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Adaptive control of ideomotor effect anticipations

Roland Pfister [a],*, Andrea Kiesel [a], Tobias Melcher [b]

[a] Department of Psychology, University of Würzburg, Würzburg, Germany
[b] Centre for Translational Research in Systems Neuroscience and Clinical Psychiatry, Department of Psychiatry and Psychotherapy, Georg August University Göttingen, Germany

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ABSTRACT

According to ideomotor theory, voluntary actions are selected and initiated by means of anticipated action effects. Prior experiments yielded evidence for these effect anticipations with response–effect (R–E) compatibility phenomena using blocked R–E relations. Daily actions, however, typically evoke different effects depending on the situational context. In the present study, we accounted for this natural variability and investigated R–E compatibility effects by a trial-by-trial variation of R–E compatibility relations. In line with recent observations regarding ideomotor learning, R–E compatibility influenced responding only when participants responded in free choice trials assuming that participants then adopted an intention-based action control mode. In contrast, R–E compatibility had no impact when participants responded according to imperative stimuli throughout the experiment, thus when participants adopted a stimulus-based action control mode. Interestingly, once an intention-based mode was established because of free choice trials within an experimental block, we observed response compatibility effects in free as well as forced choice trials. These findings extend and refine theoretical assumptions on different action control modes in goal-directed behavior and the specific contribution of ideomotor processes to intention-based action control.

1. Introduction

Daily actions like driving a car, using the phone, or writing an email can be decomposed into various behavioral goals like changing gears, dialing a number, or pressing specific keys on the keyboard. The successful pursuit of such goal-directed actions essentially requires knowledge about action–effect relations that agents acquire by experience.

A conceptual framework for this learning process is the ideomotor principle (e.g., Herbart, 1825; James, 1890/1981; Lotze, 1852; for more recent formulations, see Greenwald, 1970a,b; Hoffmann, 1993, 2003; Hoffmann et al., 2007; Hommel, 1998, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1987, 1990, 1997). According to the ideomotor principle, representations of motor patterns and contingently following effects are associated bidirectionally. Due to this bidirectional relationship, anticipations of action effects gain the potential to address the corresponding motor patterns, thereby enabling the agent to produce the appropriate action. The huge body of research examining bidirectional action–effect relations can be divided into two main types of studies concentrating on different aspects of ideomotor action: ideomotor learning studies and effect-anticipation studies. In the following, we first provide an overview on effect-anticipation studies and then discuss several relevant aspects of ideomotor learning studies afterwards.

Effect-anticipation studies focus on demonstrating that a mental representation of action effects is created prior to action execution. These effect anticipations influence various aspects of action control what can be directly assessed with *response–effect (R–E) compatibility* paradigms (Janczyk, Skirde, Weigelt, & Kunde, 2009; Keller, & Koch, 2006, 2008; Koch & Kunde, 2002; Kunde, 2001, 2003, 2004; Kunde, Koch, & Hoffmann, 2004; Rieger, 2007; Stöcker, Sebald, & Hoffmann, 2003).

Investigations with the R–E compatibility paradigm apply the same logic as stimulus–response (S–R) compatibility studies. That is, if stimuli and responses overlap on any dimension, responding is typically faster (and more accurate) if stimuli and responses share a feature on this dimension as compared to incompatible features on this dimension (e.g., Fitts & Seeger, 1953; Simon & Rudell, 1967; see Kornblum, Hasbroucq, & Osman, 1990 for an overview). For example, a right key press is performed faster in response to a stimulus that is presented in the right compared to the left visual field. Now, if participants actually anticipate the action effect prior to action execution, similar compatibility phenomena are to be expected between anticipated effects and responses. For instance, Kunde (2001, Exp. 1) asked participants to press horizontally arranged keys in response to a centrally presented target stimulus whereby each key press triggered a visual action effect. Crucially, the spatial compatibility of key location and effect location was varied in two conditions. In one condition, key location and effect location were

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* Corresponding author. Department of Psychology, University of Würzburg, Röntgenring 11 D-97070 Würzburg, Germany. Tel.: +49 931 907 25 40.
E-mail address: roland_pfister@t-online.de (R. Pfister).

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compatible with right key presses triggering action effects in the right visual field and left key presses triggering action effects in the left visual field. In a second condition, key location and effect location were incompatible with right key presses triggering action effects in the left visual field, and vice versa. Even though participants were not instructed to produce any effects, they responded faster in the compatible condition than in the incompatible condition; and because both conditions employed identical target stimuli, this effect can only be attributed to the participants' anticipation of action effects (Kunde, 2001).

