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Anticipated action effects affect the selection, initiation, and execution of actions

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This study investigated the impact of contingent action effects on response production. In Experiment 1 responses of varying intensity were initiated faster when contingently followed by auditory effects of corresponding rather than of noncorresponding intensity. This response–effect (R–E) compatibility influence was robust with respect to practice, and it was not due to persisting influences of preceding R–E episodes. These results support the conclusion that R–E compatibility reflects the impact of anticipatory effect representations in response production. Experiment 2 showed that anticipatory effect codes have an impact on early processes of response production (response selection) as well as on processes that immediately precede overt responding (response initiation). Finally, they also influence the way the actions are physically performed (response execution). The results support and specify ideo-motor theories of action control that assume movements to be controlled by anticipations of their sensorial effects.

Action effects are the ultimate reason for our behavior. It therefore appears quite suggestive that action effects are incorporated in the cognitive processes that mediate motor control. Probably the most widely acknowledged function of action effects is that they allow the online control of movement execution (e.g., correcting the trajectory of a grasping hand approaching a target object). This *evaluative* function of perceptual action feedback is well established in traditional closed-loop theories of movement control (cf. Adams, 1971).

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Yet, action effects may also contribute to the cognitive antecedents that precede movement execution—that is, they may have a *generative* function for selecting or initiating a movement. This assumption is theoretically most radically expressed in historical as well as in more recent brands of the ideo-motor (IM) principle (Greenwald, 1970; Hoffmann, 1993; Hommel, 1997; James, 1890/1981; Klapp, Porter-Graham, & Hoifjeld, 1991; Prinz, 1987). The basic idea is that actors acquire bidirectional associations between movements of their body and the perceivable movement effects. Because these associations are excitable in either direction (i.e., from motor codes to effect codes and vice versa), they enable actors to intentionally recruit a movement by activating codes of the movement's sensory effects. From this perspective, a coordinated sequence of actions—for example, playing a piece of music on the piano—is mediated by imaging the succession of effects that result from carrying out the required movements in correct order. These may be images of relatively proximal effects, like tactile sensations from the moving fingers, and/or images of more distal effects, like the melody that becomes audible from the proper keypress sequence—a conjecture supported by recent evidence from sequence learning (cf. Hazeltine, 2002; Hoffmann, Sebald, & Stöcker, 2001; Ziessler, 1998). The IM principle is radical in the sense that it considers actions to be exhaustively represented in terms of their re-afferences, and that thus there is no other way to intentionally select and/or initiate an action than by anticipating its sensory effects.

The IM principle was prompted by introspection and has up to now not provoked a large body of empirical research (e.g., Elsner & Hommel, 2001; Knuf, Aschersleben, & Prinz, 2002; Kunde, Hoffmann, & Zellmann, 2002). It is thus fair to say that its basic claims are still not established very well experimentally. To do so, it is essential to show that sensory action effects actually play a role in the mental representation of the action itself, and that therefore these effects become anticipated as part of the processes leading up to action initiation. Evidence for this claim is scarce, and providing it is not trivial because anticipatory effect representations cannot be observed directly but need to be inferred somehow from behavioural data (cf. Rosenbaum & Krist, 1996).

To support this assumption, the present study pursued the following reasoning: If *postresponse* effects actually become anticipated for response production, this anticipated stimulation should exert influences on the motor system that are similar to those normally exerted by the perception of *preresponse* stimuli. Following this argument we reasoned that anticipated effects should tend to automatically prime compatible responses—thereby producing response–effect (R–E) compatibility effects—similar to the way that stimuli tend to automatically prime compatible responses—thereby producing traditional stimulus–response (S–R) compatibility effects. Observing such influences of R–E compatibility implies that the effects were anticipated in advance—otherwise they could not affect responses that precede them in time.

Some hints for these conjectured R–E compatibility effects have been reported. For example, responses in a certain location are initiated faster when they contingently lead to a spatially corresponding visual effect (e.g., the lighting up of a spatially corresponding lamp) than when they result in a spatially noncorresponding effect (cf. Ansorge, 2002; Hommel, 1993; Riggio, Gawryszewski, & Umiltà, 1986). Likewise, responses of a certain force are initiated faster when they produce auditory effects of corresponding rather than noncorresponding intensity (Kunde, 2001, Exps. 2 and 3). These observations suggest that anticipatory effect codes may indeed have the same, or similar, power to prime corresponding responses as have perceived stimuli in S–R compatibility experiments (cf. Tlauka & McKenna, 1998). Consequently, a to-be-generated response would profit from the anticipation of its corresponding effects, because these anticipatory effect codes would automatically activate the requested motor pattern (or its proprioceptive effects, which can barely be decoupled). If, however, a to-be-generated response is associated with a noncorresponding effect, the anticipation of this effect would not be beneficial (and even could be harmful) because it primed a not-requested (incorrect) response, which may result in increased response times (RTs) and/or error rates.

