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Effective Rotations: Action Effects Determine the Interplay of Mental and Manual Rotations

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The last decades have seen a growing interest in the impact of action on perception and other concurrent cognitive processes. One particularly interesting example is that manual rotation actions facilitate mental rotations in the same direction. The present study extends this research in two fundamental ways. First, Experiment 1 demonstrates that not only manual rotations facilitate mental rotations but that mental rotations also facilitate subsequent manual rotations. Second, Experiments 2 and 3 targeted the mechanisms underlying this interplay. Here, manual steering wheel rotations produced salient visual effects, namely the rotation of either a plane or a horizon in an aviation display. The rotation direction of these visual effects either did or did not correspond to the direction of the manual rotation itself. These experiments clearly demonstrate an impact of sensory action effects: Mental rotations facilitate manual rotations with visual effects of the same direction (as the mental rotation), irrespective of the direction of the manual rotation. These findings highlight the importance of effect anticipation in action planning. As such they support the contentions of ideomotor theory and shed new light on the cognitive source of the interplay between visual imagery and motor control.

Keywords: action control, mental rotation, ideomotor theory, imagery, aviation psychology

Human beings are able to act in two fundamentally different ways: either overtly by generating motor output or covertly by performing mental operations. Although at first glance motor and mental actions appear to be distinct, there is in fact a rich interplay between them. For example, motor actions have an impact on perceptual and attentional processes that can be facilitatory (e.g., Deubel, Schneider, & Paprotta, 1998; James, Humphrey, & Goodale, 2001) or detrimental (e.g., James & Gauthier, 2009; Müsseler & Hommel, 1997; Pfister, Heinemann, Kiesel, Thomaschke, & Janczyk, in press; for an integrative perspective, see Thomaschke, Hopkins, & Miall, 2011).

Influences of motor actions on mental processes become particularly apparent with commensurate tasks from both domains, such as the combination of manual and mental rotations. We first briefly review this research. We then introduce a theoretical framework—ideomotor theory—that accounts for such influences. This framework predicts that not only manual rotations affect mental rotations but, conversely, that mental rotations affect manual rotations as well. Moreover, it suggests that the sensory consequences of these actions rather than the manual actions themselves are critical for this impact. These predictions derived from ideomotor theory are tested in three experiments in an aviation setting.

Taken together, this research demonstrates how the ideomotor mechanism of sensory anticipation in action control can explain reciprocal effects of action and perception, thereby bridging several seemingly separate disciplines, such as motor control, visual imagery, and human factors research.

Interactions of Manual and Mental Rotations

The process of mental rotation (i.e., imagining object changes in two- or three-dimensional space) has received a vast amount of interest since Shepard and Metzler's (1971) seminal study. The finding of slower responses with greater angles of required (mental) rotation was taken to suggest that mental rotation bears similarities to continuous physical rotation. Indeed, mental rotations appear to be performed at a relatively high level of processing (Jolicoeur & Cavanagh, 1992), possibly involving mechanisms of action planning.

This putative link was subsequently demonstrated in experiments where mental rotations were facilitated when a manual rotation in the same direction was performed either briefly before the mental rotation (Wohlschläger & Wohlschläger, 1998) or con-

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currently with the mental rotation (Wexler, Kosslyn, & Berthoz, 1998). Moreover, merely planning a manual action seems sufficient to facilitate mental rotations in the same direction (Wohlschläger, 2001; but see Sack, Lindner, & Linden, 2007, for possible limitations). In addition to these immediate interactions, a recent training study demonstrated a more sustained influence, as manual rotation training improved subsequent mental rotation performance (Wiedenbauer, Schmid, & Jansen-Osmann, 2007). Thus, there is ample evidence for an interaction between manual and mental rotations. In the following, we refer to the facilitatory effects of identical rotation directions on either mental or manual rotations as the *mental-manual rotation congruency (MMRC)* effect.

A clear formulation of the functional link between mental and manual rotation was put forward by Wexler et al. (1998), who stated that "mental rotation is a covert simulation of motor rotation" (p. 78). This claim is in line with neuroimaging studies that found motor-related areas to be active during mental rotation, clearly suggesting a functional role of motor processes for such tasks (e.g., Alivisatos & Petrides, 1997; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; see Zacks, 2008, for a recent meta-analysis). Furthermore, Wexler et al. proposed that "visuomotor anticipation is the engine that drives mental rotation" (p. 79). This notion also points toward a direct link to ideomotor theories of action control, which place special emphasis on the anticipation of sensory action effects (Hoffmann, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001). The implications of an ideomotor account of the MMRC effect are discussed in the following section.

Ideomotor Theory and the Role of Effect Anticipations in Motor Planning

Ideomotor theory puts strong emphasis on the role of contingent action effects for motor control, i.e., on the proprioceptive, visual, auditory, and other sensory consequences that reliably accompany a motor action. It is widely acknowledged that action effects play an important role as feedback for online movement control, such as correcting an initially imprecise grasping movement (e.g., closed-loop theory: Adams, 1971; schema theory: Schmidt, 1975; feed-forward models: Wolpert, Ghahramani, & Jordan, 1995). This *evaluative* function of action effects becomes relevant only during movement execution. Ideomotor theory, in contrast, assumes that action effects also have a *generative* function in action control. The crucial point is that, with a sufficient number of action-effect encounters, a motor action becomes so closely associated with its effects that the action will eventually become cognitively represented in terms of its effects. Once such links have been established, a certain action is retrieved by recollecting its perceptual consequences. In particular, the anticipation of an intended effect primes the movement that brings about this effect. These effects need not be body-related (e.g., tactile or proprioceptive reafferences) but can be of any kind (e.g., visual or auditory "distal" effects), provided they follow the movement sufficiently reliably. Initial formulations of this idea date back to the 19th century (Harleß, 1861; Herbart, 1825; James, 1890/1981; for historical comments, see Pfister & Janczyk, in press; Stock & Stock, 2004), but only in recent decades has ideomotor theory attracted considerable scientific attention (for a recent review, see Shin, Proctor, & Capaldi, 2010).

Support for the role of anticipated action effects for action planning comes from studies on response-effect (R-E) compatibility: It is easier to produce actions that predictably produce consequences that are compatible rather than incompatible with the action itself. An example is illustrated in Figure 1A: An imperative stimulus (e.g., a colored dot) calls for a response with the left key. In one condition (R-E compatible mapping), this keypress triggers a visual effect on the left side of the display. In another condition (R-E incompatible mapping), the effect occurs on the opposite side. Responses are faster with the compatible than with the incompatible mapping—the *R-E compatibility effect* (Kunde, 2001; Kunde, Koch, & Hoffmann, 2004; Pfister, Kiesel, &

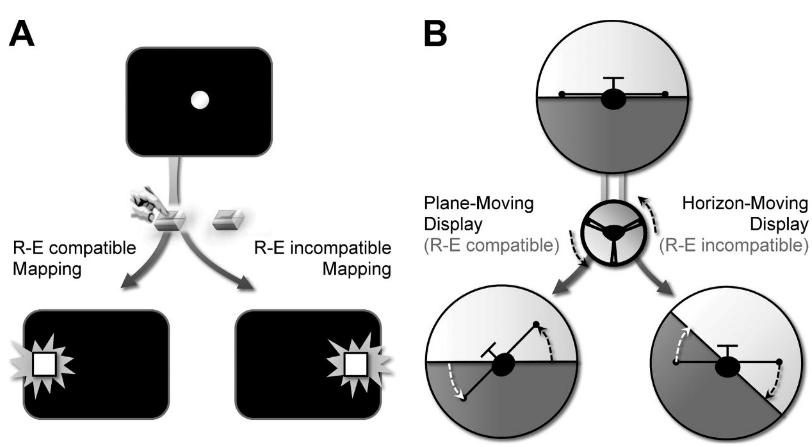

Figure 1. (A) An example of compatible and incompatible spatial response-effect (R-E) mappings. (B) Two possible versions of an artificial horizon: a plane-moving display where the horizon remains fixed and a horizon-moving display where the plane remains fixed. With the plane-moving display, control wheel and plane always move in compatible directions (counterclockwise in this example). With the horizon-moving display, by contrast, control wheel and horizon always move in incompatible directions (e.g., a counterclockwise rotation of the control wheel makes the horizon rotate clockwise).

