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Action Effects Are Coded as Transitions From Current to Future Stimulation: Evidence From Compatibility Effects in Tracking

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There is ample evidence that motor actions are stored in terms of, and controlled by, the sensory effects that these actions produce. At present it is unclear, though, whether action control is governed by intended sensory changes (e.g., the transition from darkness to brightness when switching on a light) or only by intended sensory end states (e.g., the light being on). The present study explored the role of sensory changes for action control. To address this issue, participants engaged in a spatial tracking task. We show that performance is determined by the compatibility between motor patterns and subsequent changes of a controlled stimulus, while the intended end state of the stimulus remains constant. Spatial compatibility increases performance even when perceptual changes of spatial features are not the primary target of control. These results suggest that intended transitions of stimulation have the potential to bias motor actions. We consider these results as an important step toward integrating closed-loop regulation approaches and ideomotor approaches of action control.

Public Significance Statement

We typically behave in a goal-oriented manner. Thus, we aim to achieve certain intended perceptual states. To do so we need to acquire knowledge about which motor actions are linked to which perceptual effects. Here, we argue that such effects are mentally stored as perceptual changes from current to future perceptual states rather than as perceptual states per se. We show that perceptual changes are easier produced by motor actions that are spatially compatible rather than incompatible to these changes while the intended sensory end states remain the same. These observations suggest a new look at the mental representations that enable goal-oriented action.

Keywords: Action effects, intention in action, sensory anticipations

Consider a person switching on the light in a dark room. What is the cause of that action? Cognitive psychology has basically offered two answers to this question. Stimulus-centered approaches, on the one hand, suggest that the darkness of the room drives the action, the idea being that humans respond to what they perceive. Since the days of Descartes (1664), this idea has a long tradition in biology and psychology, and it still strongly inspires current models of human cognition, which mostly start with a stimulus and end with a response, bridged by certain information processing steps in between (Donders, 1862; Sanders, 1980; Tinbergen, 1951; Ulrich, Schröter, Leuthold, & Birngruber, 2015).

Goal-centered approaches, on the other hand, suggest that it is the intended brightness that determines actions. Humans aim at reaching certain intended perceptual states—the bright room, in our case. Ideomotor models are at the forefront here. According to these approaches, voluntary behavior is based on acquired links between motor actions and subsequent sensory effects. These links are bidirectional in nature, so that activating codes of intended future stimulation reactivates the motor actions, which, according to experience, produce that stimulation (Harless, 1861; Hoffmann et al., 2007; Hommel, 2009; James, 1890/1981; for a review Shin, Proctor, & Capaldi, 2010).

Although both approaches capture important aspects of human behavior, they eventually portray an inadequate picture of action control. Stimuli do not cause actions (except perhaps reflexes). A dark room triggers nothing if the person has no intention to be in a lit room, for example, when going to sleep. Likewise, the intention to be in a bright room triggers nothing if the room is already sufficiently bright. Thus, neither current nor intended stimulation alone explain behavior. Conceivably, it is the discrepancy between current and intended stimulation, hence the intended perceptual *change,* that does so—in our example, the transition from darkness to brightness.

This analysis might come across as nitpicking. But we believe it is quite important, in particular for the ideomotor approach. As explained before, this approach assumes that motor actions are linked to, and retrieved by, codes of sensory events that these actions previously produced. Our analysis suggests that these codes might not only represent perceptual end states, but changes

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of perception from current states to intended states. If it could be confirmed that codes of perceptual changes were sufficient for the retrieval of motor codes at least two problems of the ideomotor approach might be solved.

First, assuming that motor actions are represented in terms of perceptual outcomes predicts that actions should be primed by perceiving these outcomes. Seeing a light flashing, to stick to our example, should prime a light switch action, which in one form or another, has in fact been shown many times (Elsner & Hommel, 2001; Greenwald, 1970; Hommel, 1996). Yet, this creates the problem of the so-called "circular reflex" (Greenwald, 1970). When an agent successfully produces and thus perceives an intended outcome, he or she should tend to repeat the same motor action over and over again. But such behavioral perseveration barely occurs. Why does flashing a room light not prime a keypress of the light switch all over again? The simple answer might be, because the key press is coded in terms of a transition between current and intended brightness. Achieving the intended brightness nullifies the discrepancy between current and intended stimulation, which serves to represent the motor action, whereby further motor priming is abolished.

The second problem is that of contextualization, hence the fact that reaching the same end state can require different motor actions depending on varying current states (Hommel, Pösse, & Waszak, 2000; Kiesel & Hoffmann, 2004). For example, moving a mouse cursor to a specific icon on a display might require a leftward hand movement when the cursor is currently to the right of the icon, but a rightward hand movement when it is currently to its left. Now, associations between motor patterns and certain perceptual end states as such (i.e., the cursor being on the icon) are of limited use, if the current state (where is the cursor right now?) is not taken into account. By contrast, associations between motor patterns and specific transitions from current states to the intended end state would be helpful. In other words, linking motor patterns to transitions of stimulation rather than to end states of stimulation would help to solve the problem of contextualization.

It might be that motor actions can be controlled by both, intended perceptual end states and intended perceptual changes. In fact when the starting conditions prior to action execution are always the same, hence contextualization does not play a role, both options are equally feasible and not mutually exclusive. Consequently we do not want to exclude the possibility of coding of motor actions in terms of intended perceptual end states. However, to our knowledge, there is no evidence directly supporting the idea that anticipated changes, in addition to anticipated end states of stimulation, play a role in motor behavior as well. We aim to provide such evidence. We do so by employing a strategy previously used by both, the stimulus-oriented and the goal-oriented approach, specifically by demonstrating that a certain type of compatibility—namely that between intended perceptual changes and required motor actions—shapes performance.