R–E compatibility effects may thus qualify as the required indicator of movement-generating effect anticipations. However, before making use of R–E compatibility as an inferential tool for the study of action-controlling effect anticipations, it is essential to carefully consider and rule out potential alternative interpretations. This was the first purpose of the present study, pursued in Experiment 1. The second purpose was to use this indicator to assess on which phases of movement production anticipated effects exert their impact. This was done in Experiment 2, which was designed to disentangle the potential contribution of effect codes to the selection, initiation, and execution of responses.[1]

EXPERIMENT 1

The IM interpretation of R–E compatibility outlined above focuses onto the impact of forthcoming response effects in a given individual trial. Thus it implies that each trial starts fresh and is independent of the history of preceding trials. This is not a very realistic assumption. A trial in a typical choice reaction task (CRT) is part of—and potentially affected by—the sequence of preceding trials (cf. Kornblum & Stevens, 2002, for an overview). Thus, it is important to consider that R–E compatibility effects, rather than originating from forthcoming effects (i.e., future events), might result from preceding R–E episodes (i.e., past events).

There are two not mutually exclusive ways that carry-over from preceding trials might mimic R–E compatibility effects. First, previous experiments on R–E compatibility solely used conditions with corresponding and noncorresponding response effects blocked, which is reasonable, because otherwise response effects cannot serve as reliable mental cues for response production. A potential confounding, however, with these blocked mappings is that not only the R–E mapping in the current trial, but also that in all previous trials of a given block, is either corresponding or noncorresponding. It has been shown that experiencing an incompatible event can increase RTs in subsequent trials. Although the

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[1] For the sake of simplicity we refer to the earliest phases of movement production as response *selection*, to the processes that immediately precede the overt response as response *initiation*, and to the observable motor pattern as response *execution*. We do not want to imply that these phases reflect strictly independent sequential stages as assumed in traditional stage theory (e.g., Sanders, 1980; Spijkers & Walter, 1985; Sternberg, 1969). Rather we agree with the view that they reflect different time points in a unitary response production process (cf. Hommel, 1997). Nevertheless, their distinction is reasonable for pragmatic reasons: Not every selected response is actually initiated, and hence some processing must occur to make a selected response become real, be these processes independent of selection processes or not. Likewise, many movements, after being initiated, can be altered regarding the way they are physically carried out, and hence some processes must control action execution, be these processes dependent on selection/initiation processes or not (cf. General Discussion for further consideration of this issue).

mechanisms behind these sequential influences are controversial, their mere observation is sufficient to warrant experimental control (e.g., Kornblum & Stevens, 2002; Kunde, 2003). Thus, increased RTs with a blocked noncorresponding R–E mapping may, in contrast to our assumptions, not so much reflect compatibility between responses and forthcoming effects in a given trial rather than some enduring trace of a preceding R–E episode. To test this conjecture, we employed a condition with corresponding and noncorresponding R–E mappings randomly mixed. In this condition a given trial is preceded by a corresponding or noncorresponding R–E episode with equal probability, which allows performance to be assessed as a function of preceding R–E correspondence. Another interesting implication of the mixed R–E mapping is that it can be considered a neutral baseline to explore costs and benefits of overall R–E compatibility effects, although we note already here that the issue of what qualifies as an adequate "neutral" condition is controversial (cf. Jonides & Mack, 1984, and discussion of Experiment 1).

A second, and even simpler, way that preceding incompatible R–E episodes may deteriorate performance is by violation of participants' expectations. Incompatible response effects are at odds with preexperimental experience. It is, for example, hardly ever the case that a forceful action (e.g., clapping the hands vigorously) leads to a quiet auditory effect (e.g., a quiet clap) and vice versa. The disconfirmation of participants' expectancies by incompatible effects may withdraw attention from the CRT in subsequent trials, which is likely for the very first trials, but may in a moderate fashion extend well beyond that. At any rate, if R–E compatibility effects result from surprise they should be a transient phenomenon, fading out with practice. If, however, they reflect automatic response priming by anticipated sensorial stimulation, as we claim, they should remain relatively constant with practice, or at least not decline more than traditional S–R compatibility effects (e.g., Dutta & Proctor, 1992). Previous experiments provided no hints for a dramatic decrease of R–E compatibility effects with practice, but the sessions in these experiments were presumably too short for a sensitive test of this objection (e.g., 128 trials of each mapping in Kunde, 2001, Exp. 2). Therefore, in Experiment 1 the length of each R–E mapping session was tripled to allow a more careful inspection of practice-related variations.

We tested these alternative explanations by means of an intensity-based instance of R–E compatibility. Participants were to press a key in response to a colour stimulus either softly or forcefully, which in three different sessions led to corresponding effects (soft response → quiet tone; forceful response → loud tone), noncorresponding effects (soft response → loud tone; forceful response → quiet tone), or mixed effects (soft and forceful responses were randomly followed by quiet and loud tones). It can be predicted from previous experiments that this procedure would yield R–E mapping effects that are large enough to detect even subtle quantitative variations of effect size as a function of the experimental factors we were interested in (R–E compatibility in preceding trial, practice).

