

Dissecting the response in response–effect compatibility

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Abstract Voluntary actions are guided by sensory anticipations of body-related as well as environment-related action effects. Even though action effects in the environment typically resemble the action goal proper, anticipations of body-related effects can cause interference if they do not correspond to intended environment-related effects. The present study explored which specific response features cause such interference: the spatial location of the moving limb or its anatomical connection to the body causes such interference? Using a response–effect compatibility design with normal and crossed hand-key mappings, we show that environment-related effects are predominantly related to spatial rather than anatomical response features, ensuring that goal-directed behavior is flexible and efficient at the same time. Furthermore, results indicate that this mechanism applies to both, free- and forced-choice actions.

Keywords Action control · Effect anticipations · Spatial versus anatomical codes · Ideomotor theory

Introduction

Human actions typically aim at reaching a certain goal, that is, they are carried out to produce desirable changes in the environment; these environmental changes are registered as changes in sensory input. Recent investigations have gathered considerable evidence for anticipative processes mediating between such goals and actions (Hommel et al.

2001; Kunde 2001; Shin et al. 2010).¹ More precisely, ideomotor accounts to human action assume that sensory anticipations automatically elicit actions via bidirectional action–effect associations.

The processes underlying the anticipation of action effects can be studied experimentally in *response–effect (R-E) compatibility* designs (Kunde 2001; Pfister et al. 2010). Such designs employ actions and contingent sensory effects that overlap on any physical dimension (space, time, or intensity). In R-E compatible conditions, actions predictably produce effects that share some features with the action (e.g., left-key presses triggering left visual action effects). In R-E incompatible conditions, however, actions predictably produce effects with different features than the action itself (e.g., left-key presses triggering right visual action effects). Typically, actions are initiated more quickly when they produce compatible as compared to incompatible action effects (e.g., Kunde 2001; Kunde et al. 2004; Pfister et al. 2010; Rieger 2007). Because the action effects only occur *after* the action is carried out, this finding indicates that effect anticipations play a functional role in action initiation.

From the perspective of a “strong ideomotor theory” (Shin et al. 2010), actions are exhaustively represented by their sensory re-afferences. There exists no “response” in the form of a pure motor pattern in the cognitive system. Therefore, the term “response”–effect compatibility is perhaps better described as effect–effect compatibility, that is, compatibility between the various re-afferences of a

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¹ The term *goal* is used very heterogeneously in the psychological literature and can refer to both the spatial end point of a movement and more abstract goals such as intended changes in the environment. For the following argument, we will use the term *goal* exclusively with the latter connotation, whereas we refer to a movement's end point as *spatial response feature*.

given motor output. These re-afferences can be separated into *environment-related* effects (such as lights or tones) and *body-related* effects (such as proprioceptive or visual experiences from the moving effector itself, cf. also James' 1890 distinction of remote and resident effects). Conceivably, both types of effects become linked to certain motor activity by learning, but body-related effects (proprioceptive effects in particular) are linked to more specific motor patterns than environment-related effects. What "response"–effect compatibility probably reflects is the compatibility between environment-related and body-related effects of a to-be-generated motor pattern (Fig. 1).

On closer inspection, the situation becomes even more complicated, because each motor activity typically causes several environment-related effects. Pressing a key, for example, may switch on a light and produce a click at the same time. This is also true for body-related effects: A key press may include the visual experience of the moving finger as well as proprioceptive changes that correspond to the executed movements. At present, it is unknown which body-related effects are primed by anticipated environment-related effects in R-E compatibility. There is, however, a relatively easy way to disentangle the contribution of at least two aspects of body-related effects, namely the spatial position of the moving limb and its anatomical connection to the body. These are disentangled when participants cross their hands, such that the right hand operates a key on the left side of the body and the left hand operates a key on the right side of the body. This setup allows studying whether environment-related effects have to

correspond to the hand position or the anatomical connection to facilitate responding.

Crossed-hands manipulations have often revealed a dominant role of limb position over anatomical connection. For example, in spatial R-E compatibility, stimuli prime responses mostly regarding the position of the hand and not regarding the anatomical mapping (Simon et al. 1970; Wallace 1971). Likewise, the perception of spatial stimuli is affected by the planning of spatially corresponding actions, again in terms of the position of the hand not in terms of the anatomical connection (Kunde and Wühr 2004).

