 1000 ms. The presentation of the position name (2b) followed immediately after the presentation of the type of task (2a) at a constant time-interval of 300 ms. Timing of pointing responses was started with the onset of the position name (2b) and was stopped when the joystick was tilted away from its self-centering position for more than 5° (tolerance range). On trials with pointing errors smaller than 40° from the correct direction a short (100 ms) positive feedback in form of a sinus tone (300 Hz) was given. No feedback was given for trials with errors larger than 40°. The next trial started 2 s later with the presentation of a new object location as target (1). Between experimental blocks, participants could take off the blindfold as well as the pointing tablet and move around freely in the testing room for a short period of time (about 2 min). Most participants used the short break to study the layout of position and object markers some more.

2.1.5. Design

The experiment constituted a complete within-subject design with two repositioning tasks (rotation vs. translation), crossed with four amounts of disparity (0–45°, 46–90°, 91–135°, and 136–180°), crossed with three amounts of training (blocks 1–3). Within each testing block all 32 object-position combinations for both tasks (rotations and translations mixed) were presented in random order (i.e., 64 trials per block). Dependent variables were pointing error (in angular degrees) and pointing latency (in milliseconds). Within-subjects medians per experimental cell (Task × Disparity × Training) were used, in order to reduce unwanted influences of outliers on both dependent measures. Pointing error was defined in terms of absolute error, i.e., unsigned arithmetic differences between observed and requested target direction (0–180°) were calculated.

2.2. Results

The data showed no signs of speed–accuracy tradeoffs, with the 35 individual Pearson product-moment correlation ranging from $r = -.16$ to +.36. Averaged pointing error for all participants were in the range of 23.8–74.2°, reflecting considerable degrees of spatial knowledge (as indicated by the significant differences to a 90° error that would be expected for random responding), but also large individual differences in overall pointing accuracy. Unless otherwise indicated, an α-level of .01 was used as the criterion for the statistical analyses in Experiments 1–3; a higher α-level was chosen, because of the large number of main and interaction effects to be tested.

2.2.1. Pointing error

Mean pointing error as a function of disparity is presented in Fig. 2, separately for rotations and translations and the three amounts of training. A within-subject analysis of variance (ANOVA) revealed significant main effects of Task, $F[1,34] = 75.61, MSE = 1662.5$, Disparity, $F[3,102] = 20.63, MSE = 544.8$, and Training, $F[2,68] = 21.4$,

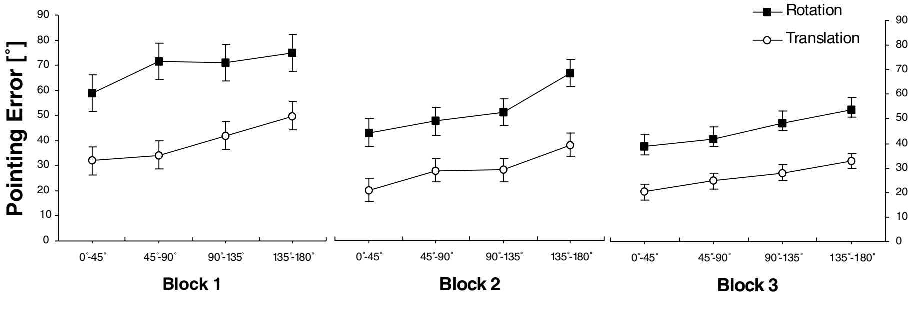


Fig. 2. Mean pointing error as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and training (blocks 1–3). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

$MSE = 1133.33$, on pointing error. None of the interactions between the three factors was significant: Task × Disparity, $F[3, 102] < 1.0, MSE = 392.6$; Task × Training, $F[2, 68] = 2.32, MSE = 849.5$; Disparity × Training, $F[6, 204] = 1.07, MSE = 309.7$; Task × Disparity × Training, $F[6, 204] = 1.15, MSE = 330.0$.

As can be seen in Fig. 2, participants became more accurate the more training they had; averaged over both tasks and disparity classes results were: 1st block: 54.3°, 2nd block: 42.1°, 3rd block: 36.0°. Planned comparisons revealed the differences in pointing errors between all three blocks of testing to be significant (1st to 2nd: $F[1, 34] = 17.54, MSE = 1179.4$; 1st to 3rd: $F[1, 34] = 27.79, MSE = 1620.2$; 2nd to 3rd: $F[1, 34] = 9.66, MSE = 540.5$). Differences of pointing accuracy between the rotation and translation tasks were found for all three amounts of training; in the first block, participants showed an overall pointing error of 69.1° for rotations and 39.4° for translations; in the second block the difference was 54.4–29.8°, and in the third 45.5–26.5°; planned comparisons revealed all three differences to be significant, $Fs[1, 34] = 38.40, 43.34, 32.88, MSEs = 1606.7, 979.8$, and 775.1, respectively.

Most importantly, participant's committed larger errors in pointing to imagined object locations the larger the amount of disparity was. Polynomials revealed significant fits for a linear trend model to the rotation data of all three testing blocks ($Fs[1, 34] = 5.30$ ($p < .05$), $23.53, 12.56; MSEs = 752.0$, 425.6, and 371.0, respectively), as well as significant fits of a linear trend model to the translation data for all three blocks ($Fs[1, 34] = 11.51, 16.00, 37.80; MSEs = 565.0, 354.3$, and 77.4, respectively); no quadratic or cubic trends were found (all p's > .11).

2.2.2. Pointing latency

Mean response time as a function of disparity is shown in Fig. 3 separately for rotations and translations and the three amounts of training. A within-subject ANOVA revealed significant main effects of Task, $F[1, 34] = 46.27, MSE = 2342633.0$, Disparity, $F[3, 102] = 6.47, MSE = 898482.4$, and Training, $F[2, 68] = 12.40, MSE = 2316246.0$, on pointing latency. None of the interactions was significant: Task × Disparity, $F[3, 102] = 1.20, MSE = 973023.1$; Task × Training, $F[2, 68] < 1.0, MSE =$

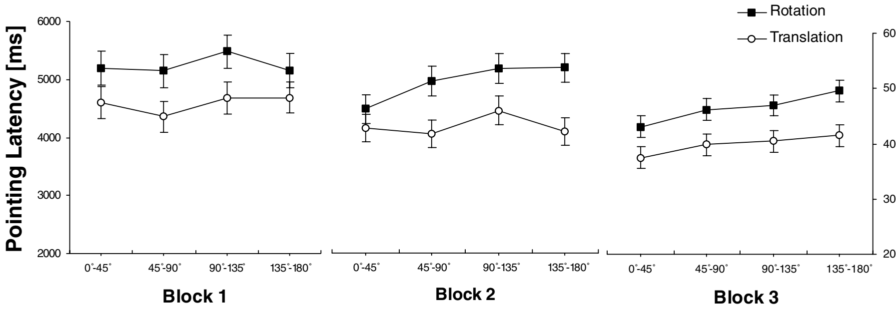


Fig. 3. Mean pointing latency as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and training (blocks 1–3). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

910646.8; Disparity × Training, $F[6, 204] = 1.98, MSE = 637072.1$; Task × Disparity × Training, $F[6, 204] = 1.03, MSE = 810759.4$.

Fig. 3 shows that pointing responses became faster with increasing amounts of training (averaged over task and disparity: 1st block: 4911 ms, 2nd block: 4802 ms, 3rd block: 4310 ms); planned comparisons revealed the difference between the second and third block to be significant, $F[1, 34] < 18.15, MSE = 2790624.0$, but no significant difference between the first and second block of testing was found, $F[1, 34] < 1.0$, $MSE = 1700221.0$. Large response time differences were found between rotation and translation tasks; in the first block participants showed an averaged latency of 5242 ms for rotations and 4582 ms for translations; in the second block the difference was 5217–4386 ms, and in the third 4642–3978 ms; planned comparisons revealed all three differences to be significant, $Fs[1, 34] = 21.93, 33.86, 22.96, MSEs = 1392192.0$, 1426880.0, and 1344855.0, respectively.

Monotonic increases in pointing latency as a function of disparity were found for half of the conditions (Task × Training) tested. Polynomial analyses revealed significant fits of a linear trend model to the rotation data of the second and third block, $Fs[1, 34] = 9.82$ and 13.42; $MSEs = 1160152.0$ and 541277.7, as well as a significant fit to the translation data of the third block of testing, $F[1, 34] = 5.01$ $(p < .05), MSE$ $= 563104.6$; no quadratic or cubic trends were found for these conditions (all p's > .14).

2.3. Discussion

In accord with earlier findings, pointing errors and latencies were significantly larger for imaginal rotations than for imaginal translations. Adding to previous research the independent manipulation of disparity led to systematic effects on pointing errors and latencies for the rotation task as well as for the translation task. For both, monotonic increases of pointing errors with increasing amounts of object direction disparity were found; monotonic increases of response times as a function of disparity were only found in the third testing block. Pointing latencies seem to have become more stable with extended training on the rotation and translation tasks, leading to a consistent picture of error and latency results on the last block of testing; in the first two blocks, participants seem to have judged faster as the objective task requirements should have allowed for, as indicated by the regular increases in pointing errors with increasing amounts of disparity for the very same pointing responses (cf. Figs. 2 and 3).

The results for the third block of testing were in good agreement with the sensorimotor interference hypothesis. The assumption that imaginal perspective switches are difficult because they force actors to cope with spatial response conflicts is supported by the very similar trends of latencies and errors found for imaginal rotation and translation tasks. The constant error differences of about 20° between rotations and translations for all three testing blocks and the constant latency differences of about 650 ms in the last testing block are compatible with the idea of an all-or-none effect of head-direction changes between real and imagined perspectives. The prediction of the transformation hypothesis that performance decreases should only be found for rotation tasks was not supported by the data. When disparity was independently varied in rotations and translations (with constant displacement distances), error and latency data revealed very similar performance decreases with increasing amounts of disparity for both tasks. Taken together it seems more reasonable to conclude that pointing performances were negatively affected by the amount of movement-induced spatial conflicts (object direction disparity, head-direction disparity) than to assume that the type or amount of imaginal movement (self-rotation or self-displacement) itself produced the effects.