Similar R–E compatibility effects were shown in a variety of settings, not only with spatial compatibility but also with respect to other stimulus and response dimensions like intensity (Kunde, 2001, Exp. 2; Kunde et al., 2004), semantic category (Koch & Kunde, 2002), or temporal duration of actions and effects (Kunde, 2003). However, all these experiments varied R–E compatibility in blocks, i.e. participants first experienced a homogeneous series of compatible R–E mappings followed by a homogeneous series of incompatible mappings (or vice versa). This experimental procedure was explained in terms of methodological constraints: “R–E compatibility will only emerge with corresponding and noncorresponding R–E mappings blocked because only in this case the effects follow the responses consistently and can thus serve as a reliable mental cue to address a certain motor pattern.” (Kunde, 2001, p. 393).

In contrast, more realistic day-to-day settings include rapidly varying relations between actions and effects. For example, while writing a text in a word processor, key presses of left-hand keys on the computer keyboard produce spatially compatible action effects at the beginning of a line (e.g., starting a new line with the letter “A” which appears on the left side of the monitor). However, action effects are spatially incompatible in the middle and especially at the end of the line (e.g., letter “A” on the right side of the monitor). Hence, assuming that preparation and execution of a specific action indeed depend on the anticipation of its effects, we argue that R–E compatibility effects may also emerge for rapidly varying R–E relations as long as effects are predictable due to the context. Thus, the main goal of the present study was to investigate whether ideomotor effect anticipations also occur if action–effect relations vary trial-by-trial and the effects do not represent the primary action goal.[1] For this purpose, we adopted Kunde's (2001) experimental setting but varied the R–E mapping on a trial-to-trial basis with a cue indicating the current mapping (that is, we applied the task cuing procedure, cf. Meiran, 1996; see Kiesel et al. 2010, for a review).

In addition, we introduce a second variation to Kunde's (2001) original paradigm by comparing free choice and forced choice actions. We derived this manipulation from recent studies on ideomotor learning that pointed towards a prominent role of ideomotor effect anticipations for free choice actions but not for forced choice actions.

Ideomotor learning studies typically apply two distinct experimental phases (Greenwald, 1970a). First, a learning phase is used to establish a relation between actions and the following effects. In this learning phase, participants perform a number of distinct actions, e.g., pressing a left or a right key, and experience contingent action effects, e.g., different tones. It is assumed that action–effect associations are formed automatically due to the highly contingent mapping of actions and their effects. In a subsequent test phase, the former action effects serve as target stimuli in a forced choice RT task. Participants are either instructed to respond with the action that formerly produced the stimulus or with the alternative action that formerly produced the alternative stimulus. Usually, responses are faster when the stimulus–response mapping of the test phase is the same as the response–stimulus (i.e., response–effect) mapping of the preceding learning phase–the non-reversal condition–as compared to a reversed mapping—the reversal condition (e.g., Elsner & Hommel, 2001, 2004; Hommel, Alonso, & Fuentes, 2003; Hoffmann, Lenhard, Sebald, & Pfister, 2009). Consistent with ideomotor theory, the non-reversal advantage indicates that action–effect associations formed in the learning phase are activated by presenting a stimulus that was previously experienced as an action effect (cf. Nattkemper, Ziessler, & Frensch, 2010).

However, Herwig, Prinz, and Waszak (2007) demonstrated that the non-reversal advantage depends on the task instructed in the learning phase. In a series of experiments, they replicated the conditions of Elsner and Hommel (2001) but altered the learning phase for several groups of participants. While the participants of Elsner and Hommel experienced a free choice between two response alternatives during the learning phase, the altered learning phase of Herwig and colleagues consisted of forced choice trials only, i.e. participants responded to an imperative stimulus that instructed a specific response. In this latter case, the non-reversal advantage as indication of ideomotor learning was absent.

To explain this difference, Herwig et al. (2007) assumed that action–effect learning and action control rely on fundamentally different systems (action control modes) when reactions are carried out in response to exogenous stimuli (*stimulus-based*) as opposed to endogenously driven actions (*intention-based*). Only intention-based actions are conceptualized to rely on ideomotor mechanisms including the prominent role of action–effect associations. That is, in the intention-based mode, motor commands are selected by anticipating to-be-expected action effects. In contrast, stimulus-based actions are conceptualized to rely on stimulus–response associations. That is, in the stimulus-based mode, motor commands are selected according to learned responses to a stimulus (see also Pfister et al., in press, for a more detailed discussion).