Melcher, 2010). In general, the term *compatibility* refers not only to an overlap of spatial features but to an overlap on any dimension of action features and features of action-contingent effects (Kornblum, Hasbroucq, & Osman, 1990). Consequently, similar R-E-compatibility effects have been demonstrated for other types of overlap, such as intensity, duration, or semantic features (Koch & Kunde, 2002; Kunde, 2001, 2003; Rieger, 2007). The action effects only follow the action in time, and hence their impact on response times must be based on an anticipated representation of the action effects. Two relevant preconditions for this phenomenon are that (a) the overlap between actions and effects is sufficiently high and (b) the action effects are actually attended (cf. Ansorge, 2002). In sum, R-E compatibility influences suggest that the effects of an action are indeed cognitively represented before the action is executed.

This ideomotor mechanism offers a parsimonious explanation for the MMRC effect (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). As noted above, it assumes that planning a manual rotation movement is actually a mental imagery process, or to use William James' words, "an anticipatory image, then, of the sensorial consequences of a movement . . . is the only psychic state which introspection lets us discern as the forerunner of our voluntary acts" (James, 1890/1981, p. 501). Thus, when a rotation movement is planned briefly before a mental rotation task, ideomotor theory assumes that in fact two mental rotations take place subsequently: First, an anticipation of the rotating action effects (i.e., visual images of the moving arms and anticipation of proprioceptive feedback) as part of movement planning, and second, the mental rotation proper. It is known that mental rotation processes prime each other when the rotations are in the same direction and when they are performed in close temporal succession (e.g., Jolicoeur, 1990; Wan, Chen, Wu, & Qian, 2011). Consequently, the mental rotation involved in movement preparation primes the subsequent mental rotation, which manifests as the MMRC effect.

In addition to parsimoniously explaining previous findings on the interplay of manual and mental rotation, ideomotor theory yields several rather counter-intuitive predictions. First, it predicts that not only a manual rotation should affect subsequent mental rotations but that a mental rotation might also facilitate the subsequent mental rotation that is required for selecting and producing a manual rotation movement. Second, ideomotor theory predicts that it is not the manual rotation per se that interacts with mental rotation but rather the imagined sensory consequences of the manual action. These action features were confounded in all previous studies. A hand moving clockwise is naturally linked to (anticipated) proprioceptive and visual effects that suggest a clockwise rotation as well. To de-confound the role of actions and their consequences, one needs conditions where, for example, a clockwise manual action produces a visual effect rotating counterclockwise. Such conditions are established in the present study and were to some extent inspired by aviation psychology, which provides a more or less realistic means to address the present research question.

Overview and Predictions of the Present Experiments: An Example Inspired by Aviation

An important instrument in aviation is the attitude indicator, or artificial horizon, which informs the pilot about the plane's orientation relative to ground. Of particular interest to the present study is roll indication (i.e., the aspect informing the pilot about deviations from the horizontal position). Two versions of the attitude indicator predominate (Previc & Ercoline, 1999; see Figure 1B): In the *plane-moving* display, the horizon remains fixed and the plane rotates around its center. In the *horizon-moving* display, by contrast, the plane remains fixed and the horizon rotates to indicate deviations from the horizontal position.[1] The horizon-moving display is prevalent in Western military and civilian aircrafts, as it mimics what a pilot actually sees out of the cockpit.

With a plane-moving display, manual action and visual action effects have the same rotation movement: Turning the control wheel counterclockwise turns the plane in the display counterclockwise as well (cf. Figure 1B, bottom left). For disentangling the role of manual actions and action effects, the horizon-moving display is more interesting. Here, turning the control wheel counterclockwise turns the visual horizon clockwise (cf. Figure 1B, bottom right). If the control wheel action is represented by its visual effects—as proposed by ideomotor theory—turning the wheel counterclockwise would involve the anticipation of a clockwise visual rotation (and vice versa). Consequently, the facilitating influence that a mental rotation has on an orientation-congruent manual rotation might attenuate or perhaps even reverse with a horizon-moving display.

To summarize, we derived two predictions from ideomotor theory that are tested in the following three experiments:

- Experiment 1 tests the prediction that not only do manual rotations facilitate mental rotations in the same direction but that the reverse relationship is also true, and a mental rotation will facilitate the production of a corresponding manual rotation. For the purpose of comparison with the subsequent experiments, we presented visual action effects as well, although these were task-irrelevant in Experiment 1 and thus were not expected to affect performance.
- Experiments 2 and 3 test the prediction that it is not the manual rotation itself that determines the interaction between mental and manual rotations but the sensory effects by which the manual movement is represented and selected. With the horizon-moving display, rotation movements produce rotation effects in the opposite direction (cf. Figure 1B, bottom right). In this case, ideomotor theory predicts the MMRC effect to be reduced or perhaps even reversed. Ideomotor theory and its modern reformulations (e.g., Hommel et al., 2001) appear to be unique in making this prediction. Traditional models of motor control, such as the concept of "response selection" in stage theory (Pashler, 1994; Sanders, 1980) or the concepts of "motor programs" (Keele, 1968), "motor schemas" (Schmidt, 1975), or "feedback" (Adams, 1971), ascribe no particular role for such visual action effects in movement planning. Consequently, according to these theories MMRC effects depend only on the congruency between mental and manual rotations, regardless of the perceptual consequences of the manual rotation.

[1] Note that there exist other instruments providing information about roll, such as multifunction display panels in advanced aircrafts (e.g., Alexander, Prinzel, Arthur, & Bailey, 2009). For the sake of clarity, we restrict our discussion to the two basic versions of the attitude indicator.

Experiment 1: Do Mental Rotations Facilitate Subsequent Manual Rotations?

Experiment 1 investigated whether an MMRC effect can also be observed for manual rotations preceded by a mental rotation. Participants were briefly presented with a rotated letter in a mental rotation task (Task 1) followed by the stimulus for a manual rotation task (Task 2). A visual action effect appeared immediately after each correct manual rotation. We expected faster responding when the direction of the mental rotation and the required manual rotation matched than when they did not. To capture the temporal dynamics of this effect, we also varied the interval between the mental and manual rotation stimuli (stimulus onset asynchrony; SOA). Conceivably, the influence of mental rotation on manual rotation is larger the more these events overlap in time.

We included both plane-moving and horizon-moving displays in Experiment 1 to facilitate comparison with Experiments 2 and 3, where display type is the critical manipulation of interest. Note, however, that in Experiment 1 display type was neither particularly salient nor task-relevant, so neither a main effect of display type nor any modulation in size or direction of the predicted MMRC effect was expected (cf. Ansorge, 2002; Hommel, 1993; Pfister et al., 2010).