3. Experiment 2

The first experiment made no attempt to answer questions related to the processing stages or mechanisms from which problems in imaginal perspective switches could result. The transformation hypothesis implies that a major part of the problems results from an early stage of task processing, namely from cognitive processes associated with the imaginal self-relocation in the environment. In contrast, the interference hypothesis suggests that problems mainly go back to later processes, namely to interference effects during specification and selection of the pointing response. Experiment 2 was designed to narrow in on the processing stages and mechanisms responsible for characteristic performance decreases observed in imaginal repositionings tasks, in general, and the disparity and task effects observed in Experiment 1, in particular.

In order to provide further tests of the contrary assumptions Experiment 2 reversed the presentation order of object and position information and varied the time-interval between position and object presentation (SOA 1–5 s); this was the first time rotation and translation tasks were examined in this way. According to the mental transformation hypothesis the availability of task and position information should allow participants to pre-process the to-be-imagined perspective; i.e., perform imaginal self-rotations and self-displacement well in advance of having to judge the object direction. The longer the SOA-interval, the more of the imaginal self-relocation process should be accomplished before the critical object location is presented. Therefore, pointing errors and/or latencies were expected to go back with increases in SOA-interval, and the more, the more difficult the imaginal repositioning task was; given enough time (SOA of 5 s) performance deficits resulting from the need to imagine self-rotations (i.e., disparity effects for rotation tasks) should largely diminish, maybe even disappear when compared to the translation task.

In contrast, the sensorimotor interference hypothesis predicts that a prolongation of the SOA-interval (1–5 s) might help participants to generally improve on the tasks, but that the characteristic processing costs related with response conflicts would remain unaffected by granting participants preparation time. The reasoning behind this prediction is that the postulated response conflict is activated at the moment the object location is presented and identified, and cannot be avoided, or in other ways resolved, beforehand (for similar considerations about the immunity of response competition effects to provision of preparation time see Rogers & Monsell, 1995). Therefore, error and/or latency differences between rotations and translations, as well as error and/or latency increases with increasing amounts of disparity were expected, independent of the length of preparation time (SOA) given.

3.1. Method

3.1.1. Participants

Thirty-six Hamburg University students (35 male and 1 female) with ages ranging from 21 to 38 years took part in the experiment in fulfillment of a research participation requirement in Introductory Psychology. None of them had participated in the previous experiment. Apparatus, stimuli, and the experimental room were the same as in Experiment 1.

3.1.2. Procedure

Differences to the previous experiment resulted from two changes of procedure. To get familiar with the apparatus and the repositioning tasks (rotation and translation) participants were allowed to perform 48 repositioning trials (2 tasks × 8 positions × 3 SOAs with random assignment of objects) before entering the three critical testing blocks. In order to avoid spatial training on the specific repositioning items used in the critical testing blocks participants were tested while standing in an arbitrary position and facing direction. The second difference concerned the presentation order of object and position information, and a variation of the presentation interval between both. One experimental trial consisted of the following series of computer-triggered acoustical keyword displays: (1a) Task (as indicated by the German word "IN" for translations or "NACH" for rotations), (1b) Position (i.e., one of the letters "B," "S," "F," "M," "X," "T," "H," or "Z"), and (2) Object (i.e., one of the numbers "1," "2," "3," or "4"). The time between the acoustical display of the type repositioning task (1a) and the display of the object name (2) was varied, and could either be 1000, 3000, or 5000 ms (SOA). Timing of pointing responses was started with the onset of the object name (2) and was stopped, when the joystick was tilted away from its self-centering position by more than 5°. As in Experiment 1, participants were given a positive acoustical feedback when the pointing error on a trial was smaller than 40° from the correct direction.

3.1.3. Design

The experiment constituted a complete within-subject design with two repositioning tasks (rotation vs. translation), crossed with 4° of disparity (0–45°, 46–90°, 91–135°, 136–180°), crossed with three SOA-intervals (1, 3, and 5 s). As in the first experiment, participants were tested in three consecutive blocks of 64 trials (2 Tasks × 4 Objects × 8 Positions). For each participant, trials were presented in random order with rotation and translation trials intermixed; SOA-interval (1, 3, and 5 s) for a given trial was randomized on the basis of all three testing blocks (192 trials). As before, dependent variables were absolute pointing error (in degrees) and pointing latency (in milliseconds).

3.2. Results

None of the participants showed signs of a speed–accuracy tradeoff, with individual Pearson product-moment correlations ranging from $r = -0.09$ to +0.29. Averaged pointing error for all participants were in the range of 17.1–53.4°.

3.2.1. Pointing error

Mean pointing error as a function of disparity is presented in Fig. 4 separately for rotations and translations and the three SOA-intervals. A within-subject ANOVA revealed a significant main effect of Task, $F[1, 35] = 44.55, \mathit{MSE} = 455.8$, and a significant main effect of Disparity, $F[3, 105] = 33.95, \mathit{MSE} = 281.6$, on pointing error. Neither the main effect of SOA, $F[2, 70] < 1.0, \mathit{MSE} = 146.9$, nor any interactions between the three factors was statistically reliable: Task × Disparity, $F[3, 105] = 2.14, \mathit{MSE} = 227.2$; Task × SOA, $F[2, 70] < 1.0, \mathit{MSE} = 100.2$; Disparity × SOA, $F[6, 210] = 1.28, \mathit{MSE} = 150.7$; Task × Disparity × SOA, $F[6, 210] < 1.0, \mathit{MSE} = 144.3$.

Fig. 4 shows a similar pattern of pointing errors as in Experiment 1 with the difference, that the overall error level as well as the rotation–translation differences was strongly reduced in the present experiment (cf. Fig. 2). For all three SOA-intervals, accuracy differences of roughly 10° were found between rotation and translation conditions (SOA 1 s: 34.0° vs. 24.4°, SOA 3 s: 32.6° vs. 23.8°, SOA 5 s: 33.9° vs. 23.1°); planned comparisons revealed all three differences to be significant ($F\text{s}[1, 35] = 38.99, 21.11, 36.99$, and $\mathit{MSE}\text{s} = 169.3, 262.3, 224.5$, respectively). Participants committed larger errors in pointing to imagined objects the larger the degree of disparity between task-defined and body-defined direction of the object location was; polynomials revealed a significant fit for a linear trend model to the rotation data ($F[1, 35] = 52.71, \mathit{MSE} = 372.9$), as well as to the translation data ($F[1, 35] = 45.30, \mathit{MSE} = 215.9$); no quadratic or cubic trends were found (all p's > .31).

3.2.2. Pointing latency

Mean pointing time as a function of disparity is shown in Fig. 5 separately for rotation and translation trials and the three SOA-intervals. A within-subject ANOVA revealed significant main effects of Task, $F[1, 35] = 17.25, \mathit{MSE} = 1787426.0$, Disparity, $F[3, 105] = 11.24, \mathit{MSE} = 2083460.0$, and SOA, $F[2, 70] = 112.54, \mathit{MSE} = 940563.0$, on pointing latency. The interaction between Task and Disparity, $F[3, 105] = 3.99, \mathit{MSE} = 1044543.0$, was also significant. All other interactions between the three factors were not significant: Task × SOA, $F[2, 70] = 2.26$, $\mathit{MSE} = 481879.3$; Disparity × SOA, $F[6, 210] < 1.0, \mathit{MSE} = 635421.4$; Task × Disparity × SOA, $F[6, 210] = 1.24, \mathit{MSE} = 489804.7$.

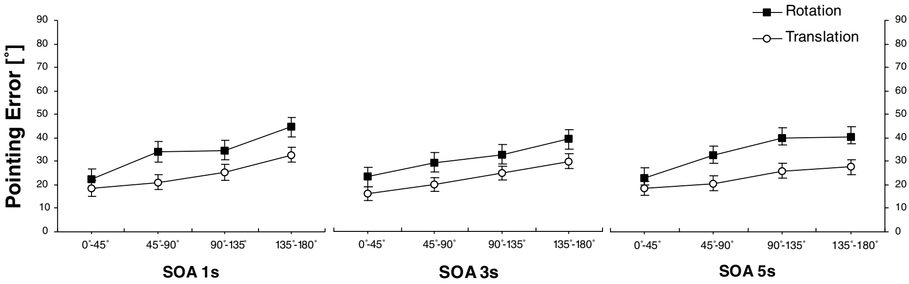


Fig. 4. Mean pointing error as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and SOA-interval between presentation of position and object information (1–5 s). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

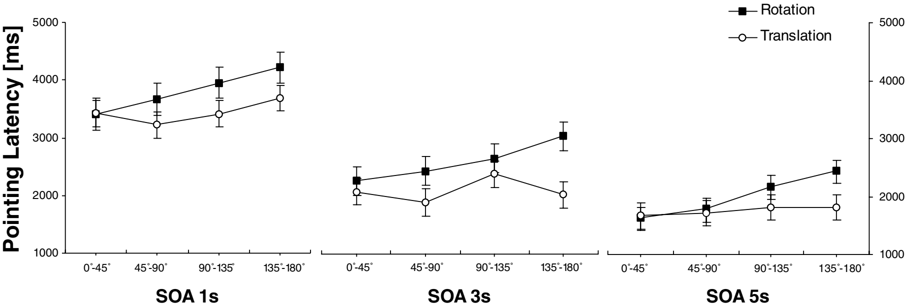


Fig. 5. Mean pointing latency as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and SOA-interval between presentation of position and object information (1–5 s). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

Fig. 5 shows that response times decreased the longer the time-interval between object and position information was (SOA 1 s: 3623 ms; SOA 3 s: 2349 ms; SOA 5 s: 1879 ms); planned comparisons revealed significant differences between all three conditions (SOA 1 s to SOA 3 s: $F[1,35] = 116.38, MSE = 2007419.0$; SOA 1 s to SOA 5 s: $F[1,35] = 135.42, MSE = 3233964.0$; SOA 3 s to SOA 5 s: $F[1,35] = 31.55, MSE = 1008999.0$). Pronounced latency differences between rotation and translation tasks were found for all three preparation intervals (SOA 1 s: 3811 ms vs. 3435 ms, SOA 3 s: 2600 ms vs. 2098 ms, SOA 5 s: 2007 ms vs. 1751 ms); planned comparisons revealed all three differences to be statistically reliable ($F\text{s}[1,35] = 10.67, 15.41, 7.58$, and $MSE\text{s} = 950188.0, 1177394.0, 623602.4$).