Compatibility and Action Outcomes

The term compatibility means that there is a certain match between features of task components, such as spatial location or direction (Fitts & Seeger, 1953; Kornblum, Hasbroucq, & Osman, 1990). The stimulus-oriented approach is at first glance supported by the phenomenon of stimulus-response (S-R) compatibility. Here compatibility is defined by the relationship between a stimulus and the response which it requires. For example, performance is superior when humans have to respond to a stimulus (e.g., a stimulus flashing on the right side) with a spatially compatible (right) rather than an incompatible (left) motor action (Fitts & Seeger, 1953), which still holds true even when stimulus location is not relevant for the task (Simon & Rudell, 1967). Basically, this seems to apply to stimulus changes as well, such that stimuli moving in a certain direction are responded to more quickly with spatially corresponding actions irrespective of the location of the stimulus (Bosbach, Prinz, & Kerzel, 2005). This observation suggests that there is a natural tendency to respond to certain stimuli with spatially compatible responses.

Later, the ideomotor approach has made it clear that this inference is probably incorrect. What counts is not the relationship between stimuli and responses, but that between stimuli and perceptual events which the required motor pattern produces. For example, when participants intend to switch on a light with a keypress, it is the spatial relationship between the stimulus and the light that counts, not the relationship between stimulus and keypress. If participants aim to switch on a light on their right side by means of a left keypress, it becomes actually easier to respond to a right stimulus with a left keypress (Hommel, 1993). This suggests that it is not the "response" in S-R compatibility research, which is crucial here, but the response-related sensory effects (such as the tactile sensations from moving the finger or pressing a key).

Moreover, independent of an overlap between stimuli and responses or effects, the compatibility between body-related and body-external action effects as such shape performance. It is, for example, easier to produce a visual effect on the left with a left rather than right motor action, even when there is no spatial stimulus at all (Ansorge, 2002; Kunde, 2001; Pfister & Kunde, 2013; Wirth, Pfister, Janczyk, & Kunde, 2015). Several such action-effect (A-E) compatibility effects have been reported. For example, pressing a button softly (and thus generating weak tactile feedback) is easier when that action foreseeably produces a soft rather than a loud tone (Kunde, Koch, & Hoffmann, 2004). Or pressing a button briefly (thereby generating brief tactile feedback) is easier when that action foreseeably produces a short rather than long tone (Kunde, 2003). In such studies, action consequences impact action production, although these consequences can only be anticipated, as they are not yet present at the time of action selection. Thus, anticipated sensory consequences seem to contribute to action selection as the ideomotor approach proposes.

Still, at this point it is unclear whether these codes represent intended end states (e.g., a light switched on, or a certain sound being played) or intended changes (e.g., the transition of a light from being switched off to being switched on, or the transition from silence to a certain tone being presented). Despite this ambiguity, current formulations of the ideomotor approach seem to favor the idea that these codes reflect end states rather than changes (e.g., Watson, van Steenbergen, de Wit, Wiers, & Hommel, 2015, p. 45).

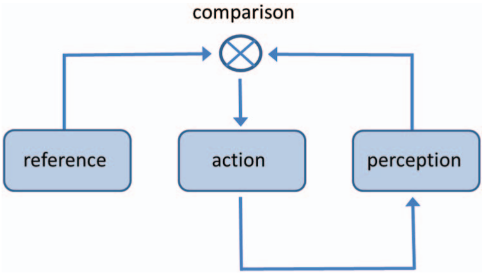

Figure 1. A closed control loop. Actual perception is compared with reference values. In case of discrepancies, an action to compensate that discrepancy is generated. Carrying out the action changes perception, and also subsequent comparisons to reference values. See the online article for the color version of this figure.

The Present Study: Continuous Control as an Alternative to "Single Trial-Atomism"

With the present study, we aim to demonstrate that transitions of perception shape behavior irrespective of—and possibly in addition to—the perceptual end-state. In other words, we want to show that a crucial determinant in effect-based action control is the *reduction* of the discrepancy between current and intended stimulation, and not only the intended end state of the stimulation itself.

When taking the idea that humans always aim to reduce discrepancies between intended perception and currently given perception seriously, the traditional response time methodology, which is widely used by stimulus-centered as well as the goal-centered approaches, might not be the best choice. This method segments behavior into little snippets and focusses on the perceptual states that are produced in individual trials. However, assuming that humans aim to reduce perceptual discrepancies comes down to saying that action is the "control of perception" (Mansell & Marken, 2015; Powers, 1973). Controlling something means to continuously monitor and minimize discrepancies between actual and intended states. Such control systems can thus be described as a loop as shown in Figure 1.

A task that captures such control better is tracking, such as keeping a randomly moving cursor aligned with a certain perceptual reference value by means of manual actions (Poulton, 1974). In such a control situation, there is circular causality. The discrepancy between actual and intended perception determines the required action, which changes the perceptual input, which then determines subsequent required actions and so on. Consequently, the analysis in this sort of task is neither concerned with how quickly subjects respond to, or produce, certain stimulation. Rather, the analysis is more concerned with the question of how well participants manage to align perception and reference on average. Typical measures are for example root mean square error (RMSE) between actual and intended stimulus properties.

We consider a continuous control task ideal to make our point. Specifically, we asked participants to move a visual cursor to a central target position on a tablet PC, while the cursor randomly drifted away from the target position (see Figure 2). So the instructed (and thus intended) perceptual end state is the cursor in the center position. At any moment that a discrepancy between the current cursor position and the center position is registered, the required perceptual transition is the movement of the cursor from the perceived position back to the intended position. To achieve this transition a finger movement is necessary.