There are, however, also observations for a distinct role of anatomical features in R-E learning and effect-based response priming (Hoffmann et al. 2009). Participants in this study learned the contingency between manual key presses and low- or high-pitched tones. In a subsequent test phase, some participants were asked to respond to the tones either with a constant key-tone mapping (non-reversal group) or a changed mapping (reversal group) relative to the acquisition phase. Participants in the non-reversal group responded faster due to exogenous response priming by previously experienced action effects (cf. Elsner and Hommel 2001). To test whether the tones had been linked to certain motor patterns (deflecting the left or right index finger) or to the keys that were operated by the fingers, some participants worked through the test phase with crossed hands after having completed the learning phase with normal key-tone mapping (see also Ticini et al. 2012). If direct links between motor patterns and tones had been acquired, the typical non-reversal advantage should turn into a reversal advantage for these participants. This was not observed, however. Instead, reversal and non-reversal group revealed the same level of performance.

To account for this outcome, Hoffmann et al. (2009) suggested that effect tones did not directly prime certain motor patterns but certain body-related action features, namely anatomical features (e.g., left arm) as well as spatial features (e.g., position of the left hand relative to the body) to a similar degree. They further speculated that body-related effects might generally mediate between environment-related effects and motor activity. In any case, the observation suggests that environment-related effects can, in principle, interact simultaneously with several body-related features. The acquisition of multiple associations is in line with the idea of automatic feature integration across perception and action (Hommel 1996, 2004; Hommel et al. 2004). Previous findings and theoretical accounts suggest that all features of actions and effects are used automatically to form "action concepts" with some features being intentionally weighted differently than other features (Hommel 1996; Memelink and Hommel 2012).

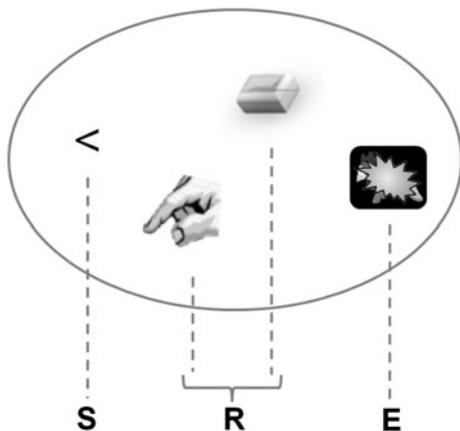


Fig. 1 Schematic of different feature codes which are integrated in an action concept. This exemplar action concept includes the relevant stimuli (S), anatomical and response features (R; codes relating to the effector and the intended end point of a movement, respectively), as well as effect codes corresponding to intended changes in the environment (E). From the perspective of ideomotor theory, an action can be addressed by both, body-related action effects (R) and environment-related action effects (E)

To summarize, previous research makes different predictions about the contributions of spatial and anatomical features to R-E compatibility. Therefore, we combined the crossed-hands setup with an R-E compatibility paradigm. If both anatomical and spatial features of the learned R-E relation are weighted equally (Hoffmann et al. 2009), R-E compatibility effects should at least depend partly on the hand-key mapping. If action planning preferentially exploits spatial action features, the R-E compatibility effect should only depend on the key location, irrespective of the effector involved. As an additional variation, we investigated this mechanism for both freely chosen actions and forced-choice actions. This manipulation was shown to impact ideomotor action control in certain instances even though the exact differences between these types of actions are still debated (e.g., Herwig et al. 2007; Herwig and Horstmann 2011; Pfister et al. 2010, 2011; Wolfensteller and Ruge 2011).

Experiment 1

Participants pressed a left or right response key to produce a salient visual action effect. More precisely, centrally presented target stimuli prompted participants to shoot virtual chicken on the left or right side of the monitor, and the shot chickens (action effects) were only visible after the key press action. Crucially, we varied the mapping of action effects to the response keys (compatible vs. incompatible) as well as the assignment of the participant's hands to the response keys (normal vs. crossed; cf. Fig. 2). If ideomotor effect anticipations are equally related to spatial and anatomical features, R-E compatibility effects should be reduced or even reversed with crossed hands (Hoffmann et al. 2009). However, if ideomotor action control mainly draws on spatial features of the operating effector, similar R-E compatibility effects should emerge for both, the normal and the crossed-hands condition (e.g., Hommel 1993; Kunde and Wühr 2004).