Method

Participants

Twelve students from the University of Würzburg (2 men, 10 women) aged 19 to 27 years participated in fulfilment of a course requirement.

Apparatus and stimuli

The presentation of the stimuli, the recording of responses and reaction times, and the presentation of the response effects were provided by an IBM-compatible HighScreen PC with a Sony VGA-Graphics display. The viewing distance was approximately 60 cm. A single pressure-sensitive response key (20 mm × 20 mm) was positioned in front of the participants. The key measured the response force in a range from 0 cN up to 3000 cN. A maximum force of 3000 cN depressed the plate by about 0.5 mm. The response force was sampled by the computer with a rate of 500 Hz. Participants were instructed to comfortably rest the index finger of the right hand on the key, so that a pressure above 20 cN and below 200 cN was measured. Half the participants were instructed to press the response device softly (>200 cN and ≤800 cN) when a green response signal (45 mm in diameter) was presented, and forcefully (>800 cN) when a red stimulus appeared, whereas this mapping was reversed for the other participants. Participants were instructed to press the response device briefly with the requested force and then to return to the rest pressure. RT was measured from the stimulus onset to the point in time when a response force of more than 200 cN was reached, which is a force well within the range necessary to depress an all-or-none response key normally used in RT experiments. Peak force was identified online when force was equal to, or lower than, any force within the last 8 ms.

Immediately after the maximum force of the response was identified, either a quiet (65-dB) or loud (78-dB) tone (300 Hz) was presented by two loudspeakers positioned on the left and right side of the monitor, according to the current R–E mapping. The tones were produced by the soundcard of the computer, which was programmed to produce a tone of maximal rise of loudness and a decay over a period of about 500 ms duration. This resulted in the impression of a gong sound.

Procedure

Each trial started with a (100-Hz) warning click of 20 ms. Following an interval of 500 ms a red or green colour stimulus was presented and remained visible until the peak force was reached. Then the appropriate sound under the current R–E mapping was emitted immediately. With a corresponding R–E mapping a loud tone was presented after detecting a forceful response, and a quiet tone was presented after detecting a soft response. With a noncorresponding mapping this R–E relation was reversed. With a mixed R–E mapping soft and forceful responses were randomly followed by quiet and loud tones. Visual error feedback was provided when the peak force was identified as the wrong response alternative (i.e., when a soft response was given, but a forceful response was required or vice versa). After an intertrial interval of 1000 ms the next trial started.

Each session started with 24 trials of practice. The sessions with corresponding, noncorresponding, and mixed R–E mapping consisted of 24 miniblocks of 16 trials each, with an opportunity for a brief rest after every 4th block. The order of stimuli was random. The sessions lasted about 40 min each and were administered on separate days but completed within a week. The order of corresponding, mixed, and noncorresponding R–E mappings was counterbalanced over participants.

Participants were informed that each response would lead to a certain sound, but that this tone was irrelevant for the task. They were also informed about the respective R–E mapping. It was emphasized that the response for the presented stimulus should be given as quickly and accurately as possible, irrespective of the sound that resulted from the required response.

Results

Response times. Responses with RTs below 100 ms and above 1000 ms were considered outliers and discarded (1.9% of the data). RTs were entered into an analysis of variance (ANOVA) for repeated measures with the variables of response type (soft vs. forceful),

TABLE 1
Reaction times and error rates as a function of R–E mapping, response type, and response effect in Experiment 1

	Blocked R–E mapping				*Mixed R–E mapping*			
	Quiet response effect		*Loud response effect*		*Quiet response effect*		*Loud response effect*	
Response	*RT*	*PE*	*RT*	*PE*	*RT*	*PE*	*RT*	*PE*
Soft	429	1.5	482	2.0	473	1.9	476	1.3
Forceful	387	5.0	366	3.5	383	1.9	381	2.4

Note: RT = Response time (ms). PE= Percentage of error (%).

assigned response effect (quiet vs. loud), and R–E mapping (blocked vs. mixed). Table 1 shows the means of the factorial combinations of these variables. An influence of R–E compatibility was found, indicated by a significant interaction of response type and response effect, $F(1, 11) = 6.64$, $p < .05$: Soft responses were initiated faster when followed by a quiet tone, whereas forceful responses were initiated faster when followed by loud tone. The compatibility effect was exclusively present with a blocked R–E mapping (i.e., when effects followed responses contingently), resulting in a triple interaction of R–E mapping, response type, and response effect, $F(1, 11) = 7.57$, $p < .02$. The interaction of response type and response effect was significant with blocked R–E mapping, $F(1, 11) = 7.29$, $p < .05$, but nonsignificant with mixed R–E mapping, $F < 1$. The influence of the effect tones was stronger for soft than for forceful responses, which led to overall faster responses with a quiet tone, $F(1, 11) = 6.04$; $p < .05$. Additionally, soft responses were overall initiated more slowly than forceful responses, $F(1, 11) = 25.60$, $p < .01$, which accords with previous reports and is probably due to biomechanical properties of the responding effector, as well as to the fact that the accepted range of soft responses (>200 cN but ≤800 cN) was more constrained than that of forceful responses (>800 cN), and hence soft responses had to be performed with greater precision (e.g., Carlton, Carlton, & Newell, 1987).