To demonstrate what determines motor actions here, we manipulated the spatial relationship between finger movements and cursor movements in Experiment 1. The cursor either moved in the same direction as the finger, or in the opposite direction. The main outcome is that the spatial compatibility between the intended change of the cursor and the required movement of the finger

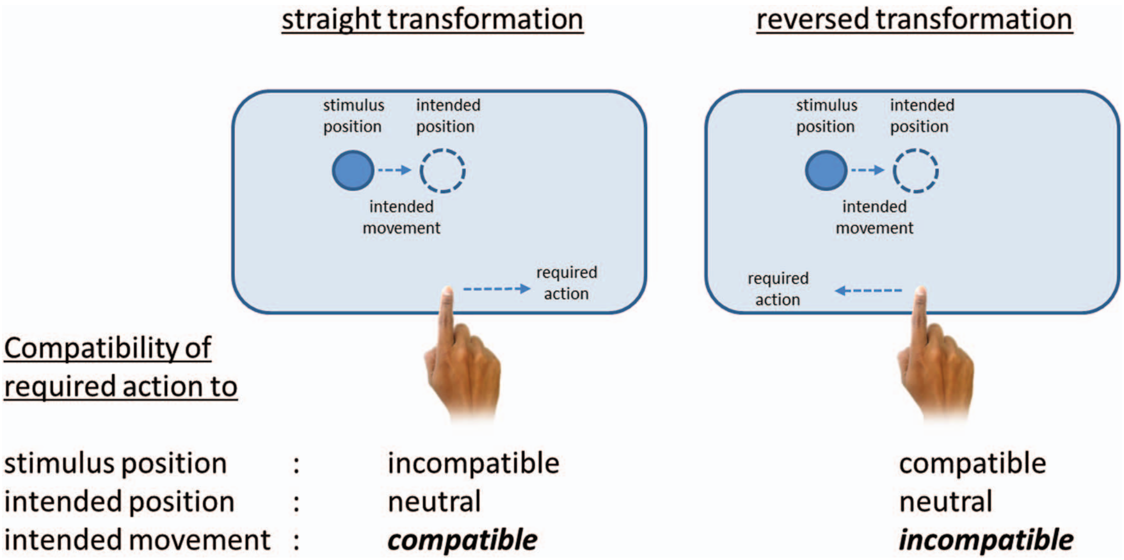

Figure 2. Procedure in Experiment 1. A randomly moving cursor had to be brought in alignment with a central target position by means of either straight or reversed finger movements. These conditions create various forms of compatibility as explained in detail in the text. See the online article for the color version of this figure.

shapes performance, while the intended end state of the cursor remained constant. In Experiment 2, the instructed end state of the cursor was a nonspatial property (cursor size). Still, the spatial relation between finger movement and cursor movement affected behavior, suggesting that even cursor changes that are spatially neutral with regard to motor actions become coded in spatial terms when the similarity of motor actions and ensuing perceptual changes is high. Finally, in Experiment 3, vision of the hand was occluded, which revealed that proprioceptive rather than visual codes of the finger movements interfered with spatially incongruent cursor movements. We conclude by suggesting modifications of traditional ideomotor approaches to action control.

Experiment 1: Position Tracking by (Un)Transformed Finger Movements

Experiment 1 was a simple spatial tracking task. Participants were instructed to keep a dot, which moved randomly to the left or right, in a center position, by means of left and right finger movements. The crucial variation concerned the transformation of finger movements to cursor movements. In the straight condition, the cursor moved in parallel with the finger, whereas it moved mirror symmetrically to the finger in the reversed condition. The transformation was manipulated in a blocked manner, and thus the cursor movement was perfectly predictable as a function of finger movement in either condition.

These conditions allow us to evaluate the contribution of (a) compatibility between current stimulus position and required response (stimulus-action compatibility), and (b) compatibility between intended stimulus changes and required response (action-change compatibility). The compatibility between the intended end state of the stimulus and required actions (action-end state compatibility) remained at a constant neutral level and did thus not contribute to performance differences between conditions here (cf. Figure 2).

The figure shows an arbitrarily selected time point during the course of the experiment. Though arbitrarily selected, the following analysis applies to each and every point in time of the experiment (except to those in which the cursor was in the intended center position, or the participants failed to touch the screen). The stimulus is currently on the left side requiring compensation to move it back.

With a straight transformation, the required action (rightward) is spatially incompatible to the stimulus position (left), spatially *compatible* to the intended stimulus change (to the right), and neutral to the intended end state of the stimulus (always middle position). With a reversed transformation, however, the required action (leftward) is spatially compatible to the stimulus position (left) but *incompatible* to the intended stimulus change (to the right), and again neutral with respect to the intended end state (middle). The question is now, what will determine performance? If stimulus-action compatibility counts, the reversed transformation condition should be superior (in terms of the mean squared deviation of the cursor from the middle target position) to the straight transformation condition, because here, compensation movements always require a movement toward the current stimulus position. If, however, action-change compatibility affects performance, the straight condition should be superior to the reversed condition. If actions are governed solely by the intended perceptual end state irrespective of the current action-change compatibility, no difference between the two conditions should occur.

Method

Participants. We recruited 24 participants (mean age = 23.63 years, 18 female, 3 left-handed). Handedness was determined via self-report, and all participants further reported normal vision and hearing. They were naïve concerning the hypotheses of the experiment. Participants either got course credit or 3 Euro as compensation for participation in all experiments and signed informed consent.