On first inspection, the employed design resembles that of Hommel (1993) who investigated the Simon effect as a classical example of stimulus-response (S-R) compatibility. As in the current study, responses produced left or right visual action effects; the location of these effects and the location of the target stimuli could either correspond to spatial and anatomical features of the action or not. In this study, the observed Simon effect depended mainly on the overlap between stimulus location and intended effect location, even though both, spatial and anatomical response features also contributed reliably to the results. In fact, this experiment already included several control conditions that were highly similar to the present experiments (Hommel 1993, Experiment 2, conditions 3, 6, 9, and 12). These

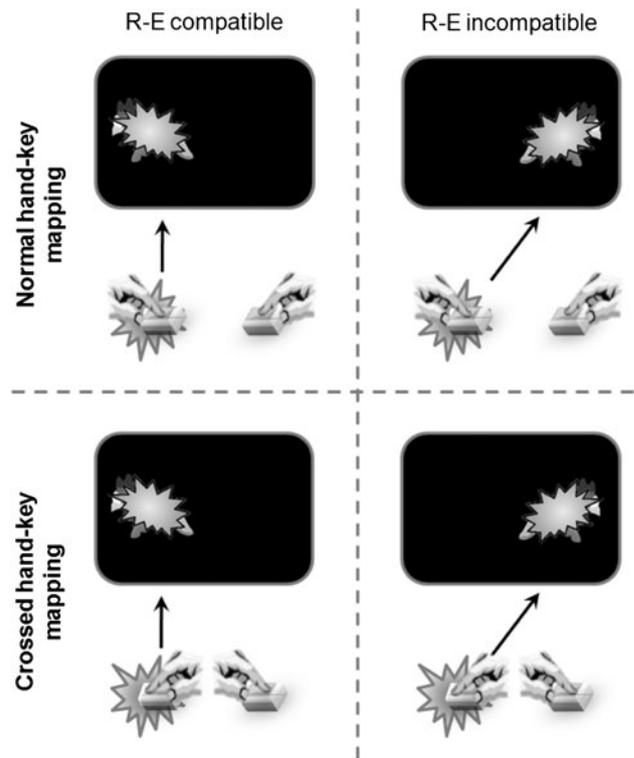


Fig. 2 Participants pressed a *left* or *right* response button to produce a visual action effect on the *left* or *right* side of the computer screen; they typically react faster in the R-E compatible condition ($R_{\text{left}} > E_{\text{left}}$) than in the R-E incompatible condition ($R_{\text{left}} > E_{\text{right}}$; responses are coded with respect to the key location). With a normal hand-key mapping (*top row*), the contributions of anatomical response features and spatial response features to this effect are confounded (e.g., “*left hand*” vs. “*hand located to the left of the body*”). With a *crossed* hand-key mapping (*bottom row*), anatomical, and spatial features counteract each other and can be dissociated experimentally

conditions employed target stimuli that appeared simultaneously to the left and to the right (tones played by two speakers). This rendered stimulus-effect compatibility as well as S-R compatibility neutral and allows for a direct assessment of R-E compatibility. For uncrossed hands, Hommel (1993) observed responses to be 10 ms faster when they led to compatible effects than to incompatible effects. An even stronger effect of 38 ms emerged for the crossed-hands condition (coded according to the response key). These results can be taken as first evidence that R-E compatibility effects are mainly driven by spatial rather than anatomical response features. Please note, however, that these differences were not statistically tested in this study because the mentioned conditions represented control conditions that were implemented for a different purpose. The present study aims at replicating these conditions with explicit focus on R-E compatibility.

Furthermore, we contrasted free-choice actions and forced-choice actions within this design. This manipulation

is based on recent findings that suggested R-E learning to be diminished or absent for forced-choice settings (Herwig et al. 2007; but see Pfister et al. 2011; Wolfensteller and Ruge 2011). First evidence also indicates that freely chosen actions have a stronger tendency to employ anticipations of environment-related effects than forced-choice actions (Pfister et al. 2010). These findings, however, result from R-E compatibility designs that used context-specific (i.e., trial-by-trial varying) relations between actions and effects which decrease the overall impact of environment-related effect anticipations (see also Ansorge 2002). For conditions with more enduring action–effect relations (i.e., block designs), R-E compatibility effects can be obtained for both types of actions (e.g., Kunde 2001; Kunde et al. 2011; Rieger 2007). As of to date, the difference between both types of actions was not investigated systematically for these settings.

Taken together, we expected a standard R-E compatibility effect to occur for the normal hand-key mapping. In the crossed-hands condition, we expected the R-E compatibility effect to be mainly based on the current key-effect mapping (i.e., driven by spatial response features), whereas it should be less influenced by the current hand-effect mapping (i.e., by anatomical response features). Accordingly, R-E compatibility is coded with respect to the response key hereafter. Furthermore, we expected R-E compatibility effects to be more pronounced in the free-choice condition than in the forced-choice condition.