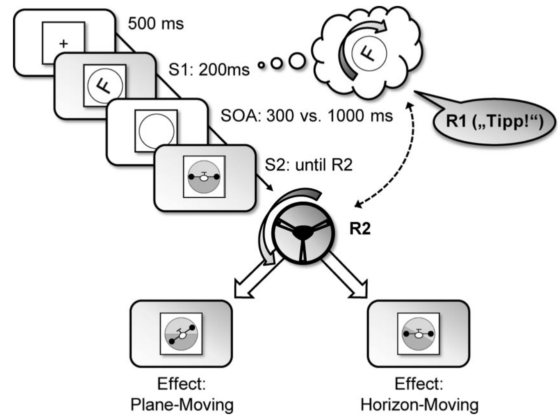

Figure 2. Trial structure of Experiment 1. Participants first performed a mental letter rotation task with a vocal response (R1); Task 1 stimuli (S1) were pictures of the letter *F* (mirrored or normal), rotated in steps of 60°. The following plane task (Task 2) used a manual wheel rotation response (R2). The hull of the airplane was colored either red or green and served as the imperative stimulus for this task (S2). SOA = stimulus onset asynchrony.

Method

Participants. Twenty-four undergraduate students from Dortmund University of Technology (19 women, mean age = 24.25 years) participated for monetary compensation (8€). All participants were naive regarding the hypotheses underlying this experiment and reported normal or corrected-to-normal vision.

Apparatus and stimuli. A standard IBM compatible PC was used for stimulus presentation and response collection. Stimuli were presented against a white background on a 17-in. CRT monitor with a viewing distance of approximately 65 cm. Task 1 stimuli (S1) were normal or mirror-reversed images of the letter *F,* rotated in steps of 60°. Task 2 stimuli (S2) and action effect pictures were images of an artificial horizon showing a plane in a horizontal position or flying a curve. The hull of the airplane was red or green. A control wheel was placed in front of the participants, and participants grasped the wheel with both hands (one hand on the left side, one hand on the right side).

Procedure. Participants were tested individually in a single session of about 60 minutes. Each trial started after the control wheel remained in the center position for at least 500 ms. The sequence of events was as follows (see also Figure 2): A fixation cross appeared for 500 ms and was then replaced by S1 for 200 ms. Task 1 was to indicate vocally whether S1 was a normal or a mirror-reversed *F* by saying aloud either "tipp" or "topp," respectively (R1; neither utterance was particularly meaningful to our German participants). Response times (RTs) were measured by a voice key, and the type of the vocal response was registered by the experimenter with a keypress. S2 appeared with an SOA of either 300 ms or 1,200 ms and remained on screen until the corresponding response was given (R2). Participants were to manually rotate the control wheel clockwise or counterclockwise according to the color of the plane's hull. Correct responses triggered presentation of a display showing the plane's resultant roll attitude, with either a plane-moving display or a horizon-moving display (varied blockwise). A blank screen was presented following incorrect responses. A trial was canceled if R2 was given prior to S2 onset or if no response was given within 4,000 ms following S2 onset. After the experimenter recorded the type of R1 as "tipp," "topp," or "other" (i.e., if the participant coughed or other noise triggered the voice key), error feedback was displayed as "Letter task wrong," "Flight task wrong," or both (in German language).

Participants received written instructions, emphasizing both speed and accuracy. It was not specified that R1 had to be given before R2, and thus changes of the response order were not counted as errors. As all participants were to perform the task with both display types, they received new instructions when the new display type was introduced after the first half of the experiment.

Design and analyses. Participants completed eight blocks, of which Blocks 1 and 5 were unanalyzed practice blocks of 10 randomly drawn trials. Each (experimental) block comprised 2 (SOA: 300 ms vs. 1,200 ms) × 6 (S1 angular disparities: 0° vs. 60° vs. 120° vs. 180° vs. 240° vs. 300°; counterclockwise) × 2 (S1: normal vs. mirrored) × 2 (required R2 direction: clockwise vs. counterclockwise) × 2 (repetitions) = 96 trials, presented in random order. All stimulus-response mappings as well as the order of display types (horizon-moving vs. plane-moving) were counterbalanced across participants.

Because preliminary analyses confirmed that display type neither exerted a main effect nor entered into any interactions, we collapsed data across this factor for the following analyses. Analysis 1 focused on Task 1 data. We ran a 6 (S1 angular disparity) × 2 (SOA) repeated-measures analysis of variance (ANOVA) to establish a symmetrical angular-disparity dependent increase in RTs (and error percentages) with a peak at 180°. Such a pattern suggests that participants rotated S1 in the direction that minimized the distance to the standard, upright position of the letter. On the basis of this analysis, we categorized all trials with an S1 angular disparity of 60° and 120° as requiring a clockwise mental rotation and those with an S1 angular disparity of 240° and 300° as requiring a counterclockwise mental rotation (angular disparities of 0° and 180° were omitted, because the former required no rotation at all and the latter cannot be assigned a likely rotation direction). For Analysis 2, trials were categorized according to whether the mental rotation in Task 1 was in the same or opposite direction as the manual rotation required in Task 2. Then, performance data were analyzed with a 2 × 2 repeated-measures ANOVA with the factors SOA (300 ms vs. 1,200 ms) and direction match (yes vs. no; coded with regard to the physical manual rotation).

For percentage of errors analyses, trials with a general error (e.g., premature responses or response omissions) were excluded. For RT analyses, we considered only trials in which both R1 and R2 were correct. RTs deviating more than 2.5 standard deviations from the mean of the participant and respective design cell were excluded as outliers (<3.4% for all analyses). An alpha level of .05 was adopted for all analyses, and Greenhouse–Geisser corrections were applied where necessary (for clarity we report uncorrected degrees of freedom).

Results

Analysis 1. RT data for Task 1 (mental letter rotation) are shown in Figure 3 (left panel). As expected, RTs increased with angular disparity, $F(5, 115) = 150.08$, $p < .001$, $\eta_p^2 = .87$, and were slightly faster with the short than with the long SOA, $F(1, 23) = 6.45$, $p = .018$, $\eta_p^2 = .22$. The interaction also approached significance, $F(5, 115) = 2.19$, $p = .060$, $\eta_p^2 = .09$. Error data for Task 1 are summarized in the Appendix. In general, analyses of error percentages showed a similar pattern. The main effect of angular disparity and the interaction between SOA and angular disparity were significant (see the Appendix), reflecting a slightly larger increase in errors with increasing angular disparity for the short than for the long SOA. Taken together, these data suggest that our participants performed the mental rotation task as expected.

Analysis 2.

Task 1. RT and error data for Task 1 are summarized in Table 1. Reactions were faster for the long than for the short SOA, $F(1, 23) = 4.35$, $p = .048$, $\eta_p^2 = .16$. Neither the main effect of direction match, $F(1, 23) = 3.36$, $p = .080$, $\eta_p^2 = .13$, nor the interaction, $F(1, 23) = 0.27$, $p = .607$, $\eta_p^2 = .01$, was significant. The error data showed no significant effects (ps ≥ .143).