Apparatus and stimuli. We used an iPad on which a stimulus disk (60 pixels, 1.2 cm in diameter) was presented on the vertical midline. The iPad was fixed in landscape mode on a table and tilted by about 20 degrees relative to the table area toward the observer. The cursor moved with a speed of 160 pixels (3.20 cm) per second along the *x*-axis. The cursor position was updated every 50 ms. The movement direction of the cursor disk was varied randomly every 1, 2, or 3 s, unless the cursor reached the left or right end position of the screen. In the straight condition, the horizontal position of the finger on the tablet was subtracted from the position of the cursor. If, for example, the cursor moved rightward and the finger moved leftward with the same speed, the cursor remained in its position. In the reversed condition, the movement of the finger was transformed into a mirror-reversed movement of the cursor. Hence, when the cursor moved rightward, a rightward movement of the finger of the same speed resulted in full compensation of the cursor movement. We recorded the position of the stimulus and participants finger every 50 ms. Further, we recorded whether the participants' finger touched the screen at any given data point.

Procedure. Participants were instructed to keep the stimulus disk on a fixed target circle (60 pixels, 1.2 cm) on the horizontal midpoint by moving a slider near the bottom of the screen with the index finger of their dominant hand. Whenever the disk they controlled deviated more than 240 pixels from the central goal state, a warning tone occurred that signaled enhanced need for control. Data was collected in single sessions. The order of the straight and reversed conditions was counterbalanced. After finishing the first condition, a screen informed them that they resume with a different transformation. They then started with the second condition. The average time participants spent on the experiment was 13.42 min ($SD = 0.22$).

Data treatment. First, we analyzed the proportion of time that participants touched the screen to determine whether they performed the task properly. One participant touched the screen less than 50% of the time and was therefore excluded from further analysis. We also excluded the first 40 s of the tracking task of each participant in each condition as practice period and the data points in which participants did not touch the screen (3.64% of all collected time points). We measured for each time point the difference between cursor and middle target position in pixels and computed the squared error. We excluded time points in which the squared error value exceeded 2.5 *SD*s of the cell mean of each participant and condition (2.4% of the data points). The square root of the mean of the remaining data points gave us the RMSE as a measure of tracking performance.

Results and Discussion

A mixed analysis of variances (ANOVA) was run on the RMSE of all participants with the within-subjects factor transformation (straight vs. reversed) and the between-subjects fac-

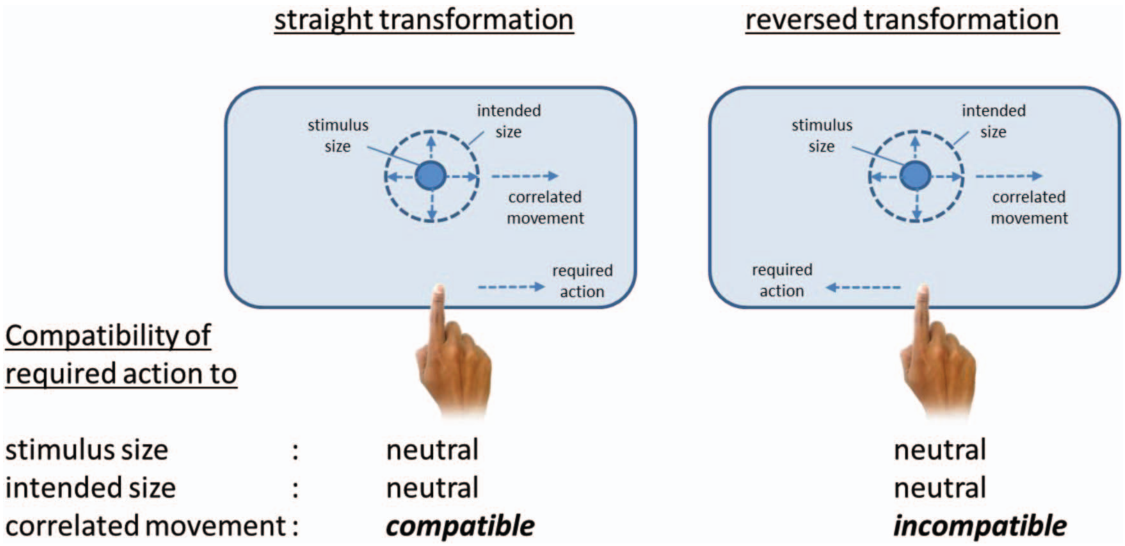

Figure 3. Procedure in Experiment 2. A randomly size-varying cursor had to be brought in alignment with a prescribed size by left versus right finger movements. The cursor moved in parallel or mirror-reversed to the finger. See the online article for the color version of this figure.

tor order of the transformations (straight first vs. reversed first). Neither the between-subjects factor order, nor the interaction with transformation was significant, F values < 1. Crucially, the within-subjects factor transformation was significant, $F(1, 21) = 21.54$, $p < .001$, $\eta_p^2 = .51$. RMSE in the straight condition ($M = 74.89$, $SD = 18.84$) was smaller than in the reversed condition ($M = 106.27$, $SD = 41.94$), indicating better tracking performance.

One contribution to the overall RMSE effects could be that participants tend to behave according to preexperimentally established action-effect associations ("To move something to the left, I have to make a left movement"). If this was so, participants should more likely initiate movements that increase rather than decrease error in the reversed transformation condition.[1] To shed light on this, we looked for time points in which the random perturbation of the cursor afforded a movement in one direction, but participants actually moved in the other direction. Such data points were counted as "direction errors." In the straight transformation condition, participants moved in the wrong direction in 23.64% of all data points, whereas this happened in 31.00% of data points in the reversed transformation condition, $t(22) = -5.60$, $p < .001$, $d = 1.16$. This suggests that one component of the increased RMSE with reversed transformation is the tendency to initiate, or failing to stop, error increasing movements.