A mixed mapping may be considered as an appropriate neutral baseline to assess costs and/or benefits of R–E compatibility. Therefore an additional ANOVA analysed the data as a function of R–E correspondence (corresponding, mixed, noncorresponding). The mean RTs from these conditions amounted to 398, 428, and 434 ms and were significantly different, $F(2, 22) = 3.68$, $p < .05$. Single comparisons showed that RTs with a corresponding R–E mapping were significantly faster than with a noncorresponding R–E mapping, $F(1, 11) = 7.57$, $p < .02$, and marginally significantly faster than those with a mixed R–E mapping, $F(1, 11) = 3.93$, $p < .08$. RTs with noncorresponding and mixed mapping did not differ significantly, $F < 1$.

Error rates. The error rates mirrored RTs. The only significant effect in the analysis of the error data was the triple interaction between R–E mapping, response type, and response effect, $F(1, 11) = 7.15$, $p < .05$. The interaction between response type and response effect was significant with blocked R–E mapping, $F(1, 11) = 9.25$, $p < .02$. Here incompatible effects produced higher error rates than compatible effects. This interaction was absent with mixed R–E mapping ($p > .25$). When analysing the data as a function of R–E correspondence (corresponding, mixed, noncorresponding) the mean PEs amounted to 2.4%, 1.9%, and 3.5% and differed significantly, $F(2, 22) = 3.83$, $p < .05$. The error rate with a noncorresponding mapping was higher than that with a corresponding mapping, $F(1, 11) = 9.99$, $p < .01$, as well as with a mixed mapping, $F(1, 11) = 4.80$, $p < .05$, whereas corresponding and mixed mapping did not differ, $F < 1$.

Sequential influences of preceding R–E episodes. The mixed R–E mapping condition allows us to assess whether the correspondence versus noncorrespondence of the response effect in trial $n - 1$ exerted an influence on performance in trial n. Thus, these data were analysed as a function of correspondence/noncorrespondence in trial n and trial $n - 1$. Mean RTs (percentages of error in parentheses) for corresponding/noncorresponding trials were 422 ms (1.5%)/424ms (2.3%) when trial $n - 1$ contained a corresponding R–E event, and 429 ms (1.8%)/432 ms (1.9%) when trial $n - 1$ contained a noncorresponding event. No effect was significant. Thus, neither the correspondence in the current trial nor the correspondence in the preceding trial affected performance. The former is not surprising as the tones with a mixed mapping were not predictable. The latter finding rules out the possibility that the experience of a noncorresponding R–E episode in the preceding trial might somehow deteriorate performance in subsequent trials.

Practice effects. To explore for a practice-related decrease of the R–E compatibility effect, we collapsed together the data after every 64 trials of practice with corresponding and noncorresponding R–E mapping, respectively (resulting in six blocks of practice) and computed the mean compatibility effect (noncorresponding minus corresponding mapping) for each practice block. The mean R–E compatibility effect for RTs (and error rates in parentheses), from the first to sixth block were 43 ms (1.1%), 41 ms (–0.3%), 31 ms (0.4%), 33 ms (2.0%), 31 ms (2.0%), and 31 ms (1.3%), respectively. An ANOVA with the variables R–E mapping and block revealed the interaction of these factors as unreliable for RTs as well as for error rates, both Fs < 1.

Discussion

Experiment 1 revealed four major results. First, it replicated the influence of R–E compatibility reported by Kunde (2001). Second, with mixed R–E mappings the R–E correspondence experienced in previous trials had virtually no influence on performance in the present trial. At least under the conditions employed (e.g., the use of a 1000 ms intertrial interval and a warning click that separated each trial from the former one), the trials existed as independent events, not notably affected by the preceding trial history. Still, robust R–E compatibility effects were found, making it unlikely that these effects merely reflect some persisting influence from previous R–E episodes. Third, R–E compatibility effects remained robust even after extensive practice, ruling out the possibility that they result from violation of expectancies based on preexperimental experience.

A fourth aspect of the data concerns the performance under the mixed-mapping condition that may be regarded as an appropriate neutral baseline for assessing costs and benefits. RTs with this condition were clearly more within the range of the noncorresponding than the corresponding R–E mapping, suggesting that benefits (30 ms) were much larger than costs (only 6 ms). At first glance, this seems at odds with the ideo-motor interpretation of R–E compatibility that predicts benefits of compatible as well as costs of incompatible mappings. In our view this data pattern should, however, not be regarded as strong evidence against an ideomotor account for two reasons.