Taken together, the present experiments investigate whether ideomotor effect anticipations also occur for rapidly varying R–E relations and whether this anticipation is moderated by the applied action control mode. Given the manifest differences between stimulus-based and intention-based action control, we expect R–E compatibility effects when participants act in an intention-based action control mode whereas we do not expect R–E compatibility effects for the stimulus-based action control mode.

2. Experiment 1: rapidly varying R–E relations

To investigate R–E compatibility effects for rapidly varying R–E relations, we applied a simplified version of Kunde's (2001) setting. Participants either pressed a left or right response key that triggered a visual effect on the monitor. Left and right key presses either induced left and right visual effects (compatible R–E relation) or right and left visual effects (incompatible R–E relation), respectively. In addition to spatially compatible and spatially incompatible action effects, we also included spatially neutral, i.e. neither compatible nor incompatible action effects (see Fig. 1). R–E compatibility varied trial-by-trial and a cue informed about the current relation.

In Experiment 1, action control modes were varied between-subjects (cf. Herwig et al., 2007). A stimulus-based mode was implemented by forced choice reactions to an imperative stimulus (*forced choice group* hereafter) whereas an intention-based mode was implemented by asking the participants to freely choose between the two response alternatives throughout the experiment (*free choice group* hereafter). Furthermore, we added nogo trials in the free choice condition to discourage participants from preliminarily preparing an action (see e.g., Kunde, 2001, Exp. 3). We expected an R–E compatibility effect for the free choice group with faster reactions under compatible than incompatible R–E mappings (Kunde, 2001),

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[1] Please note that previous studies by Ansorge (2002) and Kiesel and Hoffmann (2004) observed R–E compatibility effects for varying R–E relations only when participants were explicitly instructed to produce the context-specific effect. We refer back to these studies in the General discussion.

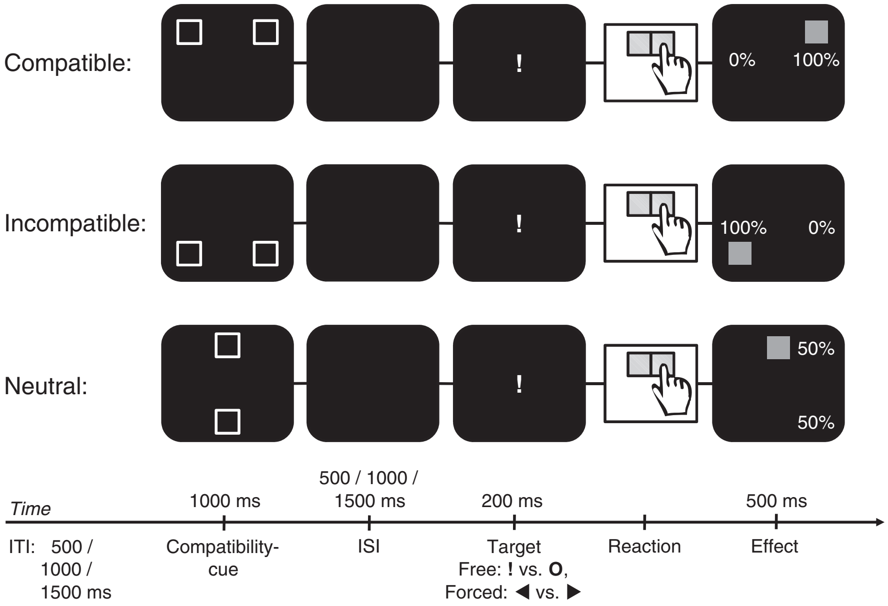

Fig. 1. Basic experimental setup of both experiments, including a trial-by-trial variation of response–effect (R–E) compatibility (compatible vs. neutral vs. incompatible) as well as the implementation of free and forced choice trials. Each trial started with a cue (white boxes) that informed about the current R–E compatibility relation (100% valid). Independent on the cue, participants were instructed to press a key in response to a target stimulus. The target either instructed free choice (exclamation mark) or forced choice responses (left or right arrows) and participants had to respond within 1000 ms after target onset. In Experiment 1, free and forced choices were varied between-subjects (including nogo trials for the free choice group as indicated by circles as targets) whereas they were varied within-subjects in Experiment 2 (without nogo trials). Correct responses triggered the presentation of a blue (90%) or orange (10%) square. In case of orange squares (deviant effects), participants had to respond again by pressing both keys simultaneously. The figure depicts a free choice trial in which the participant chooses to press a right key in a trial with compatible, incompatible, or neutral R–E mapping. The assignment of upper vs. lower cues to compatible vs. incompatible R–E mappings was counterbalanced across participants.

while we did not expect an R–E compatibility effect for the forced choice group.