Task 2. RT and error data for Task 2 are summarized in Table 1. Responses were faster for the long than for the short SOA, $F(1, 23) = 190.42$, $p < .001$, $\eta_p^2 = .89$. Additionally, a significant main effect of direction match, $F(1, 23) = 6.73$, $p = .016$, $\eta_p^2 = .23$, was modulated by a significant interaction, $F(1, 23) = 4.33$, $p = .049$, $\eta_p^2 = .16$. This latter effect reflects the fact that there was a significant effect of direction match at the short SOA, $t(23) = 2.77$, $p = .012$, $d = 0.57$, but not at the long SOA, $t(23) = 0.30$, $p = .675$, $d = 0.06$. No significant effects were observed in the error data, SOA: $F(1, 23) = 0.08$, $p = .785$, $\eta_p^2 = .12$; direction match: $F(1, 23) = 3.24$, $p = .085$, $\eta_p^2 = .12$; SOA × direction match: $F(1, 23) = 2.76$, $p = .110$, $\eta_p^2 = .11$.

Discussion

Experiment 1 tested for an MMRC effect when a mental rotation task precedes a manual rotation task. First, results from the mental rotation task replicate the typical effect of increasing RTs with increasing angular disparity, suggesting that participants mentally rotated in the shortest direction possible. As a consequence, we could reasonably classify trials according to whether mental and manual rotation directions did or did not match (except, of course, for the angular disparities of 0° and 180°). Crucially, manual rotations were indeed faster when they were preceded by a mental rotation in the same direction—the MMRC effect thus generalizes to our setting and task order. This result is in line with ideomotor theory, which assumes that a manual rotation action is selected by anticipating the resulting (proprioceptive) effect; in other words, a mental rotation is invoked during manual rotation action selection.

However, this was only true at the short SOA. This suggests that the influence of mental rotation on manual rotation is transient and requires close temporal proximity or overlap of the rotations. Furthermore, responses in the manual rotation task were much faster with the long than with the short SOA. This decrease in RTs in Task 2 is consistent with research using the psychological refractory period (PRP) paradigm, and it suggests that the rotation

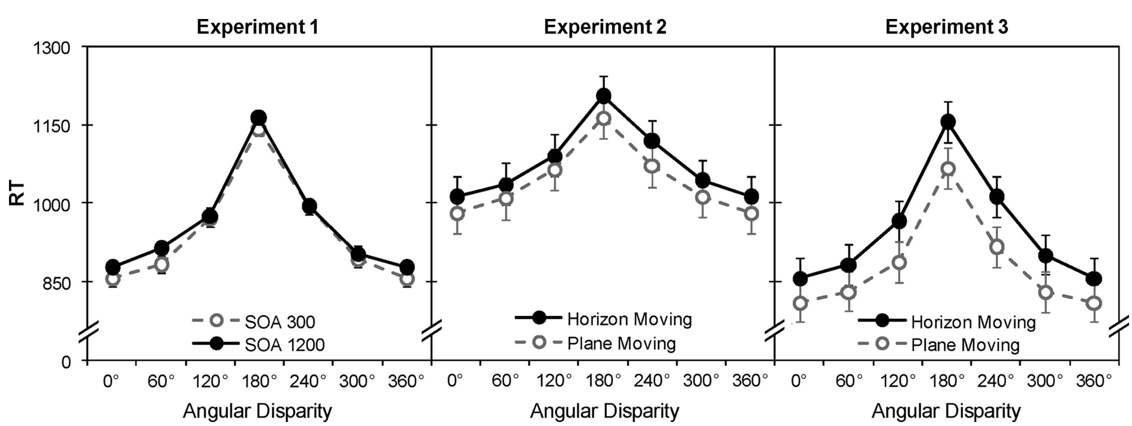

Figure 3. Mean response times (RTs, in ms) for Task 1 in all experiments as a function of S1 angular disparity and SOA (Experiment 1) or S1 angular disparity and display type (Experiments 2–3). Error bars are within-subjects standard errors, calculated from a pooled variance estimate for all conditions (Greenhouse–Geisser corrected; Loftus & Masson, 1994). SOA = stimulus onset asynchrony.

Table 1
Mean Response Times (in ms) and Error Percentages From Task 1 (Letter Task) and Task 2 (Plane Task) in Experiments 1–3 as a Function of Direction Match and SOA (Experiment 1) or Direction Match and Display Type (Experiment 2–3)

	Task 1: Letter task				Task 2: Plane task			
	RTs		% errors		RTs		% errors	
	Direction match		Direction match		Direction match		Direction match	
Variable	No	Yes	No	Yes	No	Yes	No	Yes
				Experiment 1				
SOA (ms)								
300	941	931	4.5	3.6	912	890	8.0	6.3
1,200	950	944	4.7	4.1	575	574	7.3	7.4
				Experiment 2				
Display type								
Horizon-moving	1,068	1,075	5.4	5.5	667	667	10.3	9.5
Plane-moving	1,045	1,032	5.8	5.4	653	627	10.1	6.8
				Experiment 3				
Display type								
Horizon-moving	936	940	3.6	4.5	913	920	12.1	13.2
Plane-moving	870	861	4.1	3.5	714	699	7.5	5.2

Note. RTs = response times; SOA = stimulus onset asynchrony.

tasks share a capacity-limited stage of processing, most likely related to response selection processes (e.g., Pashler, 1984, 1994; Pashler & Johnston, 1989).

In Experiment 1, the type of display (plane-moving or horizon-moving) did not affect performance, and similar results have been reported in previous studies using both display types (Yamaguchi & Proctor, 2006, 2010, 2011). The display type and the effect produced by the manual rotation (which differed between the display types), however, were completely task irrelevant and may simply have been ignored by the participants (Ansorge, 2002). As such, this experiment can be conceived of as measuring pure motor influence in a scenario where no particularly salient and task-relevant (visual) effect was produced in the environment. In Experiments 2 and 3, however, display types were rendered integral to the task to investigate their contribution to the MMRC effect.

Experiment 2: Is the MMRC Effect Due to the Manual Rotation Movements or Its Contingent Sensory Effects?

Experiment 1 demonstrated that an MMRC effect occurs when mental rotations precede manual rotations. Experiment 2 addresses the crucial question of this research: Is the MMRC effect due to congruency between the direction of mental rotation and the rotation direction of (a) the (physical) manual rotation or of (b) the emerging sensory percept? Although we manipulated the relationship of response and visual effect in Experiment 1 by varying display type, we found no influence of this variable (see also Yamaguchi & Proctor, 2006, 2010, 2011). However, in the first experiment only the color of the plane's hull determined the required manual response; thus, the display type and the resulting percept were task-irrelevant and conceivably could have been ignored by the participants. Task relevance, however, has been identified as a major contributor to the impact of action effects (Ansorge, 2002; Hommel, 1993; Pfister et al., 2010).

In Experiment 2 we increased the display's task relevance by requiring participants to extract the required manual response direction from the attitude depicted in the display (instead of responding to the color of the plane's hull). The task was now to align plane and horizon, which requires attention to both features. The logic of our predictions is illustrated in Figure 4. As outlined in the introduction, we assume that mental rotations prime anticipated effect rotations, which are—according to ideomotor theory—linked to corresponding motor actions. For the plane-moving display, the effect is linked to a manual rotation in the same direction. Thus, mental, manual, and effect rotations are all of the same direction, and we expected to observe a typical MMRC effect (see upper part of Figure 4). The important question here is: Will the same pattern of results emerge for the horizon-moving display? Note that the effect rotation is now linked to a manual rotation in the opposite direction (see lower part of Figure 4). We suggest that, in this condition, mental rotations will facilitate manual rotations in the opposite direction, because manual rotations in the opposite direction are now linked to an anticipated effect that matches the rotation direction of the mental rotation. Hence, with the horizon-moving display we expected a diminished or even reversed MMRC effect.