First, higher benefits than costs are not an atypical finding in the S–R compatibility literature (e.g., Kornblum & Lee, 1995, Exps. 1–2). In particular, longer RTs under mixed-mapping conditions seem to be the rule rather than the exception (e.g., De Jong, 1995; Van Duren & Sanders, 1988). This has been attributed to a strategic suppression of direct response activation when this activation leads to an incorrect response in a considerable portion of trials (cf. Proctor & Vu, 2002, for a comprehensive review of this literature). A similar reasoning may apply to the present R–E compatibility effect—that is, response activation by the auditory effects may be prevented when not being unambiguously helpful (i.e., compatible). Still responses could be specified by other sensory effects even with an incompatible R–E mapping (e.g., tactile, proprioceptive, visual ones). Only the impact of the incompatible auditory effects may be selectively switched off, which accords with the observation that subjects have considerable degree of freedom concerning the sensorial effects in which they code their actions (cf. Hommel, 1993; Wulf, Hoess, & Prinz, 1998). At any rate, the observation that S–R and R–E compatibility effects appear to behave in a similar manner here, in our view strengthens, rather than disproves, the proposed functional similarity of stimulus codes in S–R compatibility and effect codes in R–E compatibility.

Second, inferences from the mixed-mapping condition should be drawn with caution for two methodical reasons. First, it is not generally agreed what qualifies as an appropriate "neutral" condition. A cost–benefit analysis should therefore rely on convergent evidence from more than just one "neutral" condition (cf. Jonides & Mack, 1984, for a critical discussion of neutral baselines). Second, RTs and error rates behaved somewhat differently in Experiment 1: Whereas benefits were higher than costs in RTs, the opposite was true for error rates (where only costs were significant). Thus, RTs in the mixed-mapping condition might be increased as a consequence of a slightly reduced error rate. Because of this inconsistency we hesitate to draw any strong conclusion from this data pattern, and it warrants further research on the cost–benefit issue.

In sum, Experiment 1 reinforced the validity of R–E compatibility as an inferential tool to investigate anticipatory effect representations in response production. Experiment 2 now used the R–E compatibility effect to explore the contribution of anticipated effects on the response production process in more detail.

EXPERIMENT 2

In the choice reaction procedure employed in Experiment 1 various processes incorporated in response production take place during the response time interval. Following stimulus presentation the response needs to be *selected* from the response set, it needs to be *initiated*, and it has finally to be physically *executed* (cf. Rosenbaum, 1980). Whether or not this intuitively plausible fractionation is mediated by independent psychological processes is a matter of theoretical debate.

Traditional information-processing stage theory treats response selection, response initiation, and response execution as three serial encapsulated processes, with a different set of experimental variables affecting each process independently. Compatibility effects are assumed to originate from the response selection stage (e.g., Adam, 2000; Sanders, 1980; Spijkers & Walter, 1985; Sternberg, 1969). This leads to the prediction that R–E compatibility effects should not occur any more after response selection has been completed (i.e., when an already selected response is to be initiated).

Ideo-motor approaches to action control, in contrast, tend to see response selection and initiation not as independent stages but as different phases of one and the same dynamic activation of anticipatory effect codes (cf. Hommel, Müsseler, Aschersleben, & Prinz, 2001). These codes are assumed to become activated and to remain active until the response is actually carried out. From this perspective, action effects (as revealed by influences of R–E compatibility) might affect relatively early phases of response production (which traditional stage theory would localize in a response selection stage) as well as phases that immediately precede overt responding (which stage theory would localize in a distinct response initiation stage). Yet, the question of whether effect codes actually play a role in early and late phases of response production has not been investigated so far and thus calls for empirical clarification.

The first purpose of Experiment 2 was to disentangle the impact of anticipatory effect codes on response selection and response initiation. Response selection takes place after participants are informed about the next response but need to wait for a go-signal to start the execution of the selected action. Response initiation takes place between presentation of the go-signal and beginning of the physical response. Cueing responses sufficiently in advance thus allows responses to be selected prior to the RT interval and provides a method to assess whether anticipated response effects (as indicated by R–E compatibility effects) exert their influence during response selection, response initiation, or both.

One can think of three possible outcomes of such a cueing procedure. First, with valid response cueing the influence of R–E compatibility may decrease with increasing preparation time and vanish completely when responses are fully prepared. This would suggest that response effects become anticipated exclusively during response selection. Second, R–E compatibility may be entirely unaffected by cue validity and preparation time. This would suggest that anticipated effects exert their influence exclusively during response initiation. Third, the impact of R–E compatibility may still be present but reduced. This would suggest that anticipated effects have an impact on response selection as well as on response initiation.

The second purpose of Experiment 2 was to explore whether anticipated action effects also affect response execution (i.e., the way the response is physically carried out). The IM hypothesis is concerned primarily with the processes that precede overt responding. Therefore a clear prediction for an influence of forthcoming effects on action execution can barely be derived (though a plausible post hoc explanation can well be, see Discussion section). Nevertheless, forthcoming response effects may exert (and as the results will show actually do exert) an influence on measures of execution, in addition to and different from their influence on RTs. Identifying such influences would be of considerable theoretical interest and practical relevance (e.g., for optimizing manual input devices, movement-modifying training procedures in sports, etc.). Therefore, we also analysed parameters of the physically performed action as a function of forthcoming effects. We focused on the most commonly investigated execution parameter of force-varying responses, which is the peak amplitude of the force course or, simply, peak force (PF; cf. Mordkoff, Miller, & Roch, 1996; Ulrich, Rinkenauer, & Miller, 1998).