2.1. Method

2.1.1. Participants

Twenty-four undergraduate students at the University of Würzburg (9 males; 3 left-handed) were recruited and received either course credit or were paid for participation. The mean age was 23.83 years (*SD* = 3.42), participants reported normal or corrected-to normal vision and were naive as to the purpose of the experiment.

2.1.2. Apparatus and stimuli

Stimuli were displayed on a 17″ monitor at a refresh rate of 75 Hz and responses were collected by two external keys that were connected to an IBM-compatible PC. The keys were arranged horizontally with an intercenter distance of 15 cm and key locations were matched to the lateral locations of cue boxes and effect squares in compatible and incompatible trials (see Fig. 1). Cue boxes, presented in white, and effect squares, presented in blue or orange, measured 2.5 cm × 2.5 cm. The two cue boxes indicating neutral trials were shown in the center of the screen (vertically aligned) whereas cues for compatible and incompatible trials were shown at the left and right in the upper or lower half of the screen (horizontally aligned). The mapping of cue positions (high vs. low) and compatibility conditions (compatible vs. incompatible effects) was counterbalanced across participants so that cue boxes in the upper half indicated compatible trials for one half of the participants and incompatible trials for the other half. Target stimuli (i.e. left and right arrows, exclamation marks, and circles) were displayed in a 24 point font in the center of the screen (arrows: 0.5 cm × 0.6 cm, exclamation mark: 0.1 cm × 0.6 cm, circle: 0.6 × 0.6 cm).

2.1.3. Procedure

Each trial started with the presentation of a cue that informed about possible effect locations and the current R–E compatibility relation (100% valid; see Fig. 1). The cue was presented for 1000 ms followed by a blank screen with a variable duration of either 500, 1000, or 1500 ms.[2] Then, the target stimulus was displayed for 200 ms and participants had to respond within 1000 ms after target onset. For the forced choice group, the target stimulus was a left or right arrow instructing either a left or a right key press whereas for the free choice group, an exclamation mark instructed participants to freely choose one of the two keys while a circle indicated a nogo trial. Correct responses triggered a 500 ms presentation of a blue effect square in 90% of the trials whereby the location of the square depended on the current compatibility condition. Thus, in compatible trials, the effect square was presented on the side of the key press, whereas in incompatible trials, the effect square was presented on the opposite side. In neutral trials, the square was randomly presented either in the top or bottom center. To increase the salience of the effect squares, the color of the effect square was orange in 10% of the trials (referred to as deviant effects hereafter). In this case, participants were to press both keys simultaneously (maximum offset: 50 ms) and as fast as possible with a maximum RT of 1500 ms after effect onset. The next trial started after a variable ITI of 500, 1000, or 1500 ms. Responses prior to the target stimulus, wrong key presses in forced choice trials, non-simultaneous key presses after deviant effects, and key presses in response to normal effects stopped the trial immediately and an error message indicating the type of error was displayed for 1000 ms.

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[2] The variable inter-stimulus interval was included to further decrease the possibility of anticipating the target stimulus and pre-programming a response in the free choice group. For a better comparison between the free choice and the forced choice group, it was also implemented for the forced choice group. For both groups in Experiment 1 as well as in Experiment 2, participants responded slower after an ISI of 500 ms than after ISIs of either 1000 ms or 1500 ms (Experiment 1, free choice group: 391 ms vs. 371 ms vs. 372 ms, $F(2, 10) = 6.95$, $p = .013$, $\eta_p^2 = 0.58$; Experiment 1, forced choice group: 370 ms vs. 347 ms vs. 348 ms, $F(2, 10) = 15.39$, $p = .001$, $\eta_p^2 = 0.76$; Experiment 2: 411 ms vs. 397 ms vs. 397 ms, $F(2, 10) = 6.86$, $p = .013$, $\eta_p^2 = 0.58$). However, the factor ISI did not interact with the factor compatibility for both groups of Experiment 1 (both p's > .374). In Experiment 2, neither interaction with the factors compatibility or choice nor the three-way interaction approached significance (all p's > .421).

Participants were instructed to respond as fast as possible and to decide spontaneously between the two response alternatives in free choice trials. Regarding the action effects, they were informed that only deviant action effects would be relevant to their task whereas normal action effects would not require any response.