Method

Twenty-four new undergraduate students from Dortmund University of Technology participated (17 women, mean age = 23.29 years). Experiment 2 was similar to Experiment 1 with the following modifications (see Figure 5): Two letter identities (*F* or *R*) were now used as S1, and the SOA was always 400 ms (resulting again in 96 trials per block). S2 now depicted a departure from

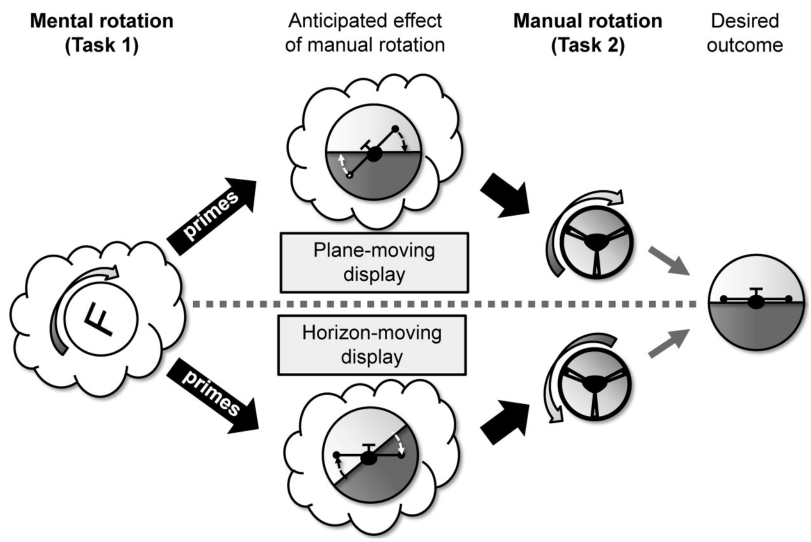

Figure 4. Illustration of the assumed ideomotor mechanism to explain the MMRC effect and its dependence on the manual rotation's contingent effects. An anticipation of the manual rotation's contingent effect is used to select/initiate the manual rotation (Task 2). This anticipation involves a mental rotation that is primed by the preceding mental letter rotation (Task 1). For the plane-moving display (top row), a clockwise mental rotation primes the corresponding clockwise rotation of the plane, which is, in turn, associated with a clockwise manual rotation. For the horizon-moving display (bottom row), a clockwise mental rotation primes the clockwise rotation of the horizon, which is associated with a counterclockwise manual rotation. MMRC = mental-manual rotation congruency.

level flight using either a plane-moving or a horizon-moving display. The participants' task was to return the plane to the horizontal position based on the roll depiction. The hull of the plane was no longer colored. Following correct responses, the effect was presented showing the plane in a horizontal position.

As in Experiment 1, we ran two separate analyses. The factor display type (plane-moving vs. horizon-moving), however, now interacted with the remaining factors and was thus used in the ANOVAs. Analysis 1 was a 6 (angular disparity) × 2 (display type) repeated-measures ANOVA on Task 1 data. Trials were then classified as in Experiment 1 and submitted to a 2 (direction match: yes vs. no) × 2 (display type: plane-moving vs. horizon-moving) repeated-measures ANOVA (Analysis 2). Importantly, direction match was coded with regard to the physical manual rotation, irrespective of its sensory consequences.

Outliers were excluded based on the same criteria as in Experiment 1 (<3.6% for all analyses). To better illustrate the effects of matched versus unmatched rotation directions, we calculated a difference score referred to as the *rotation-match index* (*RMI*). The RMI was calculated by subtracting the mean RTs (or mean percent errors) for matched-rotation trials from the mean RT (or mean percent errors) in unmatched trials. Hence, positive values indicate facilitation when mental and (physical) manual rotation were in the same direction (for plane-moving displays, the action effect was also in the same direction). In contrast, negative values indicate facilitation when both rotations were in different directions (but, for the horizon-moving display, mental and effect rotations matched in direction in this case).

Results

Analysis 1. RT data for Task 1 (mental letter rotation) are presented in Figure 3 (center panel). The results were similar to Experiment 1: RTs increased with an increasing angular disparity, $F(5, 115) = 42.08$, $p < .001$, $\eta_p^2 = .65$, and were numerically slightly higher with the horizon-moving display compared to the plane-moving display, $F(1, 23) = 1.77$, $p = .196$, $\eta_p^2 = .07$. The interaction was not significant, $F(5, 115) = 0.56$, $p = .661$, $\eta_p^2 = .02$. Error data for Task 1 show a pattern comparable to the RT data, and only the main effect of angular disparity was significant (see Appendix).

Analysis 2.

Task 1. RT and error data for Task 1 are summarized in Table 1, and the respective facilitation effect expressed as RMIs are illustrated in Figure 6. Neither the main effect of direction match, $F(1, 23) = 0.34$, $p = .565$, $\eta_p^2 = .01$, nor that of display type, $F(1, 23) = 1.68$, $p = .208$, $\eta_p^2 = .07$, was significant for RTs. The interaction, however, approached significance, $F(1, 23) = 3.45$, $p = .076$, $\eta_p^2 = .13$. This interaction reflects Task 1 facilitation, with matched rotation directions only for the plane-moving display. In contrast, for the horizon-moving display, performance with matched directions was worse than with unmatched directions. Error data showed no significant effects ($ps \geq .677$).

Task 2. As in Experiment 1, the most relevant results are those of Task 2. RT and error data from Task 2 are summarized in Table 1, and the respective facilitation effects, expressed as RMIs, are illustrated in Figure 7. Responses were faster when both rotation directions matched than when they did not, but the main effect of direction match was only marginally significant, $F(1, 23) = 4.02$, $p = .057$, $\eta_p^2 = .15$. Even though no significant main effect of display type was observed, $F(1, 23) = 0.82$, $p = .373$, $\eta_p^2 = .03$, the crucial interaction of direction match and display type was significant, $F(1, 23) = 4.72$, $p = .040$, $\eta_p^2 = .17$. As illustrated in Figure 7, the facilitation due to matched directions holds only for the plane-moving display and was almost completely absent for the horizon-moving display. Error data showed only a significant main effect of direction match, $F(1, 23) = 5.66$, $p = .026$, $\eta_p^2 = .20$, reflecting fewer errors when both rotation directions matched than when they did not. No other effect was significant, display type: $F(1, 23) = 0.74$, $p = .397$, $\eta_p^2 = .03$; direction match × display type: $F(1, 23) = 2.39$, $p = .136$, $\eta_p^2 = .09$.

Discussion

Our goal in Experiment 2 was to investigate the mechanisms underlying the MMRC effect. Previous accounts focused solely on the overlap of a (physical) manual response and the mental rotation and neglected the manual action's sensory consequences (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). Ideomotor theory, however, suggests that anticipating an action's sensory consequences is a necessary precondition for selecting and executing the action (Hoffmann, 2003; Hommel et al., 2001; Kunde, 2001).

In Experiment 2 we disentangled the directions of physical manual rotation and distal sensory effect rotation. Crucially, in contrast to Experiment 1, the displays were now rendered task-relevant. With the plane-moving display—where both physical and effect rotation went in the same direction—responding was facilitated when it was preceded by a directionally matched mental rotation; this advantage was eliminated for the horizon-moving display.[2] Although this result is promising, it still reflects some uncertainty about the relative contributions of the visual effect rotation on the one hand and the manual rotation on the other hand.