Method

Participants

A total of 16 students (7 men, 9 women) aged 19–46 years from introductory courses at the University of Würzburg participated in fulfilment of a course requirement.

Apparatus and procedure

The same apparatus, stimuli, and data collection methods as those in Experiment 1 were used. The only difference was that the auditory warning click was replaced by a fixation cross (1 cm high, 1 cm wide) of 100 ms duration. In two thirds of the trials the cross had the colour of the next imperative stimulus (i.e., was a valid cue), and in one third of trials it was white (i.e., was a neutral cue). Participants were informed that a coloured fixation cross predicted the next required response with 100% validity, and they were instructed to prepare the cued response as efficiently as possible. The cue onset preceded the stimulus onset by a randomly varying stimulus onset asynchrony (SOA) of 200, 500, 1000, or 1500 ms. The accepted PF ranges of soft and forceful responses were the same as those in Experiment 1 and thus allowed for sufficient variation as a function of forthcoming effect tones. The tones were presented only after peak force was reached to ensure that their impact was based on tone anticipation rather than on actual tone perception.

The participants worked through the conditions with corresponding and noncorresponding R–E mapping, separated by a brief rest of about 10 min. Half the participants received the corresponding R–E mapping first and the noncorresponding R–E mapping second, whereas for the other half this order was reversed. Each mapping condition consisted of 10 miniblocks of 24 trials each.

Results

Response times. Responses with RTs below 100 ms and above 1000 ms were considered outliers and were discarded (0.2% of the data). RTs from correct responses were entered into an ANOVA for repeated measures with the variables cue type (neutral vs. valid), SOA (200, 500, 1000, and 1500 ms), and R–E correspondence (corresponding vs. noncorresponding). The data of each factorial combination of these variables are depicted in Figure 1.

RTs were lower with valid than with neutral cues, $F(1, 15) = 173.90$, $p < .01$, and decreased with increasing SOA, $F(3, 45) = 50.93$, $p < .01$. This decrease was much stronger with valid cues than with neutral cues, $F(3, 45) = 22.48$, $p < .01$, for the interaction of SOA and cue type, suggesting that, as instructed, valid cues were indeed used for response selection. The decrease of RTs was asymptotic after an SOA of 1000 ms ($F < 1$, for the difference between the 1000 ms and 1500 ms SOA condition). The data separated for each type of response and response effect are listed in Table 2.

As in Experiment 1 there was a highly reliable influence of R–E correspondence: RTs were significantly faster with corresponding than with noncorresponding R–E mapping, $F(1, 15) = 20.19$, $p < .01$. The correspondence effect was significantly weaker with valid than with neutral cues, $F(1, 15) = 9.80$, $p < .01$, but did not interact with SOA, $F < 1$. Most importantly, it was quite sizeable and highly reliable with valid cues, even at an SOA of 1000 ms and 1500 ms, both ps < .01.

Cueing might reduce RTs in two not mutually exclusive ways, either by increasing the preparatory state in each individual trial or by evoking a high preparatory state in a relatively small number of trials and no preparation in the remaining trials (cf. De Jong, 2000). In the

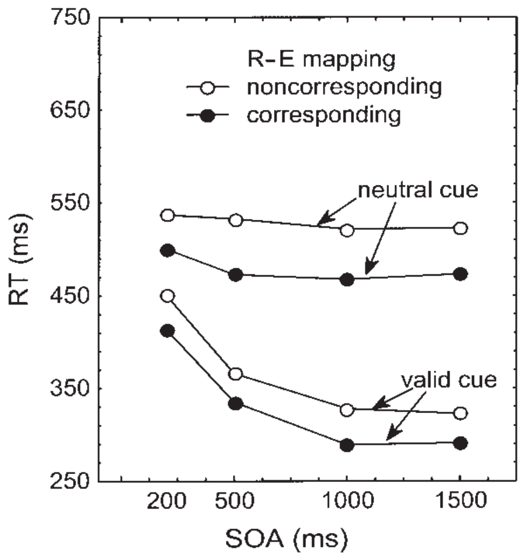

Figure 1. RTs as a function of cue type (neutral vs. valid) SOA and R–E compatibility in Experiment 2.

latter scenario the population of cued responses consisted of a mixture of prepared and unprepared responses, and R–E compatibility effects might be confined to the portion of unprepared responses. To explore this possibility we computed the distributional RT bins (quartiles) of each condition of Experiment 2. Prepared responses produce low RTs and are thus more likely to be located in the lower RT bins, whereas unprepared responses produce high RTs and are thus more likely to be located in the upper RT bins. A mixture of prepared

TABLE 2
Reaction times, percentages of error, and peak forces as a function of response cue, response type, response effect, and SOA in Experiment 2