The experiment consisted of four training blocks and six test blocks. The first three training blocks contained only one compatibility condition each whereby the order of conditions was counterbalanced across participants. The fourth training block as well as each test block contained all compatibility conditions. For the forced choice group, blocks consisted of 46 trials each. For this group, the first three training blocks consisted of 50% free and 50% forced choice trials whereas the last training block as well as the test blocks only contained forced choice trials (14 trials of each compatibility condition with normal effects and four randomly distributed deviant effects). For the free choice group, blocks consisted of 66 trials. For this group, the first three training blocks also consisted of 50% free and 50% forced choice trials to provide similar learning experiences for both groups. Forced choice trials were replaced by nogo trials in the fourth training block and the six test blocks so that these blocks consisted of 50% nogo trials and 50% free choice trials (10 trials of each compatibility condition with normal effects, and 3 randomly distributed deviant effects). We added the nogo trials to discourage participants in the free choice group from preparing their response prior to target onset because this behavior would eliminate potential R–E compatibility effects (see Kunde, 2001, Exp. 3, for a similar design).[3]

2.2. Results

Trials with responses prior to the target stimulus or RT<100 ms (0.4%), response omissions (0.3%), wrong key presses in forced choice trials (1.4%), deviant missings (0.3%), non-simultaneous key presses to deviant effects (0.6%), and key presses in reaction to normal effects (0.5%) were excluded from data analysis (3.5% in total). Remaining RTs of the six test blocks were aggregated for each participant and each level of the factor compatibility (compatible vs. neutral vs. incompatible; see Fig. 2). Trials with deviant effects were included in the analysis as responses occurred prior to effect onset. Additional analysis, however, revealed a similar pattern of results when deviant trials, trials following deviant effects, or both were excluded from the analysis. To avoid violations of sphericity, all within-subjects ANOVAs were computed as multivariate tests.

2.2.1. Compatibility effects in both groups

We computed an ANOVA on the mean RTs with the within-subject factor compatibility and the between-subject factor choice. Participants in the free choice group responded slower (378 ms) than participants in the forced choice group (354 ms), yet this difference did not reach significance, $F(1,\ 22)=1.58$, $p=.222$, $\eta_p{}^2=0.07$. Further, the factor compatibility influenced RTs significantly, $F(2,\ 21)=4.18$, $p=.030$, $\eta_p^2=0.28$, however its influence was confined to the free choice group as indicated by an interaction of compatibility and choice, $F(2,21)=4.23$, $p=.029$, $\eta_p^2=0.29$. Participants in the free choice group responded slower in incompatible (388 ms) than neutral trials (373 ms; $t(11)=2.85$, $p=.016$, $d=1.21$) or compatible trials (375 ms; $t(11)=3.49$, $p=.005$, $d=1.49$). In the forced choice group, RTs for incompatible, neutral, and compatible trials did not differ significantly (all p's>.713).

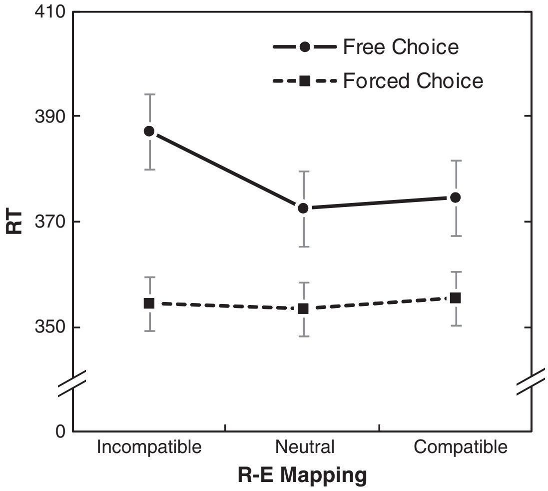

Fig. 2. Mean reaction times of the free choice and the forced choice group for compatible, neutral, and incompatible R–E relations in Experiment 1. Error bars represent 95% within-subjects confidence intervals (Loftus & Masson, 1994) that were computed independently for both groups.

2.2.3. Exploratory sequence analysis

The present design enables us to further analyze the sequential modulation of the compatibility effect. Therefore, we computed for the data of the free choice group an ANOVA with the factors compatibility and compatibility in trial n-1 while trials after nogo trials were excluded from this analysis. The factor compatibility was significant, $F(2,\ 10)=5.38$, $p=.026$, $\eta_p^2=0.52$, but neither compatibility in trial n-1 nor the interaction approached significance (both p's>.306). However, as this procedure resulted in a small number of data points for some participants ($n \geq 11$ trials per condition), this analysis is explicitly marked as exploratory. For the same reason, we did not perform any further sequence analyses for the present experiments.