The superior performance in the straight compared with the reversed condition appears remarkable to us, since the straight condition is the one in which cursor position (e.g., on the left of the screen) was spatially incompatible to the required response (rightward), and can thus be construed as S-R *in*compatible. One may argue, though, that the stimulus position was to some extent coded with respect to the finger rather than the screen. For example, when the cursor is currently on the right side of the screen but the finger is even further to the right, a leftward finger movement was required, with the stimulus currently being left of the finger. This might be construed as a time point in which stimulus and required response were actually S-R compatible rather than incompatible. This scenario happens whenever the finger was in a more lateral position than the cursor. However, this seems an unlikely explanation given that the screen center was the task-relevant point of reference. Moreover, such time points were rare (4.66% of all time points) and excluding them did not change the impact of transformation on RMSE, $F(1, 21) = 20.10$, $p < .001$, $\eta_p^2 = .49$, with $M = 73.74$ ($SD = 18.42$) for straight and $M = 101.28$ ($SD = 39.52$) for the reversed condition respectively.

Our results accord with previous observations on tracking tasks. Ehrenstein, Cavonius, and Lewke (1994) found that tracking performance dropped when orientation discrepancies between target directions and manual tracking directions were introduced. Performance was worst with an orientation discrepancy of 180°, which corresponds to our reversed condition. The authors attributed this to "spatial compatibility." Yet, they did not consider that different types of compatibility relations existed, and did not reveal which of these relations was eventually effective, as we could by directly comparing straight and reversed transformations.

Altogether, the results of Experiment 1 reveal that it is harder to control a stimulus when intended stimulus changes and required motor actions are spatially incompatible to each other, while the intended stimulus end state and motor actions remained constantly in a spatially neutral relationship. We thus conclude that intended perceptual *changes* have the power to affect action control.

Experiment 2: Tracking a Nonspatial Stimulus Feature With Correlated Spatial Changes

In Experiment 1, stimulus position was the task-relevant stimulus feature, akin to stimulus response compatibility proper. In Experiment 2, the task-relevant feature was nonspatial, namely cursor size (cf.

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[1] We thank a reviewer for calling our attention to this point.

Figure 3). Still, despite being task-irrelevant, stimulus position changed either congruently or incongruently with finger position. Thereby, we tested whether changes of stimulus features that are highly overlapping with action features impact performance, even when they are nominally task-irrelevant.

Specifically, participants had to maintain a certain size of a randomly growing and shrinking cursor by means of left or right finger movements. If, for example, the cursor was too small, a rightward movement of the finger was required, whereas when the cursor was too large, a leftward movement was required. Importantly, the cursor moved systematically with the finger in an either parallel or mirror-reversed manner as well. Consequently, the required size change of the cursor came along with, and could be translated into, a required movement direction of the cursor: For example, a cursor being too small should move to the right, whereas a cursor being too large should move to the left. Please note, because of the random variation of the cursor size, the required end position of the cursor was essentially unpredictable, only the required movement direction was.

So given the lack of dimensional overlap between cursor size and spatial finger movement, only the *inferred* required cursor direction overlapped with the required finger movement. We predicted that participants would tend to translate required size changes into required cursor movements, which again should be brought about easier by spatially compatible rather than incompatible finger movements.

Method

Participants. As the transformation was nominally task-irrelevant this time and there is barely any dimensional overlap between the size attribute of the stimulus and location transformation, we expected the interference by the reversed transformation to be smaller than in Experiment 1 and decided to double the number of participants to 48 (mean age = 27.92 years, 35 female, 4 left-handed).

Apparatus, stimuli, and procedure. Participants were instructed to track the size of a disk appearing on the midline of *y*-axis of the screen. A target circle of 60 pixels in diameter was always displayed, and the target disk size could range from 0 to 120 pixels in diameter. The disk size was updated every 50 ms. The size randomly increased or decreased every 1, 2, or 3 s by 0.4 cm per second, unless participants compensated these size changes. Please note, these random size changes occurred independently of the position of the cursor. So keeping the cursor in the middle position (as in Experiment 1) was not a useful strategy here. Actually, the cursor started in the middle position, and remained there if participants did nothing. So keeping the cursor at certain (e.g., middle) position would maximize the error measure to the same extent as not compensating for random size changes at all. Whenever the deviation from the target circle was more than 30 pixels, a warning tone occurred that signaled enhanced control affordances. Disk size was affected by the finger position, for example, finger movements to the right increased disk size for one half of the participants, but decreased it for the other half. Finger movements of 8 pixels changed disk size by 1 pixel. On top of disk size, the finger position also affected disk and target position. With a straight transformation, disk and target jointly moved in parallel and directly above the finger, whereas disk and target jointly moved mirror-reversed to the finger in the reversed condition. The spatial transformation changed midexperiment after participants were allowed to take a short break. Order of spatial transformation conditions and mapping of movement direction to size change (whether a movement to the right shrinks or enlarges the disk) was counterbalanced across participants. Mapping of movement direction to size change was constant over the course of the experiment. Data treatment was analogous to Experiment 1. Participants took on average 13.46 min (*SD* = 0.41) to complete the experiment. One participant was excluded for insufficiently touching the screen during the whole experiment (less than 30% of the time). Additionally, time points at which the screen was not touched (1.33%), or the squared deviation between instructed and actual cursor size deviated more than 2.5 *SD*s of the individual cell mean (1.8%) were excluded.