		Neutral cue						*Valid cue*					
		Quiet response effect			*Loud response effect*			*Quiet response effect*			*Loud response effect*		
Response	*SOA*	*RT*	*PE*	*PF*	*RT*	*PE*	*PF*	*RT*	*PE*	*PF*	*RT*	*PE*	*PF*
Soft	200	518	0.6	364	579	1.9	312	433	1.6	367	488	6.9	315
Forceful		492	8.1	1593	481	9.4	1477	414	4.7	1609	394	6.0	1438
Soft	500	505	1.3	338	572	6.9	298	356	1.3	376	399	6.4	322
Forceful		489	9.4	1584	440	6.3	1455	333	3.9	1627	313	7.0	1443
Soft	1000	502	1.3	354	566	3.8	305	312	4.3	352	364	2.3	313
Forceful		474	6.9	1642	432	6.3	1479	293	4.2	1581	266	7.6	1380
Soft	1500	505	2.5	342	569	1.3	297	309	2.3	355	365	2.6	303
Forceful		476	7.6	1588	442	3.8	1462	279	6.0	1570	272	8.1	1410

Note: SOA = Stimulus onset asynchrony (ms). RT = Response time (ms). PE = Percentage of error (%). PF = Peak force (cN).

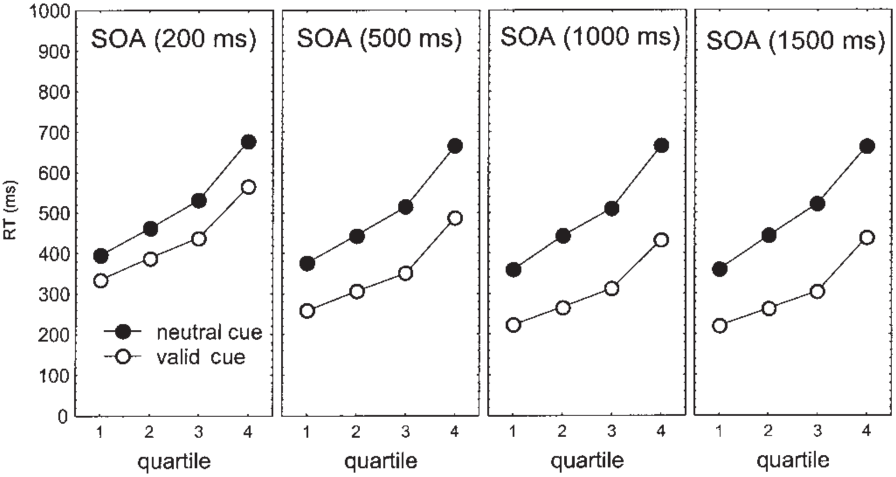

Figure 2. RTs as a function of RT-quartile, cue validity, and SOA in Experiment 2.

and unprepared responses should result in a large benefit of the valid over the neutral cue condition in the lower RT bins, where prepared responses of the cued population are compared with the necessarily unprepared responses from the uncued condition. In contrast, RTs should not differ in upper bins, where responses in both conditions are unprepared—either due to a lack of preinformation in the neutral cue condition, or due to a lack of using preinformation in the cued condition (e.g., Luce, 1986; Miller, 1998). In other words, a mixed population should show up as an interaction of RT-bin and cueing condition.

Figure 2 shows the RT distributions as a function of cue condition and SOA. The curves differ in all quartiles by a comparable size, ruling out the possibility that the decrease of RTs with valid cues originates from a small proportion of prepared responses.

Error rates. The mean error rate was lower with a corresponding than with a non-corresponding R–E mapping (4.3% vs. 5.2%), but the interaction of response type and response effect was not significant, $p > .05$. More errors were committed with forceful than with soft responses, $F(1, 15) = 12.74, p < .01$. It seems possible that the relatively long sessions of the present experiment could have encouraged the participants to adopt an economical strategy of producing response forces as minimal as possible, particularly when a forceful response was required. Adopting such a strategy might occasionally have produced PFs within the range of soft responses, which then counted as response error. Finally, with valid but not with neutral cues there were more errors when responses were mapped to a quiet tone, $F(1, 15) = 5.45$, $p < .05$, for the interaction of cue type and mapped response effect. The analysis of peak force shows (see below) that quiet auditory effects increase peak force. Therefore it appears possible that the slight error increase for prepared responses with quiet tones results from anticipatory increase of force, which occasionally may have led to the erroneous execution of a response. No other effect reached significance.

Response force. As a first analysis we computed for each participant the correlation coefficients between RT and PF across trials within each factorial combination of cue type, SOA, response type, and response effect. As has been found previously (e.g., Mordkoff et al., 1996; Ulrich et al., 1998) the averaged within-condition correlation between reaction time and PF was virtually zero, $r(\mathrm{RT, PF}) = -.046$.