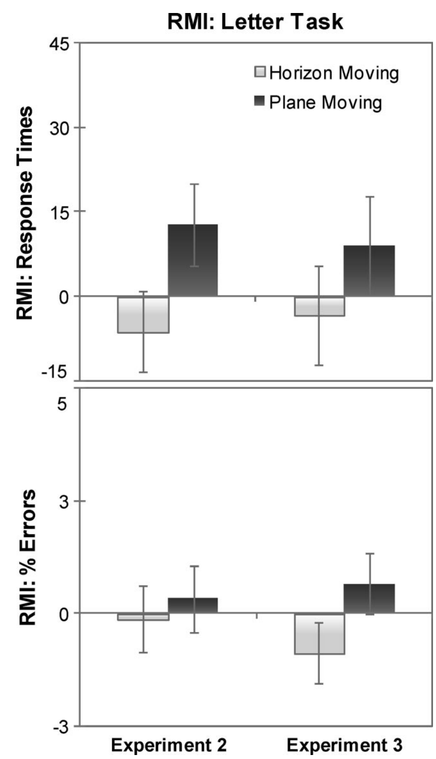

Figure 6. Rotation-match indices (RMIs) for response times (in ms) and error percentages in Task 1 (letter task; Experiments 2–3). Positive RMIs indicate facilitation when the directions of mental and manual rotations matched; negative RMIs indicate facilitation when mental and manual rotations went in opposite directions. Error bars are within-subjects standard errors.

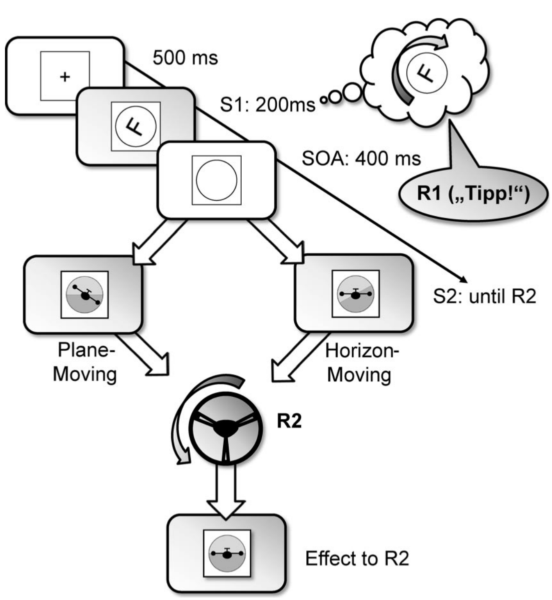

Figure 5. Trial structure of Experiments 2 and 3: Participants first performed a mental letter rotation task with a vocal response (R1); Task 1 stimuli (S1) were pictures of the letters *F* and *R* (mirrored or normal), rotated in steps of 60°. Stimuli in the following plane task (Task 2) were depictions of a plane departing from horizontal flight (S2), either with the plane-moving or the horizon-moving display. This task required a manual wheel rotation response (R2). SOA = stimulus onset asynchrony.

Thus, in Experiment 3 we sought further evidence for the role of anticipatory effect rotations.

Experiment 3: Continuous Sensory Consequences

The results from Experiment 2 lend support to our hypothesis that the MMRC effect is not based on the physical direction of a manual movement but rather on its emerging sensory (visual) consequences. In Experiment 2, the stimulus display (of Task 2) changed into an effect display abruptly, which gave the impression of display rotation by means of apparent motion. Thus, a contin-

[2] One might question our conclusion by arguing that the critical interaction was significant only for RTs and not for errors, which show only a main effect of direction match. Yet, we believe that this does not undermine our conclusion. As is common in such research, RTs were the main dependent variable of interest. Errors were considered only inasmuch they may reveal a speed–accuracy trade-off, but this is clearly not the case: The interaction is numerically in the same direction for RTs and errors. Thus, we are convinced that our conclusion is tenable, and in fact, the data from Experiment 3 provide further support for our interpretation.

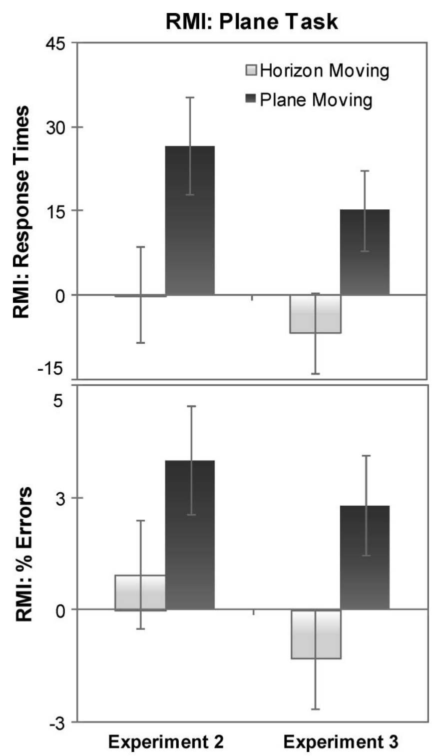

Figure 7. Rotation-match indices (RMIs) for response times (in ms) and error percentages in Task 2 (plane task; Experiments 2–3). Positive RMIs indicate facilitation when the directions of mental and manual rotations matched; negative RMIs indicate facilitation when mental and manual rotations went in opposite directions. Error bars are within-subjects standard errors.

uous response was combined with a discrete effect, resulting in relatively low dimensional overlap.[3] Experiment 3 employed an effect display that continuously rotated with the wheel rotation to increase the dimensional overlap of actions and effects. High overlap has been identified as a crucial factor to measure influences of anticipated action effects (Koch & Kunde, 2002). We therefore predicted an observable influence of (spatial) response-effect compatibility: Wheel rotation responses should generally be initiated more quickly when the manual rotation and the effect rotation go in the same direction (as is the case with the plane-moving display) than when they move in opposite directions (as is the case with the horizon-moving display). Moreover, we expected to replicate the key finding of Experiment 2, namely that the MMRC effect depends on the directional overlap between the mental rotation and the rotation of the action's consequences. If the present manipulation further enhances the impact of anticipated action effects, an increase of the MMRC effect appears likely as well.

Method

Twenty-four undergraduate students from the University of Würzburg participated in this experiment (19 women, mean age = 26.3 years). In general, Experiment 3 was similar to Experiment 2 with the exception that turning the wheel was now continuously translated into a corresponding visual effect rotation at a spatial resolution of 0.20° and a temporal resolution of approximately 10 ms (monitor frequency = 100 Hz). RTs were measured as soon as the control wheel deviated from the central position by more than 0.05 rad (2.9°). The end of the movement was defined as a deviation of 0.52 rad (30°) from the central position. Errors were automatically coded according to the initial rotation direction, even if the participants reversed the direction within the trial (which caused a change of the rotation direction in the display as well). Less than 4.0% of the trials were excluded as outliers according to the same criteria as in Experiments 1 and 2.