Methods

Participants and apparatus

Sixteen participants (4 males; 1 left-handed; mean age: 20.7 years) received monetary compensation. The study was framed as a computer game in which participants had to shoot virtual chickens by pressing an external left or right response key. This setting was motivated by the chicken hunter computer game due to the first author's gaming habits (www.moorhuhn.com).

Stimuli appeared on a 17" computer monitor at a viewing distance of approximately 60 cm. In some trials, a target stimulus either prompted the participants to shoot a chicken to the left or to the right (forced-choice; arrow stimuli: "<" vs. ">"), whereas the target stimulus did not specify the response in other trials (free-choice; "!"). Target stimuli were displayed in 24 pt Arial font. Each key press triggered an action effect: a shot chicken appearing either in the left or in the right half of the computer screen, depending on the current compatibility condition. The effect pictures measured 5 cm × 4 cm and appeared at the vertical center of the monitor (at 25 or 75 % of the horizontal axis, respectively).

Response(key)–effect mapping and hand-key mapping varied in different experimental blocks (within-subjects); their order was counterbalanced across participants. At the beginning of each block, participants were informed about the current key-effect and hand-effect mappings by statements such as “In the following block, using left/right hand will shoot to the left/right. Using the left/right key will shoot to the left/right” (in German language). Crucially, participants were instructed in terms of the action effects (cf. Ansorge 2002). A left-pointing arrow thus indicated that a chicken on the left of the screen had to be shot, irrespective of the required key and/or hand. Thus, neither anatomical nor spatial response features were specifically favored by the instructions.² Regarding the free-choice task, participants were instructed to decide spontaneously to produce one or the other action effect without relying on any specific strategy. They were told to choose each alternative about equally often, but it was stressed that the focus should be on spontaneous decisions rather than on a perfectly even distribution of responses. Accordingly, individual distributions of response choices varied to some degree across participants (responses with the left key were chosen in 36.9–64.7 % of the trials with an average of 49.7 %).

Design and procedure

In each trial, a target stimulus appeared for 500 ms, and the participants had a response window of up to 1,000 ms to perform a key press. This key press immediately triggered a shot chicken as a visual action effect which was displayed for 1,000 ms. To increase the saliency of the effects, 1 randomly drawn trial out of 11 trials featured a deviant effect (a chicken flying upside down). Participants had to detect this deviant effect by pressing both response keys simultaneously (cf. Pfister et al. 2010). Wrong key presses, response anticipations, omissions, and missed deviant effects triggered an error message (1,000 ms). The next trial started after a random interval of either 750 or 1,500 ms.

The participants completed 16 blocks of 33 trials each (11 trials for each target stimulus). Each of the four combinations

² Please note that an instruction to use either a specific key or a specific hand would have been likely to bias the participants' coding of the response—at least such an effect would be predicted by an intentional-weighting account (Hommel 1996). The same argument holds true if either key-effect or hand-effect mapping would have been constant throughout the experiment, rendering the constant mapping more reliable than the other mapping. This, however, was not the question of the present study. Instead, we aimed at studying which feature would be used preferentially if participants can freely choose what to do in situations that do not favor one or the other feature.

of key-effect mapping (compatible vs. incompatible) and hand-key mapping (normal vs. crossed) was presented in four consecutive blocks. The first block of each sequence was considered practice and did not enter the analysis.

Results

We excluded trials with errors (4.8 %) and corrected for outliers by removing trials with a reaction time (RT) that differed more than 2.5 standard deviations from the mean of the respective design cell (2.3 %), calculated separately for each participant. We then conducted a $2 \times 2 \times 2$ within-subjects ANOVA with the factors R-E compatibility (compatible vs. incompatible; coded with respect to the response key), hand-key mapping (normal vs. crossed), and choice mode (free vs. forced; see Fig. 3).

This analysis revealed a pronounced impact of R-E compatibility: Responses were faster when spatial location of the key and the action effect were compatible than when they were not (413 vs. 449 ms), $F(1, 15) = 52.15$, $p < .001$, $\eta_p^2 = .78$. Crucially, this effect was equally strong for normal and for crossed hands as indicated by a nonsignificant interaction of R-E compatibility and hand-key mapping, $F(1, 15) = 0.43$, $p = .523$, $\eta_p^2 = .03$, even though a significant main effect of hand-key mapping indicated faster responses with normal than with crossed hands (421 vs. 440 ms), $F(1, 15) = 8.04$, $p = .013$, $\eta_p^2 = .35$.