2.3. Discussion

In this first experiment, we investigated ideomotor effect anticipations under rapidly varying R–E compatibility conditions in (a) an intention-based control mode, induced by free choice responses, and (b) a stimulus-based control mode, induced by forced choice responses. As expected, we found a significant interaction between R–E compatibility and control mode because only participants of the free choice group exhibited a reliable R–E compatibility effect. In line with recent findings and related theoretical assumptions (Herwig et al., 2007; Keller et al., 2006; Pfister et al., in press; Waszak et al., 2005), this pattern of results clearly indicates that ideomotor effect anticipations are an integral part of internally guided actions whereas externally based actions do arguably not–or at least to a substantially lesser degree–rely on this control mechanism.

The concept of action control modes, however, is still not well understood. For example, it is unclear whether action control modes switch rapidly between stimulus-based and intention-based if free and forced choice trials occur in mixed blocks. Alternatively, action control modes may be conceptualized as enduring cognitive states that are maintained over a longer period of time.

Ideomotor learning studies consistently reported evidence for ideomotor action–effect associations in pure forced choice test phases that were preceded by pure free choice learning phases (e.g., Elsner, & Hommel, 2001; Hoffmann et al., 2009; Hommel et al., 2003; Melcher, Weidema, Eenshuistra, Hommel, & Gruber, 2008). This pattern of

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[3] The free choice group encountered nogo-trials during the test-phase while the forced choice group did not. As a consequence, the free choice group worked through more trials in total but encountered less effect-triggering trials than the forced choice group. Please note that the differing trial numbers are likely to increase the chances to find R-E compatibility effects in the forced choice group because action effects were more often experienced. The differing trial numbers of both groups thus arguably work against the current pattern of results and are unlikely to be a confounding factor in the design of Experiment 1.

results might indicate that an enduring intention-based action control mode was established in the free choice learning phase and that this intention-based action control mode was carried over to the forced choice test phase so that action–effect associations could influence the participants' behavior. This observation might further indicate that the intention-based action control mode is the dominant mode as it is carried over to forced choice actions instead of switching to the stimulus-based mode. In contrast, if a forced choice learning phase is followed by a free choice test phase, the participants seem to switch to an intention-based mode (Pfister et al., in press). Thus, if action control modes can indeed be conceptualized as enduring cognitive states with the intention-based mode being dominant over the stimulus-based mode, the same line of argument should hold true for effect anticipations in R–E compatibility designs. Experiment 2 addressed this speculation.

3. Experiment 2: enduring action control modes

The present paradigm enables us to test the speculation that action control modes are enduring cognitive states and especially that the intention-based mode is dominant over the stimulus-based mode (Pfister et al., in press). We assume that if an intention-based action control mode is established in free choice conditions (Herwig et al., 2007), it might also be applied to forced choice actions if both conditions occur equally often in the same experimental block. In order to test this speculation, we adopted the design of Experiment 1 (see Fig. 1) but varied free and forced choices trial-by-trial rather than as a between-subjects factor. In this design, we expected an R–E compatibility effect for both, free and forced choice actions.

3.1. Method

3.1.1. Participants

Twelve undergraduate students at the University of Würzburg (3 males, all right-handed) were recruited and received either course credit or were paid for participation. The mean age was 24.58 years (*SD* = 4.61), participants reported normal or corrected-to normal vision and were naive as to the purpose of the experiment.

3.1.2. Apparatus, stimuli, and procedure

Experiment 2 used the same paradigm as Experiment 1 (Fig. 1) with the following modifications. Participants experienced free and forced choice trials equally often and throughout the experiment. Again, the experiment consisted of four training blocks and six test blocks, each of them comprising 66 trials (10 free and 10 forced choice trials with normal effects for each compatibility condition and 6 randomly distributed deviant effects).

3.2. Results

As for Experiment 1, trials with responses prior to the target stimulus or RT < 100 ms (0.6%), response omissions (0.9%), wrong key presses in forced choice trials (2.4%), deviant missings (0.1%), non-simultaneous key presses to deviant effects (0.9%), and key presses in reaction to normal effects (1.2%) were excluded from data analysis (6.1% in total).

We computed an ANOVA on the mean RTs with the factors choice and compatibility (Fig. 3). Both, the main effect of compatibility, $F(2, 10) = 5.04$, $p = .031$, $\eta_p^2 = 0.27$, and the main effect of choice, $F(1, 11) = 12.99$, $p = .004$, $\eta_p^2 = 0.54$, were significant while the interaction of both factors did not approach significance ($F < 1$). Participants responded faster in compatible (398 ms) than in incompatible trials (407 ms, $t(11) = 2.63$, $p = .023$, $d = 1.08$.); RTs in neutral trials (400 ms) did not differ significantly from incompatible, $t(11) = 1.61$, $p = .136$, $d = 0.66$, or compatible trials, $t(11) = 0.92$, $p = .374$, $d = 0.38$.