Results and Discussion

We subjected the RMSEs (root mean squared error of the absolute difference between target size and actual disk size in pixels) to a three-way ANOVA with the within subjects factors transformation (straight vs. reversed) and the two between factors mapping (right-enlarge vs. right-shrink) and order of transformation conditions (straight first vs. reversed first). Neither mapping nor order yielded a significant main effect, *F* values < 1. Most importantly, a significant effect of transformation showed that participants performed worse with the reversed transformation condition ($M = 14.37$, $SD = 3.20$) than with the straight transformation ($M = 13.49$, $SD = 2.16$), $F(1, 43) = 6.39$, $p = .015$, $\eta_p^2 = .13$, see Figure 4). Neither the three-way interaction, $F < 1$, nor the two-way interaction between transformation and order, $F(1, 43) = 3.16$, $p = .083$, $\eta_p^2 = .07$, nor the two-way interaction between mapping and transformation, $F < 1$, was significant.

Experiment 2 shows that participants face problems when motor actions change stimuli in a spatially incongruent manner while controlling a stimulus feature that was unrelated to the cursor's spatial position. The required changes of the nonspatial cursor feature, however, went along with the required changes of the cursor in the horizontal position. This allowed to "translate" re-

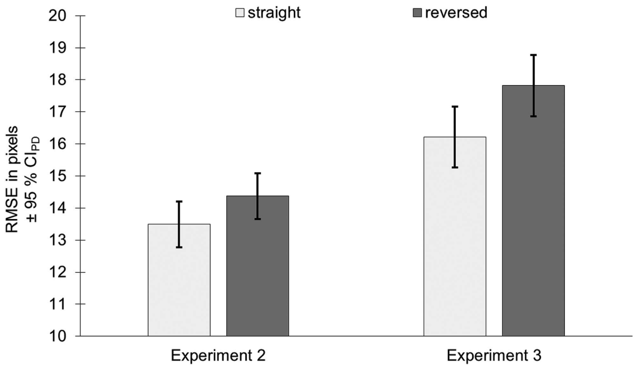

Figure 4. RSME of Experiment 2 and Experiment 3 in pixels, separated by transformation condition. Error bars represent 95% confidence intervals of paired differences, calculated separately for each experiment (CI_{PD}; Pfister & Janczyk, 2013).

quired size changes into required positional changes. Assuming that such translation actually occurred, the results confirm those of Experiment 1, showing that required changes of stimulus position are more easily brought about by motor actions that are spatially congruent to these inferred changes. Again, the compatibility was one between intended stimulus *changes* and required motor actions, confirming the conclusion of Experiment 1 that stimulus changes can play a role in action control.

Experiment 3: Tracking Task-Irrelevant Stimulus Changes Without Vision of the Action

Experiment 1 and 2 show that it is easier to generate hand movements that compensate for visual-spatial disturbances of a visual stimulus when hand and stimulus move in a spatially congruent manner. But what exactly creates the problems with cursor movements that are incongruent to hand movements? Ideomotor models claim that actions such as "hand movements" are represented in terms of the associated sensory effects. There are mainly two things to perceive of a hand movement: we can see and feel the hand moving. Apparently, problems arise when either the visual or proprioceptive component move spatially incompatible to the required cursor movement. With Experiment 3, we aim to scrutinize whether it is the visual or proprioceptive component that creates the problems here. To this end, we removed vision of the hand. Comparing a condition without vision of the hand (Experiment 3) to one with vision (Experiment 2) allows us to estimate the impact of visual codes of hand movements. If visual codes substantially contribute to the observed compatibility effect, the effect should be smaller without vision. If, however, proprioceptive codes of the hand movements were crucial, the effect should remain the same.

Method

Participants and procedure. We recruited 40 participants (mean age = 29.95 years, 22 female, 4 left-handed). Stimuli and procedure were the same as in Experiment 2. The only difference was that participants hand was occluded from view by an opaque black foil, which covered the hand and arm up to the shoulder. This foil was attached to the iPad and to a cord around the participants' neck.

Results and Discussion

Two participants had to be excluded due to low rate of touching the screen. Data from time points at which the screen was not touched (8.71%), or the squared error deviated more than 2.5 *SD*s from the individual cell means (1.9%), were discarded. Again, we calculated a three-way ANOVA with the within-subjects factor transformation (straight vs. reversed) and the between-subjects factors order (straight first vs. reversed first) and mapping (right-enlarge vs. right-shrink). No main effect, nor any interaction reached significance (all p values $> .148$) except for the predicted main effect of transformation, $F(1, 34) = 8.194$, $p = .007$, $\eta_p^2 = .19$. Straight transformation yielded better tracking performance ($M = 16.21$, $SD = 4.84$) than the reversed transformation ($M = 17.81$, $SD = 4.90$, see Figure 4).

To test for possible differences between Experiment 2 and 3, we ran a mixed ANOVA with the within-subjects factor transformation (straight vs. reversed) and the between-subjects factor experiment (2 vs. 3). Apart from the significant main effect of transformation, $F(1, 83) = 18.40$, $p < .001$, $\eta_p^2 = .18$, there was a significant main effect of experiment, $F(1, 83) = 15.25$, $p < .001$, $\eta_p^2 = .16$. Crucially, the interaction was not significant, $F(1, 83) = 1.57$, $p = .213$, $\eta_p^2 = .02$, indicating that the effect of transformation did not differ across Experiments 2 and 3.

To conclude, the congruency effects found without vision of the hand were comparable in size to those observed with vision. Hence, the congruency effects were mainly driven by proprioceptive codes of the hand movements.