The significant interaction between repositioning task and disparity goes back to different effects of disparity on the speed of responding in rotation and translation trials. Separate one-way ANOVAs for the three SOA-conditions revealed significant effects of disparity in rotation tasks ($F\text{s}[3,105] = 4.55, 4.96, 11.32$, and $MSE\text{s} = 977732.6, 811180.2, 433793.8$, respectively), but not in translation tasks ($F\text{s}[3,105] = 1.94, 2.25, 0.28$, and $MSE\text{s} = 669142.5, 700147.8, 643561.6$, respectively). On rotation trials, participants needed more time to point to unseen object locations the larger the amount of disparity was; polynomials revealed a significant fit for a linear trend ($F[1,35] = 29.68, MSE = 39279784.0$), while no fits for quadratic or cubic trend models were found (all p's $> .58$).

3.3. Discussion

The results of Experiment 2 are in different respects comparable those found in Experiment 1. Participants needed more time and committed larger errors when pointing to unseen objects after imaginal rotations than after imaginal translations. Monotonic increases of pointing errors as a function of amount of disparity were found for both tasks, while monotonic increases of pointing latencies were found for rotation trials only. Participants were obviously able to use the time-interval before presentation of object information to speed up their judgments, leading to a significant reduction of response time of approximately 1.7 s between longest and shortest preparation interval (SOA 1 s vs. SOA 5 s). However, performance differences between rotation and translation tasks, as well as the detrimental effects of increasing amounts of object direction disparity on pointing errors remained unaffected by prolongations of the preparation interval as demonstrated by the lack of interactions between SOA and Task or SOA and Disparity (all *p*'s > .10).

According to different formulations of the transformation idea, problems in imaginal rotations and translations result either from the complexity of spatial transformation operations involved (Presson & Montello, 1994; Rieser, 1989), or from the spatial extent of imaginal self-relocation processes in the mental representation of the environment (Easton & Sholl, 1995). If this is correct, our participants should have been able to use the preparation interval to reduce performance decreases associated with the amount of imaginal self-rotation (reflected in amounts of disparity), as a consequence reducing performance differences between rotations and translations. The missing interactions with SOA indicate that our participants were not able to reduce the disparity or task effects with increases in SOA—this stands in clear contrast with the predictions of different formulations of the transformation account. On the other hand, the missing preparation time effects are correctly predicted by a sensorimotor interference account. The interference hypothesis predicts that any processing going on in the time-interval before presentation of object information, should not have allowed participants to avoid—or in other ways reduce—detrimental effects of object direction or head-direction disparity, because the postulated response conflict is triggered and activated at the very moment object information becomes available and begins to be processed.

A noticeable difference to Experiment 1 was that participants showed no latency increases on translation trials with increases in disparity. While the error data nicely agree with an interference assumption, the flat slopes in the latency data could be taken as evidence that object direction disparity was not effective on translation trials. However, reasons for the flat slopes could also go back to an improper choice of accuracy feedback criterion. Note, that the observed mean pointing errors dropped noticeably below 40° (i.e., acoustical feedback criterion) for all twelve translation conditions tested in Experiment 2 (3 SOA × 4 disparity conditions; see Fig. 4). This may have lead to an almost complete withdrawal of negative feedback with respect to the error sizes actually committed. If the participant's mode of responding relied to any substantial degree on the accuracy feedback given, speed of the pointing judgments may have become insensitive to the objective task difficulty as, for example, indicated by the stable error size increases as a function of disparity. In order to exclude this potential source of missing latency effects the feedback criterion was lowered from 40° to 30° in the third experiment.

4. Experiment 3

Experiment 3 repeated the previous experiment while testing participants for spatial knowledge they had learned from a topographic map instead of by inspecting the testing space directly. Learning a larger environmental layout by active real-world explorations, according to at least some authors, might allow people to build up spatial representations of the environment that are orientation independent (Presson & Hazelrigg, 1984; Rossano, Warren, & Kenan, 1995; Sholl & Nolin, 1997; but see Waller et al., 2002). It could be reasoned that participants in Experiments 1 and 2 were able to build up orientation independent representations of the testing space allowing them to make their pointing judgments on the basis of purely egocentric representations and retrieval processes (e.g., by retrieving locations from multiple perspectives represented in long-term memory). This would have allowed them to avoid allocentric representations and retrieval processes altogether in Experiments 1 and 2, so that an important prerequisite of Easton & Sholl's retrieval model (viz. participation of allocentric representations and retrieval processes) might not have been met with. To make sure that allocentric representations and retrieval processes were involved, Experiment 3 examined whether comparable results would be found when actors learned the spatial layout from a topographic map before being tested in the real-world setting. Predictions of the transformation and interference accounts were the same as in Experiment 2.

4.1. Method

4.1.1. Participants

Twelve Hamburg University students (7 male, 5 female), 24–36 years old, participated in the experiment in partial fulfillment of a research participation requirement in Psychology. None of the participants had taken part in Experiment 1 or 2.

Apparatus, *stimuli*, and *experimental room* were the same as in previous experiments. Learning of the spatial layout was accomplished by using a topographic map (1:10) of the spatial layout printed on white cardboard (see Fig. 6). The map

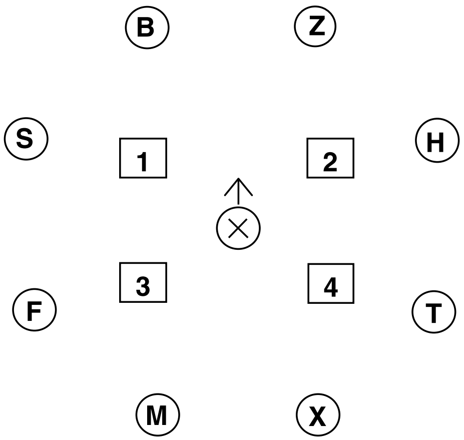


Fig. 6. Topographic map (1:10) of the spatial layout of objects (squares) and positions (circles) used for learning in Experiment 3. The circle with a cross indicates the physical position of the actor during testing.

represented object and position markers as squares and circles with the top of the map corresponding to the direction the participants would be facing towards in the testing phase of the experiment to follow (in terms of Levine et al., 1982, an aligned map of the testing space was used).

4.1.2. Procedure

The main difference to Experiment 2 was that participants learned the testing space from a map instead of exploring it directly. Instruction and training in the use of the joystick as well as learning of the spatial layout from the map was accomplished in a separate room before entering the testing room with the critical repositioning tasks. Participants were given 10 min to learn the layout of object and position markers from the map. During the first 5 min participants were free to memorize the spatial information given on the map, the second 5 min were used for three short cycles of testing the complete set of four object and eight position marker locations while the map was covered with a piece of white cardboard, and providing visual feedback by uncovering the map again. During the learning and pre-testing session the map was attached to a table, forcing participants to learn the layout from a fixed orientation with the position markers B and Z on the top side of the cardboard (see Fig. 6). As in the previous experiments the spatial knowledge was tested in the real-world environment. Participants were blindfolded before entering the testing room, lead into the middle position of the configuration and asked to place their feet on the cardboard markers (see Fig. 1). Participants were told that they were positioned in the middle position of the layout they had learned from the map and that they were surrounded by cardboards indicating the object and position markers in distances between 1 and 3 m. They were not allowed to leave this position or take the blindfold off before all three testing blocks with imaginal repositionings were completed.

A smaller procedural change concerned the acoustical feedback given on positive trials; it was tightened up from 40° to 30° pointing error per judgment, in order to make it more effective on the easier translation trials. As in earlier experiments, participants were asked to respond as fast as possible without sacrificing accuracy of their responses.

4.2. Results

None of the participants showed signs of speed–accuracy tradeoffs, with individual Pearson product-moment correlations ranging from $r = +0.03$ to +0.22. Observed overall pointing errors per participant ranged between 27.2° and 68.4°, again revealing considerable interindividual differences.

4.2.1. Pointing error

Mean pointing error as a function of disparity is shown in Fig. 7 separately for rotations and translations and the three SOA-intervals. A within-subjects ANOVA revealed a significant main effect of Task, $F[1,11] = 51.17, MSE = 578.0$, as well as a significant main effect of Disparity, $F[3,33] = 11.57, MSE = 378.9$, on pointing

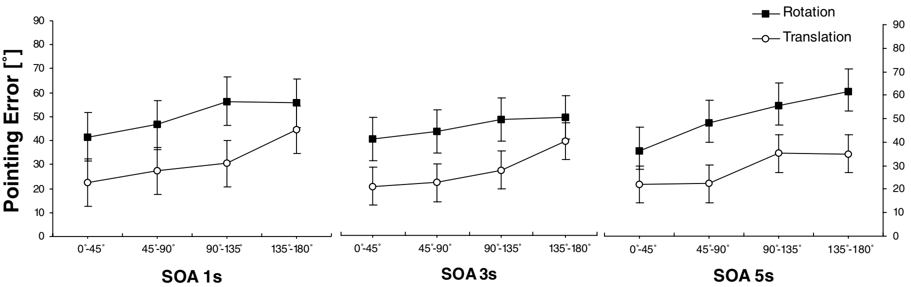


Fig. 7. Mean pointing error as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and SOA-interval between presentation of position and object information (1–5 s). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

error. Neither the main effect of SOA, $F[2,22] < 1.0, MSE = 206.2$, nor any interactions between the three factors were statistically reliable: Task × Disparity: $F[3,33] < 1.0, MSE = 402.4$; Task × SOA: $F[2,22] < 1.0, MSE = 408.7$; Disparity × SOA: $F[6,66] < 1.0, MSE = 345.2$; Task × Disparity × SOA: $F[6,210] < 1.0$, $MSE = 402.3$.