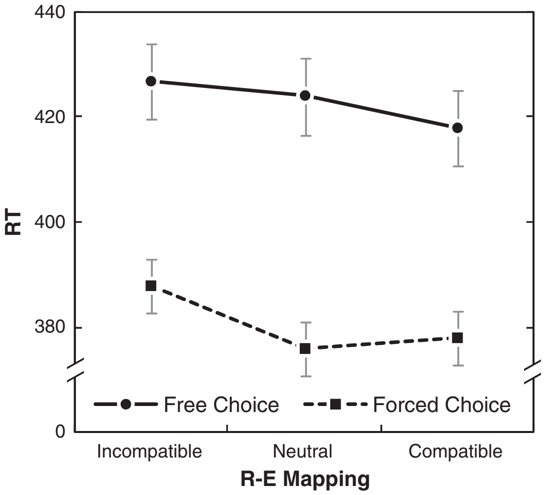

Fig. 3. Mean reaction times in free and forced choice trials for compatible, neutral, and incompatible R–E relations in Experiment 2. Error bars represent 95% within-subjects confidence intervals (Loftus & Masson, 1994) that were computed independently for both conditions.

3.3. Discussion

Experiment 2 extended the findings of Experiment 1 to situations with free and forced choices occurring intermixed in one experimental block. Here, equally strong R–E compatibility effects resulted for both, free and forced choice trials. Thus, it seems that participants anticipated the effects according to the current context in order to initiate the respective response in free as well as forced choice trials. We take this as evidence that participants adopt an enduring intention-based action control mode when free and forced choice trials occur randomly intermixed.

4. General discussion

The present experiments investigated whether ideomotor theory can account for action control under more ecologically valid settings in which an action will produce different action effects dependent on the situational context. To this end, we employed an R–E compatibility design (Kunde, 2001) with trial-to-trial varying R–E relations. In each trial, a cue informed participants about the current spatial compatibility of responses and effects while the response was triggered by a free or forced choice target stimulus. To assess the impact of R–E compatibility, reaction times in compatible trials were compared to reaction times in incompatible trials. Additionally, we assessed the role of different modes of action control (stimulus-based versus intention-based mode; Herwig et al., 2007; Herwig, & Waszak, 2009; Pfister et al., in press). Action control in the stimulus-based mode is conceptualized to be based on S–R associations, whereas action control in the intention-based mode is conceptualized to be based on ideomotor mechanisms including the prominent contribution of effect anticipations. In Experiment 1, we investigated ideomotor effect anticipations separately in stimulus-based and intention-based action control, which was implemented in otherwise comparable groups working under forced choice and free choice conditions, respectively (cf. Herwig et al., 2007). A substantial R–E compatibility effect was observed for the free choice group whereas the forced choice group did not show a difference between compatible and incompatible response–effect relations. These results indicate that R–E compatibility effects can indeed be induced on a trial-to-trial basis if an intention-based mode is adopted under free choice conditions.

In Experiment 2, we elaborated whether participants adopt an enduring intention-based mode when free and forced choice trials switch randomly. In this setting, we observed R–E compatibility effects for free choice responses and for forced choice responses. Thus, R–E compatibility effects can also result for forced choice actions if participants are in an action control mode that fosters anticipation of to be expected effects (cf. Pfister et al., in press). We will refer back to this issue later.

Taken together, our findings indicate that the ideomotor principle provides a valid account for action control under ecologically valid conditions, i.e. effect anticipations are used for action initiation and execution not only under constant but also under rapidly varying response–effect relations. Furthermore, ideomotor action control can be applied to endogenous (free choice) as well as exogenously prescribed (forced choice) actions, given that an intention-based action control mode is adopted.

The assumed role of intention and intention-based action control is in line with findings on S–R compatibility effects, where specific instructions were used to induce an intention-based action control mode (Guiard, 1983; Hommel, 1993; Ansorge & Wühr, 2004). For instance, an intention-based action control mode was shown to reverse the typical Simon effect (Simon & Rudell, 1967) if intended effect locations and respective motor commands counteracted (Hommel, 1993).