Results

Analysis 1. RT data for Task 1 (mental letter rotation) are presented in Figure 3 (right panel). As in the previous experiments, RTs increased with increasing angular disparity, $F(5, 115) = 73.88$, $p < .001$, $\eta_p^2 = .76$, and—unlike in Experiments 1 and 2—the main effect of display type was also significant: RTs were faster with the plane-moving display than with the horizon-moving display, $F(1, 23) = 7.94$, $p = .010$, $\eta_p^2 = .26$. In addition, the interaction was significant, $F(5, 115) = 3.02$, $p = .033$, $\eta_p^2 = .12$, although for both display types RTs increased with increasing angular disparity (see Figure 3, right panel). Error data for Task 1 exhibited a pattern comparable to the RT data, and only the main effect of angular disparity was significant (see Appendix).

Analysis 2.

Task 1. RT and error data for Task 1 are summarized in Table 1, and the respective facilitation effects, expressed as RMIs, are illustrated in Figure 6. The main effect of display type was significant, $F(1, 23) = 6.97$, $p = .015$, $\eta_p^2 = .23$, whereas the main effect of direction match was not, $F(1, 23) = 0.23$, $p = .637$, $\eta_p^2 = .01$. Although on a descriptive level RTs showed that the facilitation observed with the plane-moving display was reversed with the horizon-moving display (see Figure 6, upper-right panel), the interaction was not significant, $F(2, 23) = 0.98$, $p = .334$, $\eta_p^2 = .04$. The error data descriptively exhibited the same pattern as the RT data, but no effects were significant (ps $\geq .136$).

Task 2. RT and error data from Task 2 are summarized in Table 1, and the respective facilitation effects, expressed as RMIs, are illustrated in Figure 7. Responses were much faster with the plane-moving than with the horizon-moving display, $F(1, 23) = 10.77$, $p = .003$, $\eta_p^2 = .32$. The main effect of direction match was not significant, $F(1, 23) = 0.39$, $p = .539$, $\eta_p^2 = .02$, but—most importantly—the interaction was significant, $F(1, 23) = 4.67$, $p = .041$, $\eta_p^2 = .17$. As illustrated in Figure 7, the MMRC effect observed with the plane-moving display was reversed with the horizon-moving display. The RT pattern is substantiated by the error data, which yielded two significant effects. First, participants made fewer errors with the plane-moving display, $F(1, 23) = 15.52$, $p < .001$, $\eta_p^2 = .40$, and second, the significant interaction reflected a reversed MMRC effect with the horizon-moving display, $F(1, 23) = 4.64$, $p = .042$, $\eta_p^2 = .17$ (see Figure 7). The main

[3] Note that the concept of dimensional overlap refers to a global commensurability of actions and effects and does not refer to the congruency of action and effect directions in a particular trial. In technical terms, the former is labeled "set-level compatibility," whereas the latter is labeled "element-level compatibility" (Kornblum et al., 1990).

effect of direction match was not significant, $F(1, 23) = 1.19$, $p = .287$, $\eta_p^2 = .05$.

An additional between-experiments analysis targeted the most relevant RT effects: the main effect of display type and the interaction between display type and direction match. This analysis yielded a significant interaction between experiment (2 vs. 3) and display type, $F(1, 46) = 6.66$, $p = .013$, $\eta_p^2 = .13$, with a larger effect of display type in Experiment 3. However, the interaction between display type and direction match did not differ between experiments, as mirrored in the nonsignificant three-way interaction, $F(1, 46) = 0.09$, $p = .770$, $\eta_p^2 < .01$.

Discussion

Our aim in Experiment 3 was to generalize the novel findings from Experiment 2 to a situation where the resulting sensory effect rotation was continuously controlled by the manual wheel rotation. This procedure effectively increased the dimensional overlap between actions and their contingent effects (Kornblum et al., 1990).

First, the data corroborate our conclusion based on Experiment 2: A facilitatory MMRC effect was observed when the directions of mental rotation and effect rotation matched, irrespective of the manual rotation direction. Second, participants were now faster and less error-prone when working with a plane-moving display than with the horizon-moving display. This finding can be conceived as an R-E compatibility effect (as it depends only on the action and the effect of Task 2). We discuss this issue more thoroughly in the General Discussion.

This effect was also evident in Task 1 RTs and thus constitutes an instance of "backward crosstalk" (e.g., Ellenbogen & Meiran, 2011; Hommel, 1998; Miller, 2006; note that the same applied descriptively to the MMRC effect in Experiments 2 and 3). Such findings suggest that response selection actually comprises two stages (e.g., Hommel, 1998; Lien & Proctor, 2002): a first stage of stimulus-response translation and a second stage of final response selection. The former stage seems to run in parallel with other (capacity-limited) stages and thus gives rise to backward crosstalk effects. Hence, the reported Task 1 effects are well in line with recent theoretical developments in the dual-task literature.

General Discussion

The present research investigated the interaction between mental and manual rotations and the impact of a manual rotation's contingent sensory consequences in a simulated aviation setting. Facilitation of mental rotation by concurrent or preceding manual rotations (the MMRC effect) has been studied extensively in previous research (Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). In Experiment 1, we showed that this effect can also be observed for manual rotations preceded by mental rotations in the same direction. Furthermore, this effect seems to emerge only with high temporal task overlap (i.e., with a short SOA). This effect was replicated in Experiments 2 and 3. Crucially, the results from these latter experiments point to an important role of sensory action effects in the interplay between mental and manual rotations.

The (Cognitive) Source of the MMRC Effect

The MMRC effect has been observed in situations where the manual action is merely planned (Wohlschläger, 2001), suggesting a link between mechanisms of mental rotation and motor preparation. This is consistent with ideomotor theory, which states that motor actions are prepared by recollecting their sensory consequences (Harleß, 1861; Herbart, 1825; Hommel et al., 2001; Shin et al., 2010). Consequently, the question remains whether a physical rotation itself or its resulting (distal) effect is responsible for the MMRC effect. The findings from our experiments clearly suggest that (distal) effects are critical. When a plane-moving display was used, the physical rotation and the resulting effect rotation were in the same direction and responses were facilitated by a preceding mental rotation in the same direction. Most importantly, this effect was eliminated or (in most analyses) even reversed for the horizon-moving display. Here, incongruent mental and physical manual rotations resulted in congruent mental and visual effect rotations. In other words, it is not the physical manual rotation that matters but rather the rotation of its contingent (visual) effect.

The numerical size of the MMRC effect (expressed as the difference in RMI scores between the plane-moving and the horizon-moving display) was about 25 ms in Experiments 2 and 3. Compared with the effects found in similar studies, this seems rather small. For example, in studies by Wohlschläger (2001; Wohlschläger & Wohlschläger, 1998), the size of the MMRC effect was between 230 ms and 460 ms, depending on experimental factors. A direct comparison, however, is difficult for several reasons. First, RTs were overall much higher in these studies (between 2,000 ms and 6,000 ms) than in our experiments. Second, several experimental factors may contribute to the difference (e.g., the order of both tasks or the mere fact that our participants grasped the control wheel with both hands, whereas a knob was turned with only one hand in other studies). Isolating factors that influence the size of the MMRC effect is thus an interesting question for future research. Yet, the observation that the size of the MMRC effect was comparable in Experiments 2 and 3 is at first glance puzzling,[4] given the larger influence of action effects in Experiment 3. One theoretically possible account is that the assumed priming processes between mental rotations are of a discrete nature. In other words, what counts is simply the direction match between the two rotations, not the magnitude of the rotations. This is consistent with recent research on the continuous end-state comfort phenomenon, which also suggests that rotation actions are planned discretely in terms of clockwise or counterclockwise turns, whereas the actual turning angle plays only a minor role for planning processes prior to action execution (Herbort & Butz, 2010, 2011).