Furthermore, freely chosen responses were slower than forced-choice actions (454 vs. 408 ms), $F(1, 15) = 21.40$, $p < .001$, $\eta_p^2 = .59$, and the effects of crossed as compared with normal hands were stronger for forced-choice actions than for free-choice actions, $F(1, 15) = 4.73$, $p = .046$, $\eta_p^2 = .24$. More importantly, however, the factor choice

mode also interacted with R-E compatibility, $F(1, 15) = 24.66$, $p < .001$, $\eta_p^2 = .62$, driven by more pronounced R-E effects for *forced-choice* than for *free-choice* actions. The three-way interaction was not significant, $F(1, 15) = 1.62$, $p = .222$, $\eta_p^2 = .10$.

Discussion

Experiment 1 investigated whether action control via sensory anticipations preferentially relies on anatomical or spatial features of an action (Hoffmann et al. 2009). To this end, we employed an R-E compatibility design and asked our participants to operate the response keys either with normal or crossed hand-key mappings (cf. Fig. 2). The results clearly indicate that spatial rather than anatomical response features are preferentially addressed for action initiation: The R-E compatibility effect depended entirely on the spatial locations of response key and visual action effect, irrespective of the hand used for operating the key.

Furthermore, we tested whether the anticipation of environment-related effects would be moderated by the current action mode (Herwig et al. 2007; Pfister et al. 2011; Wolfensteller and Ruge 2011). More precisely, we expected freely chosen actions to boost anticipations of environment-related effects, that is, to increase R-E compatibility effects. This prediction was motivated by the finding that freely chosen actions (in contrast to forced-choice actions) tend to include such anticipations even when R-E relations vary rapidly depending on their context (Pfister et al. 2010; see also Ansorge 2002; Kiesel and Hoffmann 2004). The results of Experiment 1, however, showed the opposite pattern: R-E compatibility effects were, in fact, more pronounced for forced-choice than for

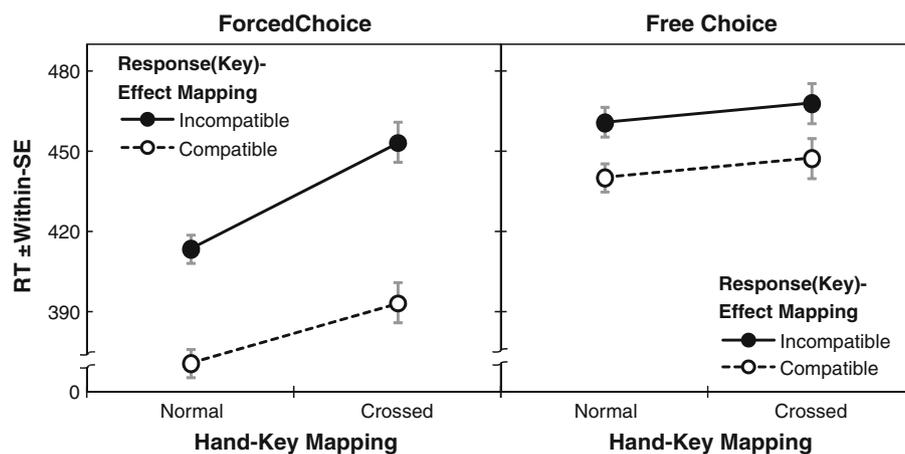


Fig. 3 Results of Experiment 1. Participants responded faster when the mapping of response key and visual action effect was compatible than when it was incompatible, irrespective of the hand that operated the response key. This pattern of results was present for both forced- and free-choice actions and suggests a preference for spatial instead

of anatomical response features in action control. *Error bars* indicate within-subjects *standard errors*, computed separately for each pairwise comparison of R-E compatible and R-E incompatible conditions

free-choice actions. Before drawing definite conclusions from this finding, we wanted to test two possible explanations derived from the present target stimuli (i.e., left- and right-pointing arrows): spatial saliency on the one hand and stimulus-effect congruency on the other hand.

Experiment 2

The first goal of Experiment 2 was to replicate the central finding of Experiment 1, that is, a precedence of spatial instead of anatomical response features for R-E compatibility. Second, Experiment 2 tested the speculation that the reported R-E compatibility effect for forced-choice actions might have been artificially inflated by the use of spatial target stimuli. The relevance of a salient spatial dimension was recently described for other compatibility effects such as the social Simon effect (e.g., Dittrich et al. 2012; Dolk et al. 2011; Guagnano et al. 2010). These studies suggest that compatibility effects between stimuli and responses only emerge when the spatial dimension of the responses is salient (cf. Ansorge and Wühr 2004). The same argument might hold true for R-E compatibility; accordingly, the use of arrows as target stimuli in the forced-choice condition might have assigned a stronger weight to spatial features.