General Discussion

There is a long tradition in assuming that motor actions are stored and retrieved in terms of their sensory effects. The basic idea of this so-called ideomotor mechanism is that motor patterns become associated with consistently produced perceptual states, so that either imaging or perceiving such states primes their associated motor patterns (cf. Shin et al., 2010). However, producing a sensory effect implies that there is not only a certain perceptual end state, but a transition of stimulation from a given state prior to the action, to an end state after action execution. Here we asked whether such transitions of stimulation have the potential to contribute to motor control as well. We found that changes of a stimulus that were required to reach a certain perceptual end state are more easily achieved by motor patterns that are spatially compatible rather than incompatible to the required stimulus changes (Experiment 1). Moreover with a high spatial overlap between motor actions and stimulation changes, there is a tendency to code task-relevant size changes in task-irrelevant spatial terms (Experiment 2). Finally, the problems with incompatible hand and cursor movements originate from interference between required visual transitions of the cursor and proprioceptive transitions of the moving hand (Experiment 3).

These observations suggest a central specification of ideomotor theory. If we maintain the core assumption that motor actions were represented by codes of their sensory effects, these codes likely encompass changes from current to intended stimulation, rather than codes of end states alone. Previous research has been ambivalent regarding the potential role of changes of stimulation. Consider the observation that it is harder to generate a manual action that foreseeably flashes a light at a location that is incompatible rather than compatible with respect to that action (Ansorge, 2002; Kunde, 2001). Although this suggests that the compatibility between actions and anticipated stimulation impacts performance, it is impossible to say whether it is the relation of the action to the light "being switched on" (end state) or to the "increase of brightness" (change) that counts here. To answer the question whether the change in stimulation is anticipated, the compatibility of motor actions to end states should remain constant while the compatibility of the action to effect changes should vary. This is exactly what we did here when comparing the straight and reversed transformation conditions. Please note that, based on the present observations, we cannot evaluate whether the recruitment of motor actions in terms of sensory end states is possible as well, since this intended end state (i.e., the cursor stimulus matching the instructed criterion) was intentionally kept constant rather than varied in the present experiments. What we can conclude, though, is that perceptual *changes* play a role in such codes as well.

Figure 5 shows a model that the present observations suggest. Basically, it shows an "ideomotor-enriched" control loop. We assume that agents have no direct access to motor codes, but only to perceptual codes, which are linked to motor codes in a bidirectional manner (Harless, 1861; Hommel, Müsseler, Aschersleben, & Prinz, 2001). However, these perceptual codes represent *transitions* between perceptual states before action execution and perceptual states after action execution (e.g., changes). Such transition codes are linked to motor patterns by repeatedly experiencing which motor patterns go along with, and thus likely produce, which transitions.

When an action has to be generated, the perceptual state after action execution represents an intended goal state. Activating a transition that bridges current to intended stimulation primes a corresponding motor code, and can eventually result in action execution. This changes the current situation, and thus the actual stimulation in the next time step and so on. Actions normally produce transitions in different modalities such as vision and proprioception. Either of these transitions can, in principle, serve to represent and recollect a corresponding motor pattern. Interference arises when required transitions in one modality (e.g., vision) mismatch transitions in another modality (e.g., proprioception) with respect to spatial and possibly other features. Conceivably, this interference accounts for the deteriorated performance in the current action-change incompatible conditions, in which visual and proprioceptive transitions spatially mismatch. This model is an admittedly coarse level of description. But even at this stage, we believe, it prompts some interesting conclusions.

Contextualization

First, the foundation of voluntary action with respect to learning is probably more complicated than traditional Jamesian models suggest. Ideomotor action outcome learning is often exemplified as follows: "accidentally touching a light switch and turning on the light would create an association between the representation of the light being on and the motor pattern of touching the switch" (Watson et al., 2015, p. 45). However, what humans acquire during learning are possibly not links between motor patterns and certain perceptual end states (e.g., a light being on) rather than links between motor patterns and transitions of stimulation (e.g., a light turning from being off to being on). Everything else regarding learning might be as ideomotor theory suggests, namely that motor patterns are linked to such transitions by repeated experience and that this happens automatically (Hommel, 2009).

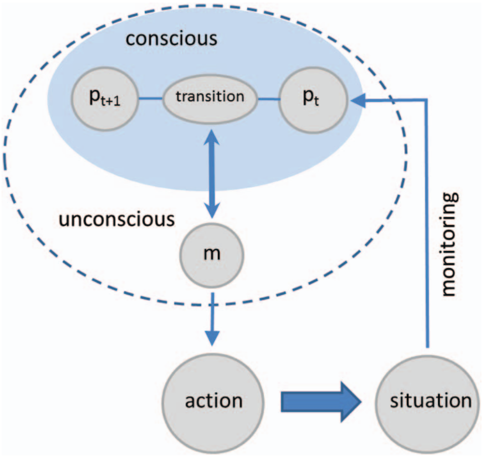

Figure 5. An ideomotor action control loop based on linkages between motor codes (*m*) and transitions from current percepts (p_t) to future percepts (p_{t+1}). See the online article for the color version of this figure.

This apparently moderate modification would settle an important "to do" of the ideomotor approach, namely to solve the problem of contextualization. The problem is that the same end state is often achieved by completely different motor patterns depending on varying current states. Obviously people somehow solve that problem, as our participants did in Experiment 1, where the same end state (the cursor in the middle) had to be achieved by different motor actions depending on the current position of the cursor. We suggest that participants did so, because they learned which motor patterns transform a currently given cursor position into the intended cursor end position. There have been related suggestions how ideomotor learning solves the contextualization problem, such as the creation of state-action-effects triples, so that motor actions are bound to both, sensory states that precede the action as well as effects that follow it (Herbort & Butz, 2012). However, this solution is eventually equivalent to the idea that actions are bound to transitions from current to subsequent stimulation. Another way to achieve contextualization to some extent is that intended end states are bound to relatively coarse codes of motor patterns that allow the generation of a first motoric "guess" to achieve an end state, while context-dependent variations of the eventually required motor actions are controlled online (Hommel, 2015).