Furthermore, the main result of a pronounced impact of (distal) action effects on the interaction of mental and manual actions fits well with other recent results. For instance, the well-known and robust advantage of homologous responses in bimanual coordination can be overcome and even reversed when homologous responses produce nonidentical (visual or tactile) effects, but nonhomologous responses produce identical effects (Janczyk, Skirde, Weigelt, & Kunde, 2009; see Mechsner, Kerzel, Knoblich, & Prinz, 2001, for converging evidence). It thus appears that ideomotor theory indeed provides a good explanation for a variety of behaviors.

[4] We thank an anonymous reviewer for pointing out this interesting issue.

Response-Effect Compatibility and Wheel Rotation Responses

We focused our analyses on the interaction between the rotation directions in Tasks 1 and 2 (i.e., on the MMRC effect). In Experiment 3, when considering only the Task 2 data, we also found generally impaired performance with the horizon-moving display as compared to the plane-moving display and, hence, an R-E compatibility effect for wheel rotation responses. Previous studies did not find such an effect (Yamaguchi & Proctor, 2006, 2010, 2011) and suggested that not the actual visual effect is crucial but rather the implied direction of the plane's flight, irrespective of the display type. Accordingly, an R-E compatibility-like effect was reported when the plane's direction changed in the direction opposite from the intended movement (Yamaguchi & Proctor, 2011).

Why then did an R-E compatibility effect emerge in our experiment? To begin with, remember that in Experiment 2 the effect rotation was induced by apparent motion, whereas in Experiment 3 the effect rotation was continuously controlled by the wheel rotation response. This renders high dimensional overlap (Kornblum et al., 1990), a necessary precondition for observing R-E compatibility effects with continuous responses (for converging evidence with tool movements, see also Janczyk, Pfister, & Kunde, 2012; Kunde, Pfister, & Janczyk, 2011). High dimensional overlap was also present in the studies by Yamaguchi and Proctor (2006, 2010, 2011), yet no R-E compatibility effect was reported there. In our study we focused on RTs and error data while the task itself was paced trial by trial. This complicates comparison with the study by Yamaguchi and Proctor (2010), where participants were continuously responding to induced perturbations to keep the plane in a horizontal position. Thus, the squared mean deviation from the horizontal alignment, which is possibly less sensitive than the present measures, was used as the dependent measure. This does not apply, however, to other studies (Yamaguchi & Proctor, 2006, 2011) that reported no performance differences between the two display types when manipulated between subjects (compared to the within-subject manipulation in our study). An important difference, however, relates to the stimuli used in previous studies, which were either differently pitched tones or colored visual stimuli (presented laterally). In contrast, in our Experiments 2 and 3, the response-determining stimulus was an inherent and clearly task-relevant feature of the display. Note that when participants responded to a color stimulus in our Experiment 1, performance was completely unaffected by the type of the display.

Given these considerations, two factors appear necessary for R-E compatibility effects with wheel rotation responses: task-relevant displays and effects closely linked to each other, and a high dimensional overlap of actions and effects. Both factors have been highlighted in previous work (Ansorge, 2002; Hommel, 1993; Kornblum et al., 1990; Pfister et al., 2010).

The R-E compatibility effect in Experiment 3 and the lack thereof in Experiment 2 also nicely rule out a potential alternative explanation in terms of facilitated perceptual encoding. The preceding perception of a rotated letter in Task 1 might prime the encoding of a subsequent stimulus presented in a similar orientation (Kunde & Hoffmann, 2000) and thus partly explain the observed results. This would facilitate encoding of stimuli showing planes or horizons oriented in the same direction as the letter in Task 1. In effect, these are the conditions of congruent mental and manual rotations with the plane-moving display and of incongruent mental and manual rotations with the horizon-moving display. Importantly, however, the start displays were absolutely identical in Experiments 2 and 3. Still, a larger R-E compatibility effect was observed in Experiment 3, where dimensional overlap of actions and their effects was higher. This clearly rules out explanations in terms of perceptual encoding. The influence of display type must therefore be due to differences in anticipatory codes for the different displays.

Summary and Conclusions

In sum, the present study yields two main findings. First, Experiment 1 showed a pronounced influence of mental rotations on subsequent manual rotations, which, up to now, has been reported only in the reverse direction. Hence, actions both influence and can be influenced by unrelated but similar cognitive processes. Furthermore, our data suggest that the MMRC effect is driven by a match between the directions of the mental rotation and the perceptual consequences of a manual rotation, not the physical rotation direction per se.

Well in line with ideomotor theory, this result highlights the importance of the perceptible outcomes of actions, which are likely being anticipated as a means to access a desired action. This interpretation also speaks to the underlying mechanics of the MMRC effect. Given that two subsequent mental rotations can prime each other (e.g., Jolicoeur, 1990; Wan et al., 2011) we suggest that—in our tasks—the mental rotation of the letter primes the anticipated (mental) rotation of the effect required for selecting the corresponding manual rotation. These results also inform neuroscientific accounts where previous findings on motor-related activity during mental rotation were taken as evidence for a functional overlap between mental and manual rotations (Zacks, 2008). The present results extend this contention and suggest that such a functional overlap might also express itself in terms of anticipatory sensory activity prior to manual rotations. In other words, whereas traditional psychological and neuroscientific accounts assume that "mental rotation is a covert simulation of motor rotation" (Wexler et al., 1998, p. 78), the present results go one step further and suggest that planning a motor rotation is nothing but the mental rotation of its sensory consequences.

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Appendix

Mean Error Percentages (Task 1) From Experiments 1–3 as a Function of S1 Angular Disparity and SOA (Experiment 1) or Angular Disparity and Display Type (Experiments 2–3)

Variable	S1 angular disparity					
	0°	60°	120°	180°	240°	300°
Experiment 1						
SOA (ms)						
100	2.1	2.4	4.2	14.1	4.4	2.1
1,000	1.9	2.5	4.7	9.3	4.9	1.9
Angular disparity: $F(5, 115) = 18.24$, $p < .001$, $\eta_p^2 = .44$						
SOA: $F(1, 23) = 2.99$, $p = .097$, $\eta_p^2 = .12$						
Angular disparity × SOA: $F(5, 115) = 5.99$, $p = .002$, $\eta_p^2 = .21$						
Experiment 2						
Display type						
Horizon-moving	1.8	3.3	6.9	25.7	8.1	3.7
Plane-moving	3.0	2.8	8.2	25.7	8.5	3.3
Angular disparity: $F(5, 115) = 55.15$, $p < .001$, $\eta_p^2 = .71$						
Display type: $F(1, 23) = 0.08$, $p = .781$, $\eta_p^2 = .00$						
Angular disparity × display type: $F(5, 115) = 0.32$, $p = .772$, $\eta_p^2 = .01$						
Experiment 3						
Display type						
Horizon-moving	2.2	1.7	4.2	21.9	7.9	2.5
Plane-moving	1.9	2.8	3.8	19.2	6.5	2.4
Angular disparity: $F(5, 115) = 35.23$, $p < .001$, $\eta_p^2 = .61$						
Display type: $F(1, 23) = 0.63$, $p = .436$, $\eta_p^2 = .03$						
Angular disparity × display type: $F(5, 115) = 0.86$, $p = .513$, $\eta_p^2 = .04$						

Note. S1 = Task 1 stimuli; SOA = stimulus onset asynchrony.

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