Furthermore, arrow direction and spatial effect location were always congruent because a left-pointing arrow indicated that a chicken on the left had to be shot. This additional stimulus-effect congruency might also have contributed to the effect observed in forced-choice trials (e.g., Kunde et al. 2007; Müsseler and Skottke 2011). Thus, we controlled for the impact of spatial saliency and stimulus-effect congruency by using spatially neutral target stimuli.

Methods

Sixteen new participants were recruited (7 males; 2 left-handed; mean age: 24.9 years). The design was similar to

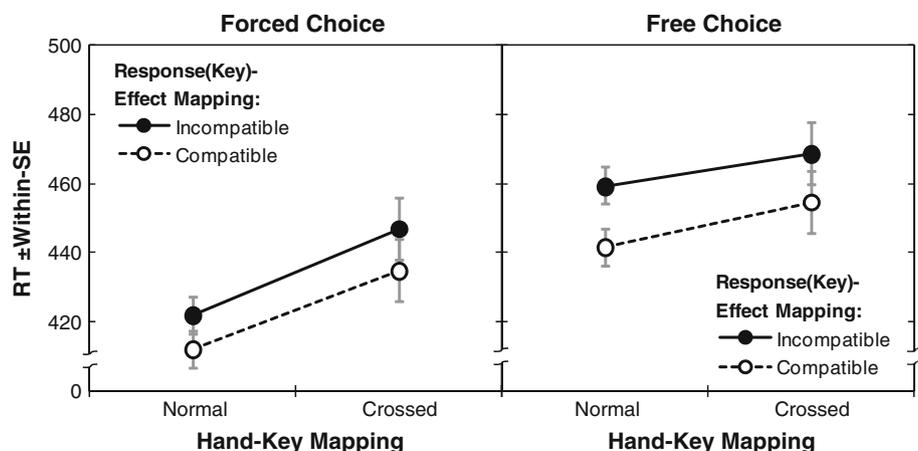
Experiment 1, but the former target stimuli (<, >, !) were replaced by colored circles (blue, orange, and gray; 1 cm × 1 cm). Gray target stimuli always indicated free response choices, whereas blue and orange circles indicated forced choices (left vs. right; counterbalanced across participants). Again, participants chose both keys about equally often in free-choice trials (overall: 46.4 % left-key responses). One participant, however, showed a strong preference for right-key responses (81.8 % of the trials), whereas the remaining participants had a similar distribution as in Experiment 1 (36.4–58.0 % left-key responses). Exploratory analyses ensured that the pattern of results was not driven by the deviating participant.

Results

As in Experiment 1, we excluded trials with errors (7.2 %) and outliers (1.9 %). Mean RTs were then analyzed by means of a $2 \times 2 \times 2$ within-subjects ANOVA with the factors R-E compatibility, hand-key mapping, and choice mode (see Fig. 4). This analysis replicated the impact of R-E compatibility with responses in compatible trials being faster than in incompatible trials (436 vs. 449 ms), $F(1, 15) = 6.24$, $p = .025$, $\eta_p^2 = .29$. Again, this effect was equally strong for normal and for crossed hands, $F(1, 15) = 0.01$, $p = .935$, $\eta_p^2 < .01$, whereas a significant main effect of hand-key mapping indicated faster responses with normal than with crossed hands (434 vs. 451 ms), $F(1, 15) = 5.48$, $p = .033$, $\eta_p^2 = .27$.

Freely chosen responses were again slower than forced-choice responses (456 vs. 429 ms), $F(1, 15) = 17.20$, $p < .001$, $\eta_p^2 = .53$. Crucially, however, the factor choice mode did no longer interact with R-E compatibility, $F(1, 15) = 0.47$, $p = .502$, $\eta_p^2 = .03$. Furthermore, the interaction of choice mode and hand-key mapping approached significance, $F(1, 15) = 3.28$, $p = .090$, $\eta_p^2 = .18$, driven by a numerically more pronounced impact of

Fig. 4 The results of Experiment 2 replicate the preference for spatial instead of anatomical response features. The R-E compatibility effect for forced-choice actions, however, was drastically reduced by using arbitrary, non-spatial target stimuli (rather than *arrow* targets as in Experiment 1). Error bars indicate within-subjects standard errors, computed separately for each pairwise comparison of R-E compatible and R-E incompatible conditions



hand-key mapping for forced-choice actions. The three-way interaction was far from significance ($F < 1$).