Fig. 7 shows accuracy differences of roughly 20° between rotation and translation tasks for all three SOA-intervals (SOA 1 s: 50.1° vs. 31.2°; SOA 3 s: 51.0° vs. 30.7°; SOA 5 s: 50.4° vs. 28.7°); planned comparisons revealed all three differences to be significant (Fs$[1,11] = 14.31, 34.70, 21.90$, and MSEs $= 597.7, 284.8, 512.95$, respectively). Again, participants committed larger errors when pointing to unseen object locations the larger the degree of disparity was. Polynomials revealed a significant fit for a linear trend model to the rotation data ($F[1,11] = 16.63, MSE = 347.8$), as well as to the translation data ($F[1,11] = 17.89, MSE = 406.1$); no quadratic or cubic trends were found (all p's > .31).

4.2.2. Pointing latency

Mean pointing latency as a function of disparity is shown in Fig. 8 separately for rotation and translation trials and the three SOA-conditions. A within-subjects

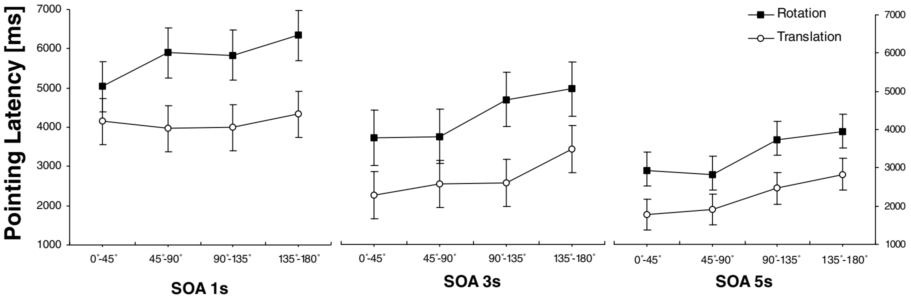


Fig. 8. Mean pointing latency as a function of repositioning task (rotation vs. translation), amount of disparity (0–45°, 46–90°, 91–135°, and 136–180°), and SOA-interval between presentation of position and object information (1–5 s). Error bars indicate 95% confidence intervals (Loftus & Masson, 1994).

ANOVA revealed significant main effects of Task, $F[1,11] = 21.76, MSE = 7140175.0$, Disparity, $F[3,33] = 9.91, MSE = 1466547.0$, as well as SOA, $F[2,22] = 46.14$, $MSE = 2453852.0$, on pointing latency. None of the interactions between the three factors was significant (Task × Disparity, $F[3,33] < 1.0, MSE = 2469552.0$; Task × SOA, $F[2,22] = 2.03$, $MSE = 1153403.0$; Disparity × SOA, $F[6,66] < 1.0$, $MSE = 1103038.0$; Task × Disparity × SOA, $F[6,66] < 1.0, MSE = 1234362.0$).

Fig. 8 shows that latencies decreased with increasing preparation intervals (SOA 1 s: 4943 ms, SOA 3 s: 3564 ms, SOA 5 s: 2800 ms); planned comparisons revealed the differences between all three SOA-conditions to be significant (SOA 1 s to SOA 3 s: $F[1,11] = 50.03, MSE = 1823017.0$; SOA 1 s to SOA 5 s: $F[1,11] = 68.58$, $MSE = 3213523.0$; SOA 3 s to SOA 5 s: $F[1,11] = 12.06, MSE = 2325017.0$). Significant response time differences between rotation and translation trials were found for all three intervals (SOA 1 s: 5776 ms vs. 4109 ms, SOA 3 s: 4380 ms vs. 2749 ms, SOA 5 s: 3355 ms vs. 2246 ms); planned comparisons revealed all three differences to be statistically reliable ($F\text{s}[1,11] = 24.20, 19.30, 8.73$, and $MSE\text{s} = 2755931.0, 3310097.0, 3380954.0$, respectively). Moreover, participants took more time to point to object locations the larger the degree of disparity was. Polynomials revealed a significant fit for a linear trend model to the rotation data ($F[1,11] = 7.94, MSE = 4013310.0$), as well as to the translation data for SOA-intervals of 3 and 5 s ($F[1,11] = 7.79, MSE = 2086605.0$); no quadratic or cubic trends were found (all p's > .37).

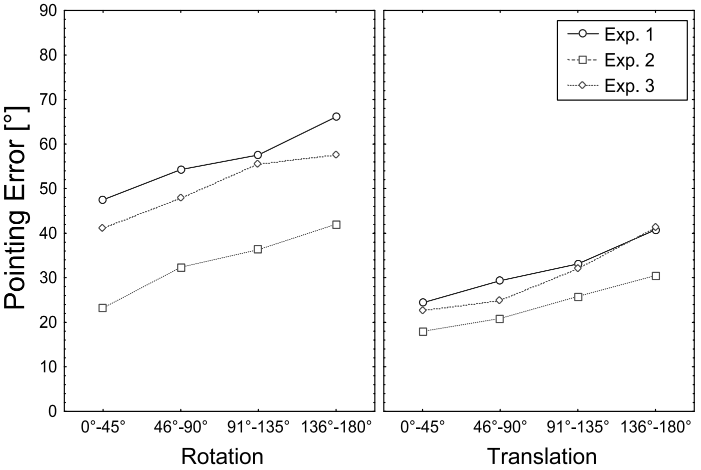
4.3. Discussion

The pattern of results was in many respects comparable to the one found in Experiment 2. Again, participants needed more time and committed larger errors after imaginal rotations than after imaginal translations. Monotonic and linear increases of pointing errors and latencies as a function of disparity were found for most experimental conditions, a notable exception being the pointing latencies for translations with a SOA of 1 s (see Fig. 8). The stricter formulation of the feedback criterion (30° instead of 40°) seems to have made participants response times somewhat more sensitive to the objective task difficulty (as reflected in the better correspondence of errors and latencies compared to Exp. 2), but still did not lead to a fully consistent picture of the results for both measures.

As in previous experiments, results ran counter to expectations from different formulations of a mental transformation hypothesis, while agreeing quite well with predictions formulated on the basis of a sensorimotor interference hypothesis; i.e., monotonic increasing effects of object direction disparity, rotation–translation differences indicating independent effects of head direction changes. Finding shorter response times for longer SOA-intervals indicates that participants were able to use preparation time to speed up their pointing responses, leading to a response time reduction of about 2.1 s between the longest and the shortest SOA-interval. Differences between rotation and translation tasks and differences in the slopes of the disparity effects remained unaffected by extensions of the SOA-interval, as can be seen from the lack of any signs of interactions between Task and SOA, or Disparity and SOA (all p's > .15). Whatever the additional processing going on during the preparation interval was, it did not allow participants to reduce the detrimental effects resulting from manipulations of task and disparity to any notable degree.

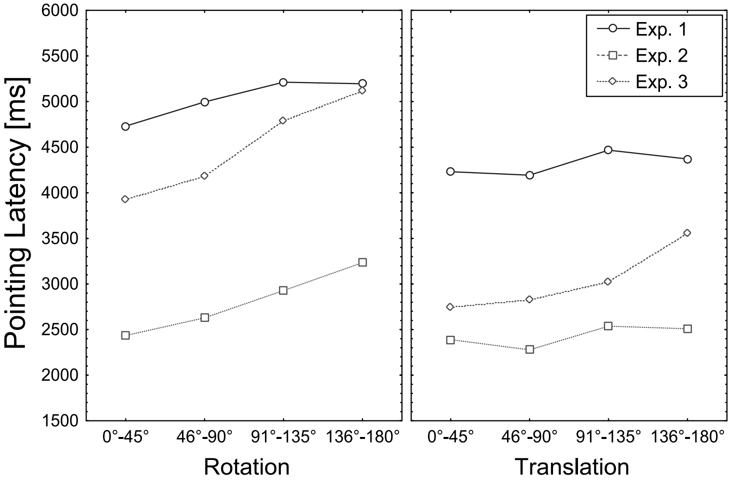
5. Interexperimental comparisons of disparity and task effects

An overarching analysis of the data from all three experiments was performed in order to examine effects of presentation order (Exp. 1: object-position; Exps. 2 and 3: position-object) and learning method (Exps. 1 and 2: exploration; Exp. 3: map learning) on the results, in general, and disparity and task effects, in particular. Mean pointing errors and latencies for Experiments 1–3 split down by disparity and task are summarized in Figs. 9 and 10.



Exp. No.	Presentation Order	Learning Method	Rotation			Translation		
			a	b	r^2	a	b	r^2
1	Obj. – Pos.	Explore	44.5	**.13**	.98	21.3	**.12**	.98
2	Pos. – Obj.	Explore	21.4	**.13**	.97	15.3	**.10**	.99
3	Pos. – Obj.	Map	39.2	**.13**	.96	17.5	**.14**	.94

Fig. 9. Summary of pointing errors found in Experiments 1, 2, and 3. Top: Mean pointing error as a function of disparity for rotation and translation tasks. Bottom: Intercepts a, slopes b and explained variance r^2 of the linear functions ($y = a + b^*x$) relating absolute error sizes to amount of disparity (in angular degree); slopes b indicate pointing error sizes (in angular degree) as a function of disparity (in angular degree).