Another consequence of assuming that motor patterns are linked to transitions rather than end states is that nothing is learned when no sensory transitions occur. Consider that an actor did not know whether a room light was on or off before she pressed the light switch (e.g., because she entered the room with closed eyes). Would she learn that her pressing the light switch caused the light bulb to flash? This seems unlikely. Conceivably, such lack of learning accounts for the "refrigerator light illusion." People tend to believe that the fridge light is on all the time because they miss to perceive that their action of opening the fridge door actually switches the light on. One may say that the action produced no "effect" here, but that boils down to saying that an "effect" implies a change of perception, which is what we suggest here. Conversely, people should learn to control their actions if previously unnoticeable perceptual changes of their actions are made noticeable. This is the case when performers improve body control by receiving augmented sensory action feedback (Todorov, Shadmehr, & Bizzi, 1997).

The Circular Reflex Problem

If motor patterns are linked to perceptual effects, the successful production, and thus perception, of that effect should, in theory, prime the same motor pattern over and over again. Such a behavioral perseveration cycle is useless at best, or even dysfunctional, because the organism risks that a just successfully produced intended state is removed again. Greenwald (1970) suggested that the circular reflex is avoided and does barely happen in practice because priming of motor actions can be attributed "to the image of feedback from an action rather than to the feedback itself" (p. 86). We suggest a slightly different solution of the problem: Codes of intended end states, be they imagined or actually perceived, might not prime motor codes at all, whereas codes of transitions between actual and intended states would do so. Please consider that when in Figure 5 an action was successfully carried out, hence the current perceptual state (p_t) matches the intended one (p_{t+1}), there is no discrepancy left anymore that could prime a motor pattern. Hence, assuming that motor codes are linked to transitions between two perceptual states removes the circular reflex problem theoretically and explains why it barely occurs empirically.

Multimodal Transition Codes

Motor actions typically produce, and can become linked to, perceptual effects in various modalities. We know already that actors have considerable degrees of freedom to represent their motor actions, for example, in terms of visual or tactile reafferences (Memelink & Hommel, 2013). For example, Hommel (1993) observed that stimuli primed responses that were spatially compatible to either the tactile or visual consequences of the responses depending on instructions. It is important to note, though, that the question of whether one effect modality is weighted more than another is orthogonal to the question whether these effects represent end states or transitions of perception. Existing evidence for such weighting is perfectly compatible with our suggestion that motor codes are linked to perceptual transitions.

However, weighting one effect modality more than another seems limited under the present conditions (Janczyk, Pfister, & Kunde, 2012). We suggest that the inferior performance with reversed cursor transformations, which we consistently observed in all three experiments, occurs because the same motor patterns become invoked by spatially incompatible visual and proprioceptive transitions. For example, in the reversed conditions, the motor patterns that move the finger rightward, become (or remain) linked to proprioceptive transitions of moving rightward, whereas they become linked to visual transitions of the cursor moving leftward. This conceivably creates interference between spatially incompatible proprioceptive and visual codes when it comes to generate a motor pattern that is linked to both codes. This interference would be completely removed if the performers managed to retrieve their motor action in terms of one modality only. Apparently they fail to do so, and this, we believe, is the reason for why performance deteriorates with reversed transformation despite instructions to focus on visual consequences alone (i.e., the position or size of the cursor). Similar observations have been made with other forms of spatial incompatibility such as when up-down motor actions produce task-irrelevant up-down scrolling movements of content on a computer display (Chen & Proctor, 2013).

An interesting implication of the assumption that the present reversed transformation costs derive from mutually incompatible visual and tactile transition codes is that there should be no compatibility effects without proprioception of the moving body. This can happen in patients such as Ian Waterman (Cole & Cole, 1995). Ideomotor theory assumes that motor patterns can be linked to visual feedback as well as proprioceptive feedback. So even agents without proprioception can learn to recruit motor patterns through retrieval of visual consequences of these patterns, and they should thus learn to control a visual cursor as well. But unlike the healthy participants tested here, it should not make a difference whether they do so by compatible or incompatible hand movements.

Limitations of the Present Study

A limitation to the current study is that we did not record eye movements. Participants might have tracked the cursor with their eyes. In reversed conditions, ocular tracking could have been harder because finger and eyes moved more frequently in opposite directions as compared with the straight condition. Shorter or less likely fixation of the cursor in the reversed transformation condition may have contributed to reduced tracking performance.

The role of eye movements in tracking compatible versus incompatible consequences of manual actions has recently been studied by Pfeuffer, Kiesel, and Huestegge (in press). These authors found that participants spontaneously move their eyes toward expected visual effects of manual actions. Interestingly, participants do so equally efficiently irrespective of whether the manual actions produce spatially compatible or incompatible effects. So when observers monitor the visual consequences of their manual actions, so as participants in the present study possibly did, there seems to be little interference between manual and ocular actions. In any case, the contribution of eye movements to the present observations should be studied further. One way to do so was by using nonspatial compatibility effects where eye movements play no role (e.g., Dignath, Pfister, Eder, Kiesel, & Kunde, 2014; Kunde, 2001, Exp. 2; Kunde, 2003). This could be done by devising a tracking task in which auditory intensity is tracked by a continuous application of finger force.

Conclusion

To conclude, we believe that the present study helps to bridge an unnecessary gap between research inspired by control theory, which describes how agents compensate discrepancies between intended and actual states in technical terms, and research inspired by ideomotor theory, which is traditionally more concerned with the question how humans eventually bring about intended perceptions. Continuous paradigms like the ones used in the present studies can provide a different angle on the interplay of perception and action than the prevailing reaction time (RT) paradigms and bring control theory and ideomotor approaches closer together to paint a more complete picture of human behavior.

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