Because Experiment 2 was motivated by the unexpected interaction of choice mode and R-E compatibility in Experiment 1, we also compared these effects directly across experiments. This was done by separate $2 \times 2 \times 2$ split-plot ANOVAs for forced- and free-choice actions, respectively. Each ANOVA was run with the between-subjects factor experiment and the within-subjects factors R-E compatibility (compatible vs. incompatible) and hand-key mapping (normal vs. crossed). For forced-choice actions, this analysis yielded a significant interaction between R-E compatibility and experiment, $F(1, 30) = 20.08$, $p < .001$, $\eta_p^2 = .40$, indicating stronger compatibility effects in Experiment 1 than in Experiment 2. This interaction was not present for free-choice actions, $F(1, 30) = 0.34$, $p = .562$, $\eta_p^2 = .01$.

Discussion

Experiment 2 replicated the reported precedence of spatial response features for R-E compatibility effects. Again, R-E compatibility effects were driven by the correspondence of response key and effect location, independent of the effector involved. Contrary to Experiment 1, however, R-E compatibility effects were equally strong for free- and forced-choice responses. This finding suggests that the interaction between R-E compatibility and choice mode in Experiment 1 was indeed driven by spatial features of the target stimuli and, possibly, their correspondence with spatial response features (S-R compatibility; Riggio et al. 1986; Simon et al. 1970) as well as with the to-be-expected effect location (stimulus-effect congruency; Janczyk et al. 2012a; Kunde et al. 2007; Müsseler and Skottke 2011).

General discussion

The present study investigated the contribution of anatomical and spatial response features to ideomotor action control using the R-E compatibility paradigm. Crucially, participants operated a left and a right response key with a normal hand-key mapping in some blocks but with a crossed mapping in other blocks (cf. Hoffmann et al. 2009; Hommel 1993). This procedure allowed us to disentangle the role of spatial and anatomical response features for action control via sensory anticipations. The results showed the R-E compatibility effect to be driven by spatial response features (i.e., the correspondence of hand position and effect location), whereas the effector's anatomical connection (left vs. right arm) did not play an important role in the current setting.

Implications for ideomotor theory

According to ideomotor theory, effect anticipations automatically evoke the associated action (Hommel et al. 2001; Kunde 2001). The present results show that this anticipative process preferentially targets spatial aspects of the moving body part (i.e., the effector location in space) instead of relying on the anatomical connection of the effector to the body (cf. Butz et al. 2007).

This interpretation is in line with several lines of research on perception and action. First of all, research on spatial S-R compatibility (e.g., Ansorge and Wühr 2004; Hommel 2011; Simon and Rudell 1967) indicates that the location of a target stimulus predominantly primes the spatial location of a response and only to a lesser degree its anatomical features (Heister et al. 1990; Klapp et al. 1979; Riggio et al. 1986). Thus, features of perceived stimuli seem to be translated into spatial response features, regardless of the anatomical connection of the effector (but see Conde et al. 2011, for a possible impact of stimulus valence).

Furthermore, this conclusion does not only hold true for the influence of perception on action but also for the influence of action on perception as revealed by studies on action-induced blindness (Müsseler and Hommel 1997; Pfister et al. 2012). Action-induced blindness refers to consistent findings that action planning impairs the perception of conceptually overlapping stimuli; for instance, preparing a “left” action was shown to impair the detection of left-pointing arrows as compared to right-pointing arrows (Müsseler and Hommel 1997). Supporting the present findings, this blindness effect is entirely driven by the spatial target position of the planned action, irrespective of the hand's anatomical connection (Kunde and Wühr 2004). Thus, blindness to left-pointing arrows is induced by planning to operate a left key, irrespective of the hand assigned to the key.

Finally, research on bimanual coordination has shown that salient environment-related action effects have the power to override typical anatomical constraints, such as the usually observed preference for acting with homologous fingers. In fact, this preference is reduced or even reversed if non-homologous fingers produce identical effects in the environment (Janczyk et al. 2009; see also Mechsner et al. 2001; Mechsner and Knoblich 2004; Weigelt et al. 2007). Taken together, these findings suggest a predominance of spatial representations in the human motor system. As such, they also support the present interpretation that ideomotor effect anticipations are preferentially related to spatial response features rather than their anatomical counterparts.