Exp. No.	Presentation Order	Learning Method	Rotation			Translation		
			a	b	r^2	a	b	r^2
1	Obj. – Pos.	Explore	4712	**3.6**	.86	4176	**1.6**	.50
2	Pos. – Obj.	Explore	2266	**6.0**	.99	2304	**1.4**	.45
3	Pos. – Obj.	Map	3662	**9.4**	.98	2506	**5.9**	.87

Fig. 10. Summary of pointing latencies found in Experiments 1, 2, and 3. Top: Mean pointing latency as a function of disparity for rotation and translation tasks. Bottom: Intercepts a, slopes b, and explained variance r^2 of the linear functions ($y = a + b^*x$) relating response times to amount of disparity (in angular degree); slopes b indicate pointing error sizes (in angular degree) as a function of disparity (in angular degree).

5.1. Pointing error

A mixed ANOVA with Experiment as between-subjects variable and Task and Disparity as within-subjects variables revealed significant main effects of Experiment, $F[2,80] = 16.88, MSE = 3154.4$, Task, $F[1,80] = 129.13, MSE = 985.5$, and Disparity, $F[3,240] = 49.51, MSE = 406.8$, on pointing error. A significant interaction between Experiment and Task, $F[2,80] = 12.13, MSE = 985.5$, was also found. Further significant interactions between the three factors were not found: Experiment × Disparity, $F[6,240] < 1.0, MSE = 406.8$; Task × Disparity, $F[3,240] = 1.08, MSE = 321.6$; Experiment × Task × Disparity, $F[6,240] < 1.0, MSE = 321.6$.

Planned comparisons of errors between Experiments 1 and 2 showed that participants committed larger errors when object information was presented before position information ($F[1,80] = 31.45, MSE = 3154.4$); this effect did not depend on the overall longer SOA-interval in Experiment 2 (average SOA of 3 s), as can be seen from the significant difference between the last testing block of Experiment 1 (with SOA 1 s) and the shortest preparation interval (also SOA 1 s) in Experiment 2 ($Ms = 36.0°$ vs. 29.2°; Tukey's HSD; $p < .02$). Comparing error sizes between Experiments 2 and 3 revealed that participants committed larger pointing errors when the spatial layout was learned from a map as compared to participants exploring the testing environment directly ($Ms = 40.4°$ vs. 28.6°; $F[1,80] = 9.42, MSE = 3154.4$); error size increases due to map learning were significant for rotations ($Ms = 33.5°$ vs. 50.5°; $F[1,80] = 11.99, MSE = 2608.0$), but not for translations ($Ms = 23.8°$ vs. 30.2°; $F[1,80] = 2.93, MSE = 1531.9$; $p > .09$).

The slopes of the linear functions relating pointing error to disparity showed that differences of presentation order and learning method had little influence on the error increases as a function of disparity (see Fig. 9, bottom). Finding no two- or three-way interactions with Disparity (all p's > .35) underscores the stability of the linear slopes for errors over all three experiments. Pronounced pointing error differences between rotation and translation tasks were found in all three experiments, the interaction between Task and Experiment going back to comparatively smaller errors on rotation tasks in Experiment 2 as compared to rotations tasks in Experiments 1 and 3. Preparation time in combination with exploratory learning (Exp. 2) obviously allowed participants to improve on overall pointing accuracy, although differences between rotations and translations still remained significant ($Ms = 33.5°$ vs. 23.8°; $F[1,80] = 20.60, MSE = 985.5$).

5.2. Pointing latency

The same mixed ANOVA showed significant main effects of Experiment, $F[2,80] = 13.61, MSE = 66439204.0$, Task, $F[1,80] = 102.44, MSE = 275939.0$, and Disparity, $F[3,240] = 28.84, MSE = 995001.6$, on pointing latency. The analysis also revealed significant interactions between Experiment and Task, $F[2,80] = 11.75$, $MSE = 2759392.0$, Experiment and Disparity, $F[6,240] = 2.89, MSE = 995001.6$, and Task and Disparity, $F[3,240] = 3.33, MSE = 1210086.0 (p < .05)$; the three-way interaction between the factors was not significant, $F[6,240] < 1.0, MSE = 1210086.0$.

Comparing latencies between Experiments 1 and 2 revealed that participants needed significantly more time when object information was displayed before, and not after, position information ($F[1,80] = 27.14, MSE = 66439204.0$); the effect did not result from an overall prolonged SOA-interval (Exp. 2) as revealed by the significant difference between the last testing block of Experiment 1 and the SOA-1 s-interval in Experiment 2 ($Ms = 4310$ ms vs. 3623 ms; Tukey's HSD; $p < .001$). Comparing latencies between Experiments 2 and 3 showed that participants needed significantly longer to point to unseen objects when they had learned the spatial layout from a map as compared to exploratory learning in the testing space ($Ms = 3769$ ms vs. 2617 ms; $F[1,80] = 4.32, MSE = 66439204.0; p < .05$). Latency increases for map learning were significant for rotations ($Ms = 4504$ ms vs. 2806 ms; $F[1,80] = 8.18, MSE = 38075824.0$), but not significant for translations ($Ms = 3035$ ms vs. 2428 ms; $F[1,80] = 1.28, MSE = 31122770.0$).

The slopes of the linear functions relating pointing latency to disparity also revealed differences between experiments. Slopes in Experiments 1 and 2 (learning by direct experience) were generally flatter as the slopes found in Experiment 3 (map learning); separate ANOVAs (Experiment × Disparity) revealed significant interactions when comparing Experiments 1 and 3 ($F[3, 135] = 5.29, MSE = 1037343.0$), and Experiments 2 and 3 ($F[3, 138] = 2.77, MSE = 1066342.0; p < .05$), but no reliable interaction when comparing Experiments 1 and 2 ($F[3, 207] = 1.19, MSE = 919828.0$). The flatter slopes in Experiment 2 resulted mainly from the translation conditions as indicated by a separate ANOVA (Task × Disparity) showing a significant interaction ($F[3, 105] = 4.00, MSE = 1044543.0$); the same analyses for Experiments 1 and 3 indicated slope differences between rotations and translations to be not significant (both p's > .30), although visually slight differences seem to exist (cf. Fig. 10).

5.3. Discussion

The interexperimental comparisons provide insights into modifications of results by presentation order (i.e., advance object information is less useful than advance position information), and learning method (i.e., map learning makes imaginal repositionings more difficult). Most importantly, interexperimental comparisons reveal that Disparity and Task were the two main factors determining the accuracy and the latency of the participants' pointing performances. The interference hypothesis explains the monotonic increasing slopes in pointing errors and latencies by postulating spatial incompatibility conflicts, the strength of which depends on the amount of disparity of egocentric object directions between real and imagined perspective. Significant and very similar error slopes as a function of disparity were found for rotation and translation tasks in all three experiments. Significant and quite comparable latency slopes as a function of disparity were found in Experiments 1 and 3 for both tasks, however in Experiment 2 only for the rotation task. A sufficient familiarity with the task (see discussion in Exp. 1) and the choice of an appropriate feedback criterion (see discussion in Exp. 2) seem to be necessary conditions for obtaining monotonic increases of pointing errors *and* latencies on rotation *and* translation trials (Exp. 3). Although none of the three experiments showed signs of speed–accuracy tradeoffs, speed of responding seems to have been more affected by strategical decisions on the side of the participants than was the case for the level of accuracy reached.

Averaged over all three experiments very stable error differences were found between rotation and translation tasks for the four disparity amounts put to test (δ's = 15.7°, 19.8°, 19.4°, 17.7°, respectively), while latency differences between both tasks increased with increasing amounts of disparity (δ's = 576, 838, 967, 1039 ms, respectively). The constant accuracy differences between rotations and translations seem compatible with the idea of an additional—in the sense of all-or-none—interference effect, while the monotonic increasing differences between rotations and translations seem to hint at interference effects that take the amount of head-direction disparity between real and imagined perspective into account. The present data do not permit to give a definite answer on the kind of the mechanisms underlying head-direction conflicts, as the increasing latency differences between both tasks are directly linked to the overall flatter slopes found under translation conditions, which have been discussed critically on methodological grounds. Overall, the error data seem more trustworthy than the latency data, but further research is needed to pin down the exact nature of the mechanisms leading to differences between imaginal rotations and translations.

6. Circular analysis of pointing errors

In order to learn more about the alleged interferences during response specification and selection, a qualitative analysis of pointing errors was performed on the combined data from Experiments 1 and 2. The data from the first two experiments were chosen, because they are comparable in sample size ($N = 35$ and 36, respectively), and hereby allow for generalization over different presentation orders (object-position vs. position-object). The leading question for the error analysis was whether pointing responses to the imagined object location (target) were influenced by the egocentrically defined object location in sensorimotor space (distractor). In principle, two kinds of systematic influences between target and distractor are conceivable: (1) *Attractor effects*, i.e., the distractor influences the observed response by pulling it into its own direction and away from the target. (2) *Repellor effects*, i.e., the distractor influences the observed response by pushing it to the opposite side of the target away from the distractor. A neurologically plausible basis for both types of influences is provided by the concept of directional population vectors underlying hand-movements in premotor and motor cortices (see Georgopoulos, 1995; Tipper, Howard, & Houghton, 2000).