Further evidence for a fundamental difference between intention-based and stimulus-based actions is provided by neuroanatomical and neurophysiological studies. Most importantly, both action control modes seem to be based on distinct neuroanatomical systems (see Haggard, 2008 for an overview). Intention-based actions were related primarily to (pre)frontal areas such as the supplementary motor area (e.g., Goldberg, 1985) and parietal association cortices (Desmurget et al., 2009) while stimulus-based actions seem to depend on specialized task-dependent systems (Toni, Rushworth, & Passingham, 2001). Furthermore, neurophysiological differences between both action control modes are mirrored in differential patterns of muscular activity (EMG signal; Obhi, & Haggard 2004).

In addition, there is evidence that the motor system for intention-based actions is shielded against possible influences of stimulus–response associations. For instance, preparing an intention-based action reduced general “reactivity” (Astor-Jack & Haggard, 2005). Astor-Jack and Haggard, (2005) asked their participants to press a key at a freely chosen time in a given trial. In some trials, however, action preparation was interrupted by a target stimulus forcing the participants to perform the partly prepared key press as fast as possible. Interestingly, participants responded slower to the target stimulus when they had already prepared the same response in the free choice condition compared to a condition in which participants always responded to the target stimulus without any self-intended action preparation. Astor-Jack and Haggard concluded that the observed response costs mirror a process of deactivating the intention-based system and activating the stimulus-based system.

Taken together, there is evidence for two complementary modes of action control in several different paradigms. To date, however, it is still unclear when exactly participants adopt intention-based or stimulus-based action control modes. According to Herwig et al. (2007; as in the manuscript), free choice trials induce an intention-based action control mode while forced choice trials induce a stimulus-based action control mode. Yet, also forced choice conditions reveal R–E compatibility and thus, participants are assumed to anticipate to-be-expected effects also in forced choice conditions. First, R–E compatibility effects occur reliably when R–E relations remain constant over blocks of forced choice trials (e.g., Kunde, 2001, 2003; Koch & Kunde, 2002). Thus, the easier participants can acquire R–E relations the more likely they rely on effect anticipations to select and initiate a response.

Second, to the best of our knowledge, there are two studies demonstrating R–E compatibility effects for forced choice responses when the R–E relations vary context-specifically (Ansorge, 2002; Kiesel & Hoffmann, 2004). Kiesel and Hoffmann, (2004) observed an influence of context-specific and arbitrary effects in a task switching setting. In these experiments, participants were to press a bottom left or top right key (diagonal arrangement; cf. Meiran, 1996) in response to a forced choice target stimulus that appeared in one of the quadrants of a large fixation cross. Participants either responded according to the horizontal (task A) or vertical (task B) position of the target stimulus. Square brackets presented to the left and right or the top and bottom of the screen indicated whether the horizontal or vertical task was required. After a correct response, the round target stimulus either moved slowly or fast towards the nearest square bracket while the speed entirely depended on the task. Responses were faster, when a fast movement was to follow as compared to a slow movement even though the movement speed was irrelevant to the task at hand. Yet, in this setting, the effects were very salient because Kiesel and Hoffmann, (2004) referred to their target stimulus as a ball and instructed their participants to “shoot the ball into the nearest goal” (p. 157). Thus, it seems that instructing participants to intend an effect boosters effect anticipations even in settings with context-specific R–E relations.

This conclusion fits nicely to the second study that demonstrates R–E compatibility effects when varying R–E relations trial by trial. Ansorge (2002) applied a somewhat similar design as the present study; in each trial, a cue informed participants about compatible or incompatible response–effect relations and a forced choice response had to be performed after an arbitrary target stimulus appeared on the center of the screen. After a left or right key press, the target stimulus was relocated to the left or right side of the monitor, leading to compatible or incompatible effects. Ansorge (2002) found R–E compatibility effects only if participants were explicitly instructed to produce left or right effects (for similar findings see Kunde, Krauss, & Weigelt, 2009; Kunde, & Weigelt, 2005) but not if participants were told to respond according to the target stimulus despite that they experienced the same effects afterwards. This latter condition corresponds to the forced choice group of the present study and we thus conjecture that participants in Ansorge's study may also have adopted a stimulus-based action control mode.

To sum up, the present experiments demonstrated response–effect compatibility effects for trial-by-trial varying R–E relations and thus extend the empirical evidence for the ideomotor principle to a setting with higher ecological validity. R–E compatibility effects were obtained as long as participants established an intention-based action control mode because of the possibility to freely choose among several actions. If participants responded in a stimulus-based action control mode because they responded exclusively in forced choice conditions, trial-based response–effect compatibility effects were eliminated.

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