To choose, or not to choose

A second implication of the present experiments concerns the role of freely chosen actions as compared to forced-choice actions. For situations with rapidly varying, contextual R-E relations, freely chosen actions were shown to employ anticipations of environment-related effects more readily than forced-choice actions (Pfister et al. 2010).³ In contrast, the present results suggest that freely chosen actions do not boost the anticipation of environment-related action effects for conditions in which the R-E relation itself is blocked and, consequently, more obvious. Thus, free action choices seem to increase the tendency to anticipate environment-related action effects in conditions that would not normally promote such processes. Similar effects were reported for other factors, for instance, if action effects are rendered task relevant by instruction (Ansorge 2002). Presumably, stable (as compared to context dependent) R-E relations also promote the anticipation of environment-related action effects (e.g., Kunde 2001). If environment-related action effects are anticipated due to such stable R-E relations, free response choices do not seem to increase the overall impact of such anticipations, that is, they do not change ideomotor processing as such.

This interpretation is in line with several recent studies that found R-E compatibility effects for purely forced-choice tasks. For instance, Janczyk et al. (2012b) used a forced-choice task to investigate wheel rotation movements that produced compatible or incompatible rotations of an aircraft-like display. Here, R-E compatibility effects were absent when the continuous rotation movements produced a discrete rotation of the display. In contrast, pronounced and reliable R-E compatibility effects emerged when the saliency of the effects was increased by a continuous translation of manual rotation to display rotation. These findings indicate that R-E compatibility effects do not emerge necessarily for any type of (forced-choice) action; increased effect saliency, in turn, seems to promote the anticipation of environment-related action effects. As noted above, free-choice actions might similarly promote such processes (Pfister et al. 2010).

A noteworthy difference between free- and forced-choice actions, however, was present in terms of their susceptibility to the crossed-hands manipulation. Whereas crossed hands increased the overall response times for forced-choice actions, free-choice actions were (nearly) unaffected by this manipulation. Furthermore, previous studies suggest that the observed slowing with crossed

hands cannot be attributed to biomechanical factors (Berlucchi et al. 1977; Klapp et al. 1979). Tentatively, one possibility to account for these differences is that the processing cost of crossed hands simply does not appear for free-choice actions because it is absorbed in the overall longer response times in the free-choice condition. Another explanation draws on the existence of action-specific stimuli in the forced-choice condition but not in the free-choice condition. These stimuli might prime features of the required hand and the required key press concurrently. With a normal hand position, such priming would always target the same action. For example, a left-pointing arrow would prime the left hand operating the left key. With crossed hands, however, such priming would activate different actions, for example, the left hand (which operates the right key) or the left key (which is operated by the right hand).⁴ This speculation is in line with research on spatial S-R compatibility that indicated automatic S-R translation to occur for both spatial response features and (to a lesser degree) anatomical response features (e.g., Hommel 1993; Simon et al. 1970). Such effects of stimulus-induced priming, however, cannot occur in the free-choice condition, simply because there are no response-specific stimuli that might activate either spatial or anatomical features. Yet, the validity of this speculation is only addressed indirectly by the present study and is certainly worth more detailed investigations.

Conclusions

The present experiments investigated how anticipations of action effects can evoke overt motor action (Hommel et al. 2001; Kunde 2001). More specifically, they addressed the question whether environment-related effect anticipations are preferentially related to spatial or anatomical features of an action in order to bridge the gap between sensory anticipation and ultimate action (Hoffmann et al. 2009). Consistent with several findings across perception and action, the present experiments show that anticipated effects in the environment are predominantly related to spatial rather than anatomical features—ensuring that goal-directed behavior is optimally flexible and efficient at the same time. Furthermore, these effect anticipations were equally

³ This difference might result from an altered learning process (Herwig et al. 2007; Wolfensteller and Ruge 2011), or from a differential tendency to actually apply learned action-effect associations (Pfister et al. 2011).

⁴ The color stimuli in Experiment 2 did not carry an inherent spatial meaning as the arrows in Experiment 1 did. Still these color stimuli may have become linked to spatial features (and eventually acquire the power to activate them) by the instructions to shoot either a left or right chicken (see Metzker and Dreisbach 2009 for a similar logic). The merely acquired spatial meaning of color stimuli compared with the inherent spatial meaning of arrows may also explain the somewhat smaller effect size of the interaction of hand-key mapping and choice mode in Experiment 2 compared with Experiment 1.

present for free- and forced-choice actions, indicating a ubiquitous mechanism that applies to any kind of action.

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