6.1. Method

The sensorimotor interference account does not specify the type of effect expected, but leads to the more general prediction that because of the postulated cross-talk between sensorimotor and cognitive codes during response specification and selection significant attractor and/or repellor influences should be observed. Attractor effects would be expected if the influence of the distracting sensorimotor code could not be fully avoided, repellor effects, if the influence of the distracting sensorimotor code was overcompensated during response specification and selection. To test for attractor or repellor biases, the pointing responses were analyzed with a statistical approach introduced by Batschelet (1981, pp. 3–31). Circular statistics treats goal-directed spatial behavior as observations that can be broken down into a systematic component, defined as mean polar angle, and a stochastic component, defined as mean polar radius. The systematic component describes the averaged pointing direction of a set of responses; to obtain a quantitative measure (θ) we calculated the mean angular departures of the observed pointing responses from the requested target direction. Systematic pointing errors in direction of the distractor (i.e., attractor effects) were defined as positive errors (+), systematic pointing errors in the direction opposite to the distractor (i.e., repellor effects) were defined as negative errors (−). The stochastic component is described in form of a concentration measure (R) that can vary between 0.0 and 1.0; the smaller the R-value, the higher the dispersion of the directional responses.[5]

6.2. Results

A similar pattern of systematic and stochastic errors was found for the vertically symmetric left-side (object 1 and 3) and right-side (objects 2 and 4) target items; e.g., B1 is a mirror-reflection of Z2, Z1 of B2, S1 of H2, S2 of H1, and so on (cf. Fig. 6). Pearson product-moment correlations confirmed the correspondence of results between the 32 left-side and the 32 right-side targets with respect to systematic errors ($r = 0.84; p < .001$), as well as concentration of pointing responses ($r = 0.79; p < .001$). In order to reduce the complexity of the analysis, data from corresponding left- and right-side targets were combined by mirror-reflecting target direction, distractor direction, and observed pointing direction about the vertical axis; such a combination of data also helped to reduce potential biases resulting, for instance, from left or right sided hand-movements preferences on the side of the participants. For practical purposes, the resulting 32 items (position-object combinations) will be spatially referred to as if participants had been tested for the right-side target objects 2 and 4, only.

Examples of circular error distributions for selected rotation and translation items are presented in Fig. 11; the full list of 32 items with θ- and R-values is given in Table 1.

6.2.1. Systematic errors in pointing responses

An ANOVA (Task × Disparity) on the absolute size of systematic errors (unsigned θ) showed a significant main effect of Task, $F[1, 56] = 39.99, MSE = 114.0$, as well as a significant main effect of Disparity, $F[3, 56] = 3.58, MSE = 114.0, p < .02$; the interaction between Task and Disparity was not significant ($F[3, 56] = 1.54, MSE = 114.0$). Pointing responses after imaginal rotations ($M = 25.4°$) revealed larger systematic errors than pointing responses after imaginal translations ($M = 7.0°$). The magnitude of

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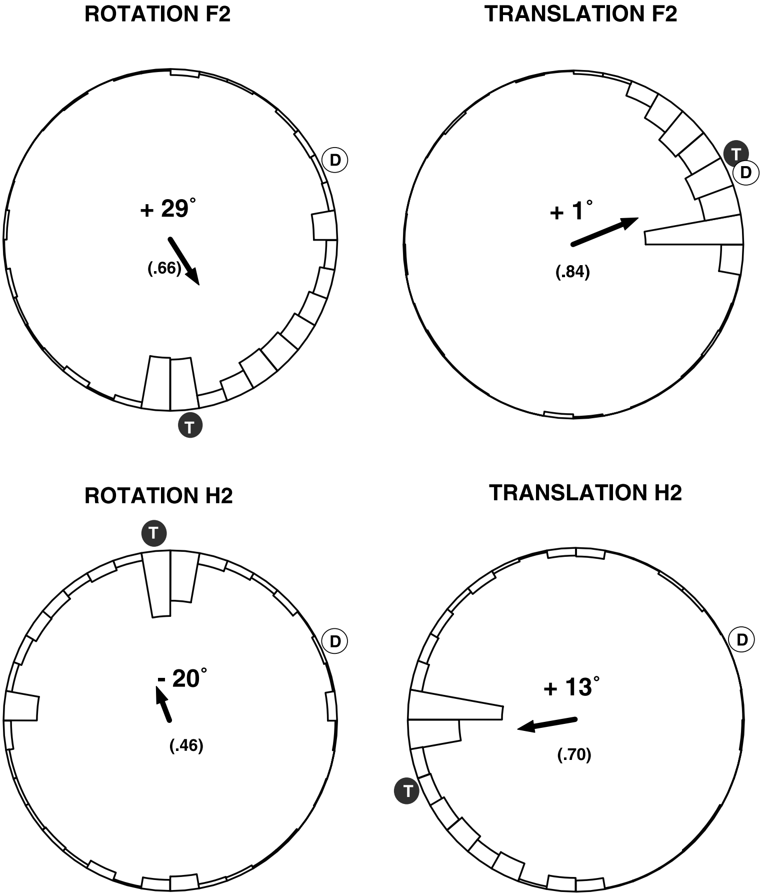
[5] In accord with earlier studies, the present experiments used absolute error (*AE*; unsigned absolute deviation from target direction) as a dependent measure. Schutz and Roy (1973) discussed problems in spatial interpretation of this type of error, as absolute error (*AE*) intermixes systematic error components, generally known as constant error (*CE*), with stochastic error components, generally known as variable error (*VE*). The standard procedure to separate both is to request repeated measurements per participant and condition. Depending on experimental design and other circumstances this can be troublesome (e.g., excessive testing), or otherwise not desirable (e.g., training effects that modulate experimental effects under scrutiny). An advantage of applying Batschelet's circular statistics is, that it allows for a post-hoc separation of *CE* (equivalent to θ) and *VE* (equivalent to $1 - R$). For the present data, the following correlations were found: *AE* with *VE*, $r = .89, p < .001$; *AE* with *CE*, $r = .16, p > .38$; and *CE* with *VE*, $r = .07, p > .71$. Thus, the systematic error measure (*CE*) and the concentration measure (*VE*) used for the present analysis describe independent aspects of the pointing behavior observed.



ROTATION F2

TRANSLATION F2

ROTATION H2

TRANSLATION H2

Fig. 11. Circular plots of pointing response distributions for two different combinations of position and object (F2 and H2) on rotation and translation tasks. Graphs depict the egocentrically defined target (T) and distractor (D) in the actor's surrounding. Frequency histograms of pointing responses are shown for 10° segments of the complete 360° surrounding; the radius of the circle corresponds to $N = 200$ responses. Note, that each plot encloses the responses of the corresponding left- and right-side target items (T1 = F2 and S1 = H2) as resulting from a mirror-reflection about the vertical axis through the actor's position. The entire set of all 32 graphs can be downloaded and printed from the following Web site: http://www.unibw-hamburg.de/PWEB/psyifk/mm/circular32.pdf.

systematic errors showed a monotonic increase over the four amounts of disparity for rotations (*M*s = 14.7°, 24.9°, 29.2°, 33.0°, respectively) and a systematic increase for translations for disparity amounts in the three larger classes (*M*s = 6.5°, 4.1°, 7.6°, 13.3°).

Table 1 summarizes the systematic error biases for the complete set of 32 combinations of positions and objects. A majority of the items (20 out of 32) showed significant biasing influences of the distractor on the pointing response observed; most of the biases (14 of 20) resulted from attractor effects (8 rotations, 6 translations), but

Table 1
Systematic error (θ) and concentration (R) of pointing responses in Exps. 1 and 2

Rotation			Translation		
Pos./Obj.	θ	R	Pos./ Obj.	θ	R
B2	+6	.69	B2	+2	.74
S2	**+15**	.67	S2	**+6**	.82
F2	**+29**	.66	F2	+1	.84
M2	**+37**	.65	M2	+3	.80
Z2	+3	.52	Z2	−3	.73
H2	**−20**	.45	H2	**+13**	.70
T2	**−31**	.59	T2	**−14**	.75
X2	**−44**	.61	X2	+1	.73
B4	−9	.74	B4	0	.78
S4	0	.70	S4	**+7**	.80
F4	**+32**	.64	F4	**+12**	.79
M4	**+30**	.48	M4	**+9**	.75
Z4	**+35**	.69	Z4	+2	.78
H4	**+53**	.48	H4	−3	.69
T4	**+26**	.36	T4	**+14**	.71
X4	**−21**	.36	X4	**−11**	.71

Note. Values in boldface indicate significant response biases in angle degrees θ towards (+) or away from (−) the distractor direction ($p < .01$; Batschelet, 1981, p. 81).

a few (6 of 20) also resulted from repellor effects (4 rotation, 2 translation). In other respects, the pattern of attractor and repellor effects is quite complex; it is, for instance, not grounded in universal effects of factors such as repositioning task, amount of disparity, target location, imagined position, as revealed by separate one-way ANOVAs on systematic errors (signed θ) showing that none of these factors had a significant influence on the pattern found (all Fs < 2.8; all p's $> .11$).

Regularities in the complex pattern of effects can be found if spatial trajectories of the actor's imaginal repositioning movements in the environment are taken into account (cf. Table 1 and Fig. 6). Significant attractor effects were generally found when the actor imagined moving away from the target object, no matter if the imaginal movement was a rotation (S2, F2, M2, F4, M4), or a translation (S2, S4, F4, M4), or when imaginal movements approached the target object, but the target did not switch to the opposite side of the actor's imagined facing direction (Rotation Z4, H4, T4). Significant repellor effects were found when the actor imagined approaching the target object, and it switched sides relative to the imagined facing direction (Rotation H2, T2, X2, X4; Translation T2), or ended up midline (Translation X4). The only exception to both observations were the two translation items, where actors had to imagine jumping over the target (H2 and T4), leaving open, whether the target switched sides in frontal half-space; the significant attractor effects found in both cases might be an artifact resulting from stereotyping of responses to the exact left in both cases (see Fig. 11, Translation H2 for an illustration).

6.2.2. Concentration of pointing responses

An ANOVA (Task × Disparity) on the concentration of pointing responses (R) showed significant main effects of Task, $F[1,56] = 47.85, MSE = 0.007$, and Disparity, $F[3,56] = 5.64, MSE = 0.007$; the interaction between both factors was not significant ($F[3,56] < 1.0, MSE = 0.007$). Pointing responses after rotations ($M = .592$) showed a reduced amount of concentration as compared to translations ($M = .746$). Concentration of responses decreased monotonically with increases in disparity for rotations (Ms $= .668, .594, .574, .531$, respectively), as well as for translations (Ms $= .808, .751, .721, .703$, respectively).

6.3. Discussion

Participants were more inaccurate (systematic error) as well as more imprecise (stochastic error) when pointing to unseen object locations after rotations than after translations. Furthermore, their pointing responses became more inaccurate and imprecise the larger the directional disparity of object locations between real and imagined perspectives was. A closer inspection of the pattern of systematic error biases revealed that two rules suffice to account for the complex pattern of attractor and repellor effects observed: Attractor effects were found when the imaginal movement in testing space receded from the target object, or when it approached the target object without having the target switch sides in frontal egocentric space (12 of 14 significant attractor effects). Repellor effects were found when the imaginal movement approached the target object, while it switched sides in frontal egocentric space or at least nearly did so (6 of 6 significant repellor effects). Finding systematic influences of the distractor provides support for the idea of a cross-talk between cognitive code (target) and sensorimotor code (distractor) during response specification and selection. In its present formulation the sensorimotor interference hypothesis does not specify the mechanisms leading to a resolution of response conflicts in imaginal perspective switches. Further going assumptions that are compatible with the pattern of biases found will be described and discussed below.

7. General discussion

The goal of this research was to test different hypotheses with respect to the processes underlying imaginal perspective switches in remembered environments. The independent variation of object direction disparity helped to clarify the pattern of findings that needs to be explained by tenable accounts of the mechanisms underlying imaginal perspective switches. Three of the present findings are especially critical for evaluating current explanations: (1) Monotonic increases of response errors and/or latencies for rotations and translations as a function of the disparity of object directions between real and imagined perspective (disparity effects); (2) absolute differences in response errors and/or latencies between corresponding rotation and translation conditions (task effects); (3) no substantial changes in both effects when pre-processing of perspectives was made possible by displaying position and

Table 2
Summary of expected and observed experimental effects

Experimental effect	Expected effects				Observed
	Transformation			Interference	
	Rieser (1989)	Presson and Montello (1994)	Easton and Sholl (1995)	May (2000)	
Self-rotation angle	YES	YES	YES	YES	YES
Self-displacement distance	?	?	YES	?	?
Object direction disparity	?	?	?	YES	YES
Rotation–translation differences	YES	YES	?	YES	YES
Pre-processing of perspective	YES	YES	YES	NO	NO
Systematic error biases	?	?	?	YES	YES

Note. Question marks stand either for "no statement made by the account" or for "not tested in present experiments."

task information well in advance of object information (missing interaction effects with SOA).

As summarized in Table 2, the present results are in good agreement with a sensorimotor interference account, while deviating in different points from a mental transformation account of imaginal perspective switches in remembered space.

7.1. Tests of mental transformation hypothesis

Different formulations of the mental transformation hypothesis (Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989) predict monotonic—or linear—increases of pointing errors and/or latencies for imaginal rotations, while no such increases are expected for imaginal translations when the repositioning distance is held constant. Of special interest for evaluating the mental transformation hypothesis was the finding that imaginal translations were negatively affected by the amount of object direction disparity; monotonic increases in pointing errors were documented by the significant linear trends for all 9 conditions tested in the three experiments (cf. Figs. 2, 4, 7), monotonic increases in latencies were found in at least 3 of the 9 tests conducted (cf. Figs. 3, 5, 8). The prediction of the transformation account that the chance to pre-process a to-be-imagined perspective should help participants to reduce specific processing costs, was not confirmed by the present results; greater savings in errors and/or latencies should have been found for rotations as compared to translations, and for rotations the larger the imagined self-rotating angle was. Contrary to this prediction, the present studies revealed no signs of a reduction of disparity or task effects for preparation intervals (SOA) up to 5 s; neither for rotations, nor for translations were decreases of slopes observed, although a significant reduction of pointing latencies (1.7 s in Exp. 2; 2.1 s in Exp. 3) indicated that a substantial amount of advance processing was going on (e.g., memory retrieval or transformation of position location code).

Both results together call in question that mental transformation accounts are very successful in explaining the full spectrum of processing problems associated with imaginal perspective switches in remembered surroundings. As shown in Table 2 predictions of self-rotation angle effects and rotation–translation differences do not allow to differentiate between transformation and interference hypothesis (see further discussion below). Table 2 also reveals that the imaginal superpositioning assumptions (Easton & Sholl, 1995) was only partially put to test in the present experiments; it would be good, if future experiments would go beyond the present research and test translation tasks with a variation of the self-displacement distance while simultaneously varying the amount of object direction disparity called forth by the imaginal self-displacement in the environment.

7.2. Tests of sensorimotor interference hypothesis

The sensorimotor interference hypothesis (May, 2000, 2001) was more successful in accounting for the pattern of results found (see Table 2). The disparity effects in rotation and translation tasks are accounted for by postulating interferences between incompatible directional codes associated with the body-defined and task-defined spatial perspectives. This is in good agreement with the monotonic disparity effects found in all rotation tasks as well as in most of the translation tasks. The absolute rotation–translation performance differences were accounted for by postulating additional interferences due to head-direction differences between real and imagined perspective. According to an interference hypothesis, no modifications of the disparity and task effects with increases of preparation time (SOA) were expected because detrimental response incompatibility conflicts are assumed to be evoked at the moment the object is identified (i.e., after the SOA-interval), and therefore should not be avoidable by any form of anticipatory processing. As can be seen in Table 2, other results, such as self-rotation angle effects (independent of disparity effects) or systematic error biases agree well with an interference hypothesis.

Although certainly in need of further development (e.g., specification of conflict-resolution mechanisms) a sensorimotor interference account seems promising, because it is able to provide a consistent explanation of the whole picture of results found. The most problematic result for an interference account were the discrepant latency and error data, especially the finding that disparity did not always lead to increases in pointing latencies in translation tasks (see Exp. 1, blocks 1 and 2; Exp. 2, all three SOAs; and Exp. 3, SOA of 1 s). Although the present results leave no doubt that object direction disparity had detrimental effects on imaginal repositionings, it remains unclear whether methodological reasons (e.g., problematic choice of accuracy feedback criterion) were responsible for the differences between both dependent measures, or whether the latency data have to be generally treated with caution, because the response speed was to a large degree under the strategic control of the participants without properly reflecting the objective task requirements (e.g., greater difficulty with increasing amounts of disparity was ignored or subjectively not experienced in translation tasks). Only further research will be able to bring light into questions related to the discrepancies between error and latency results.

Going beyond the present studies an interference account seems useful because it helps to account for performance differences between imaginal perspective switches and locomotor switches, in which actors are allowed to bodily move into the to-be-imagined perspectives before having to point to unseen objects in the surrounding. In studies comparing both types of perspective switches no performance decreases as a function of object direction disparity or repositioning amount (rotation angle or translation distance) were found when actors were allowed to physically move into the new perspective before having to answer (see e.g., May & Wartenberg, 1995; Rieser, 1989; Rieser et al., 1986, for tests with different methods). Such a finding agrees well with the assumption of response-based conflicts, since memory retrieval and associated mechanisms would also have to play a role when actors physically move into the testing position without having visual support from the surrounding. A sensorimotor interference account gives a quite parsimonious explanation in assuming that spatial conflicts do not emerge under locomotor conditions, because body-defined (sensorimotor) and task-defined (cognitive) location codes never become incompatible when actors physically move into the to-be-imagined perspective (see research on spatial updating, e.g., Farrell & Robertson, 1998; May & Klatzky, 2000).

7.3. Differences between rotations and translations

An important reason for running rotation as well as translation tasks was to be able to generate an unbiased picture of the relative performances in both tasks when disparity of object directions was under experimental control. Although not conclusive in all points, the present results make clear that imaginal rotations are more difficult than imaginal translations (i.e., significant differences in pointing latencies, systematic and stochastic pointing errors), implying that there are fundamental processing differences between both tasks even when effects of object direction disparity have been taken out of the picture.

It is important to note that the present results stand in conflict with the assumption that imaginal rotations are more difficult than imaginal translations because translations allow for a direct access to object locations, while rotations produce extra costs due to additional processes (Rieser, 1989). The object direction disparity effects for translation tasks are not compatible with such an account. On the other hand, the results do not stand in direct conflict with Presson and Montello's (1994) assumption of transformational complexity differences between rotations and translations; i.e., if spatial representations are based on Cartesian coordinates, rotation tasks will be more difficult, because the underlying transformations are computationally more complex (similar considerations can already be found in Rieser, 1989). Also, there is no direct conflict with Easton and Sholl's (1995) superpositioning model in this point, because the model does not necessarily predict rotation–translation differences, but would assume that differences would depend on the relative difficulty of mental self-rotations and self-displacements (which would be considered as an independent empirical question).

Nonetheless, we think that the present results are easier to accommodate by an account that is grounded in response-based conflicts, considering that the missing effects of pre-processing (SOA) discredit retrieval- or transformation-based explanations to a considerable degree. Head-direction disparity between real and imagined perspectives provides a straightforward explanation for the rotation–translation differences. Unfortunately, the present data do not allow to be more specific on the nature of head-direction conflicts; the error data suggest all-or-non interference effects, the latency data seem to hint at slightly increasing effects as a function of the amount of head-direction disparity (equal to self-rotation angle). For reasons already discussed, further research will be needed to pin down the exact nature of the mechanisms responsible for performance differences between rotations and translations.

7.4. Task components in memory-based imaginal perspective switches

Using the data from the studies with SOA-manipulation (Exps. 2 and 3) a tentative decomposition of processing costs into three components is possible.[6]

A first part of costs resulted from processes of *object identification and localization* as well as from processes related to *motor response generation*. These costs reflect basic processing requirements of a memory-based object localization task and can be estimated to be roughly of the size of the mean response time for the easiest translation condition when imaginal processing requirements are minimal (i.e., Translation/SOA 5 s/Disparity 0–45°-conditions). Observed response times were about 1.5 s in Experiment 2 and 1.8 s in Experiment 3, making up for approximately 36% and 29% of the response latency observed for the hardest rotation condition when processing requirements are maximal (cf. Rotation/SOA 1 s/Disparity 135–180°-conditions).

A second part of costs resulted from processes of *position identification and localization* as well as from processes associated with *imaginal self-relocation* in remembered space (for further going considerations see, e.g., Sholl, 1995, 2001). Related costs can be appraised by the additional response time needed under translation conditions without advance provision of perspective information (i.e., difference between conditions Translation/SOA 1 s/Disparity 0–45° and Translation/SOA 5 s/Disparity 0–45°). Observed response times were about 1.8 s in Experiment 2 (42% of total) and 2.3 s in Experiment 3 (37% of total).

The third and last part of costs resulted from *spatial response conflicts* and processes associated with resolving these conflicts (for further going considerations see, e.g., May, 2000, 2001). Related costs were variable and depended on the amount of object direction disparity (0–180°), and the type of repositioning task (rotation vs. translation). Maximal costs can be esteemed by the additional time requirements for the hardest rotation condition (i.e., difference between conditions Rotation/SOA 1 s/ Disparity 135–180°/Rotation and Translation/SOA 1 s/Disparity 0–45°). Observed response times were 0.9 s in Experiment 2 (22% of total) and 2.2 s in Experiment 3 (34% of total).

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[6] The present analysis has to be seen as provisional: Costs related to position retrieval and imaginal self-relocation might be somewhat underestimated, as the smallest SOA-interval of 1 s allowed for some pre-processing of position information. Costs related to response conflicts might also be underestimated, as the Disparity 0–45° conditions tested presumably were not completely free of response conflicts.

Thus, about 70% of the total processing time resulted from processes directly related with requirements of imaginal switches of perspective. The somewhat larger part of these costs (roughly 40%) went back to processes of position-related memory retrieval, and a somewhat smaller part (up to about 30%) to processes associated with overcoming the spatial conflicts induced by the imaginal repositioning task; the latter were variable and depended on the type of repositioning task and the amount of object direction disparity evoked by the to-be- imagined perspective. It is important to note, that the present studies do not—and also do not claim to—show that processing demands of imaginal perspective switches resulted from spatial response conflicts alone; as the task analysis indicates, transformation and interference processes both play a role in imaginal switches of spatial perspectives. The present studies show that factors that have previously been considered to be important for defining the difficulty of imaginal perspective switches (i.e., self-rotation angle and self-displacement distance), can be more concisely explained in terms of spatial incompatibility conflicts (i.e., object direction and head-direction disparity).

7.5. Egocentric and allocentric spatial representations

The question whether human navigation, in general, and imaginal perspective switches, in particular, rely on egocentric, i.e., self-centered, or allocentric, i.e., environment-centered, processes and representations, or on both, is discussed controversially in the literature (e.g., Shelton & McNamara, 2001; Sholl, 2000; Wang & Spelke, 2000; Woodin & Allport, 1998). The present studies focused on egocentric response conflicts called forth by imaginal perspective switches in the immediate surrounding, and therefore contributed to questions of the underlying spatial reference systems only indirectly. Taken together, the data suggest that egocentric as well as allocentric reference systems played a role in the perspective switching tasks examined. Such a hybrid basis of the performances in imaginal repositionings is compatible with assumptions formulated within the body-centered spatial retrieval model of Easton and Sholl (1995; see also Sholl, 1995, 2000, 2001), as well as with other recent models on the relation between egocentric and allocentric representations and processes (May & Klatzky, 2000; Mou et al., in press; Wang & Spelke, 2002).

To make sure that a central assumption of Easton and Sholl's retrieval model (i.e., participation of allocentric retrieval processes) was fulfilled, Experiment 3 used map learning. The overall pattern of results (i.e., Disparity-, Task-, and SOA-effects) turned out to be very similar to the one found in Experiments 1 and 2 where participants were allowed to explore the spatial layout directly. Nonetheless, learning conditions (direct experience vs. map study) seem to have influenced participants performances as revealed by the differences in absolute and relative costs of the different part processes. Map learning led to generally increased processing costs with the strongest relative increase in costs associated with processes of resolving spatial response conflicts (only 0.9 s in Exp. 2, but 2.2 s in Exp. 3). The largest part of this effect resulted from an increased difficulty of the rotation task (see Fig. 10), which according to the sensorimotor interference account is to be interpreted as an enforced head-direction conflict between actual and imagined perspective. This is, however, not the only possible interpretation for the specific differences observed between Exps. 2 and 3; they could also result from differences between the participants heading during learning (maps normally induce a heading corresponding to the upward direction on the map) and the to-be-imagined heading during testing. The present data do not allow to decide between both interpretations.

Recently, Mou et al. (in press) reported a nicely designed series of experiments that allowed them to distinguish between costs related to actual-to-imagined heading differences and costs related to learned-to-imagined heading differences. Their results demonstrated that both types of heading differences independently contribute to extra costs in terms of pointing errors and latencies, and that these extra costs were of comparable size in both cases. If one utterly overlooks that participants in our Experiments 1 and 2 had the chance to turn their upper bodies and heads while studying the layout, their perspective during learning was very much the same as their perspective during testing in all three experiments. Therefore, the present experiments do not allow to distinguish between the contributions of actual-to-tested and learned-to-tested perspective differences. Future investigations of imaginal perspective switches should try to account for the separate contributions of actual-to-tested and learned-to-tested heading differences. As the present work shows it would be most instructive to study the separate contributions of both types of head direction disparities by testing imaginal rotations and translations while independently varying the amount of object direction disparity.

7.6. Resolution of spatial response conflicts

The data from the error analysis supported the assumption that response conflicts during imaginal repositionings can be understood as a spatial competition between target and distractor codes. The task-defined object direction (target) wins, but the body-defined (distractor) exerts some influence on the observed pointing response. It seems interesting to ask whether the complex picture of significant response biases (14 attractor and 6 repellor effects) found, can tell us something about the mechanisms responsible for the resolution of spatial response conflict between target and distractor direction. The most direct way the response system could try to resolve the target-distractor competition would be to amplify or strengthen the cognitive direction code (target) until it is strong enough to win over the irrelevant sensorimotor direction code (distractor). A more indirect way of response conflict resolution would be to have the response system inhibit or suppress the distracting sensorimotor direction code until it becomes relatively weak, letting the task-relevant cognitive direction code win (for similar considerations in the context of selection-for-action problems see Allport, 1987). The amplification assumption is fully compatible with finding attractor effects, but has problems to account for repellor effects; it is hard to see how a strengthening of the target code alone would lead to responses deviating significantly to the opposite side of the distractor. The inhibition assumption, on the other hand, is able to take care of a picture of mixed, attractor and repellor effects, as can be seen from recent research on action-based mechanisms of attention (Tipper et al., 2000).

Tipper et al. (2000) used the concept of directional population vectors (Georgopoulos, 1995) to model response biases of distractors on goal-directed spatial behavior. Their experiments examined the influence of an irrelevant visual stimulus (distractor) on the spatial trajectory of hand- and eye-movements. Attractor effects were found on hand-movement trajectories (assuming a low potency of the visual distractor), and repellor effects on eye-movement trajectories (assuming a high potency of the visual distractor). The attractor effects were accounted for by postulating lateral inhibition mechanisms; i.e., activation compromise between competing directional population vectors. The repellor effects were explained by assuming an independently operating reactive inhibition mechanisms; i.e., potent distractors produce greater levels of self-inhibition of the distractor allowing for a activation compromise to the opposite side of the distractor.

The systematic response biases found in the present experiments (see Table 1 and discussion of systematic errors there) lend themselves to a similar interpretation. A parallel becomes apparent if one analyzes the perspective switching task in terms of imaginal movement trajectories, and if one assumes that the actors' imaginal line of sight functions similarly as the attentional focus in the Tipper et al. study. The error analysis revealed that attractor effects were generally found when the critical object location (defined as a target) remained in the periphery of the imaginal line of sight of the actor (8 rotation and 4 translation items). Repellor effects, on the other hand, were generally found when the critical object location entered the imaginal line of sight shortly before the actor reached the to-be-imagined perspective (4 rotation and 2 translation items). Although certainly speculative and in need of further experimental testing, the idea of a spatial conflict resolution by inhibition of the task-irrelevant code (distractor) seems in better agreement with the present data on systematic response errors as the idea of a pure amplification of the task-relevant response code (target). It is interesting to note, that the idea of inhibitory mechanisms corresponds nicely with recent developmental accounts of performances in spatial conflict situations (e.g., Diamond, 1990; Harnishfeger, 1995; Thelen et al., 2001).

7.7. Complexity of the spatial response

Pointing tasks using a joystick or a rotating dial have been widely used in chronometric experiments on imaginal perspective switches; they allow for a variety of directional responses in the 360°-surrounding, and are especially favorable when experiments aim at examining response errors in addition to response times (for a comparison of different pointing methods see Haber, Haber, Penningroth, Novak, & Radgowski, 1993). So far, experimental comparisons of imaginal rotations and translations using other response methods as joystick- or dialer-based pointing judgments are still missing, although different alternative response modes are conceivable and have been used in other studies on perspective switching; e.g., pointing with an outstretched arm or cane, verbal description in terms of clock-face labels, categorized front-back-left-right judgments, or counting objects in the imaginal field of view. Tests with behaviorally different or spatially less complex responses would be useful to generalize experimental results and to learn more about the nature of the underlying response-conflict-resolution mechanisms.

7.8. Conclusions

Difficulties people encounter when imagining spatial perspectives different from the one they are actually positioned at, seem to result from response conflicts activated by incompatible, cognitive and sensorimotor, location codes of objects in the surrounding. Cognitive transformations of location codes also play a role in imaginal perspective switches, but, as the present results suggest, are not able to explain major performance deficits typically observed in imaginal repositionings tasks (e.g., extra costs as a function of the spatial relation between real and tested perspectives, and the type of movement between perspectives). Systematic research along the lines of a sensorimotor interference account is still widely missing, but seems promising for reaching a better understanding of the processes underlying imaginal perspective switches in remembered environments. Some of the open research questions have been addressed in the preceding discussion.

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