A second analysis of PF as a function of experimental conditions revealed the (somewhat trivial) result that force was higher for forceful than for soft responses, $F(1, 15) = 136.34$, $p < .01$. More interestingly, PF was affected by the intensity of the auditory response effects. Responses were overall executed more forcefully when assigned to a quiet tone than when assigned to a loud tone, $F(1, 15) = 18.72$, $p < .01$. Finally, PF decreased slightly over SOA but more so (and slightly more systematically) with valid than with neutral cues, $F(3, 45) = 3.06$, $p < .05$ for the interaction of SOA and cue type, which accords with previous results showing that pre-knowledge of responses tends to reduce PF (cf. Mattes et al., 1997, for a discussion of this finding).

Discussion

The first purpose of Experiment 2 was to investigate whether R–E compatibility affects early processes of movement production (denoted as response selection) or late processes that immediately precede overt responding (denoted as response initiation). In replicating Experiment 1 a significant influence of R–E compatibility was found when no specific preinformation was provided, and thus response selection and initiation were both included in the RT interval. Valid preinformation reduced RTs by about 40%. This RT reduction was asymptotic after about 1 s of preknowledge, and the absolute RT level was well within the range of a simple reaction task for this type of response (Carlton et al., 1987). Distribution analysis showed that the RT reduction is not due to averaging over prepared and unprepared responses. Altogether, these results indicate that responses were indeed selected as efficiently as possible. Nevertheless a sizeable influence of forthcoming response effects persisted at long SOA, which suggests that at least the present instance of R–E compatibility affects response initiation. Yet, the R–E compatibility influence was significantly larger when response selection was fully included in the RT interval (i.e., with a neutral cue) than when it was partly or completely removed (i.e., with a valid cue in varying SOA). Hence anticipated effects exert some extra influence on response selection, which seems to take place in the first 200 ms after cue presentation, because additional preparation time did not reduce R–E compatibility more strongly (see Figure 1).

An alternative way to explain persisting but reduced compatibility effects with valid cueing is that effect codes affect response selection exclusively but then decay over time, in a similar manner to that for irrelevant stimulus codes in the Simon effect (e.g., Hommel, 1997). This reasoning is based on the observation that the Simon effect typically decreases when response time increases. Two arguments speak against this view. First, as has been reported earlier, R–E compatibility effects do not decrease but *increase* with RT. Averaged over the 2 (cuetype) × 4 (SOA) experimental conditions shown in Figure 1, the mean R–E compatibility in RT quartiles amounts to 16, 23, 41, and 87 ms. This suggests that anticipatory effect codes build up rather than decay over time (cf. Kunde, 2001, for a discussion). Second, responses were fully prepared after 1000 ms preparation time (cf. Figure 1). Yet, R–E compatibility effects did not decrease thereafter. We find it hard to explain why selection-mediating effect codes did not decay any more even though they had 500 ms to do so.

The second purpose of Experiment 2 was to explore whether forthcoming auditory response effects also affect response execution (i.e., response force). This was the case. Yet, the influence of auditory effects on response force was dissociated from their influence on RTs. First, RTs and PF were uncorrelated within experimental conditions, in agreement with the suggestion that these variables reflect independent aspects of response production (cf. Abrams & Balota, 1991; Mordkoff et al., 1996; Ulrich et al., 1998). Second, whereas effect intensity affected RTs of soft and forceful responses *differently* (e.g., a quiet tone increased RTs with forceful responses, but reduced RTs with soft responses), effect intensity affected PF of soft and forceful responses *uniquely* (a quiet tone increased PF of soft and forceful responses). To understand this data pattern it is essential to realize that PF is a measurement of the intensity of tactile feedback. Viewed like this the data accord with the idea that the intensities of tactile and auditory feedback are "averaged", and that the tactile feedback is adjusted to maintain a constant value of the averaged tactile–auditory feedback (cf. Aschersleben & Prinz, 1997; Aschersleben, Stenneken, Cole, & Prinz, 2002). Thus, when subjects intend to produce a soft response, which, however, is associated with a loud tone, this results in a compensatory reduction of tactile feedback (and thus force) to maintain a constant averaged tactile–auditory feedback for soft responses. Likewise, when subjects intend to produce a forceful response, which, however, produces a quiet tone, this results in a compensatory increase of tactile feedback. This explanation accords with similar biases of duration-varying response effects on the execution of duration-varying responses, where long effects decrease response duration relative to short effects and vice versa (Kunde, in press).

GENERAL DISCUSSION

The present study was motivated by the core assumption of ideo-motor theory that motor acts are represented in terms of—and are thus accessed by—their perceptual effects. We have argued that compatibility influences between responses and their forthcoming effects provide a useful indicator of anticipatory effect codes in response production. The present study validated this indicator and applied it to assess whether anticipatory effect codes are part of early antecedents of actions (response selection) or late antecedents that immediately precede overt responding (response initiation). Finally we investigated how anticipatory effect codes affect the way actions are physically carried out (response execution).

Summary of findings

Experiment 1 showed that the R–E correspondence experienced in the preceding trial exerted virtually no influence on performance, ruling out the possibility that R–E compatibility effects originate from sequential influences by preceding R–E episodes. Additionally, R–E compatibility effects were robust with respect to practice, ruling out the possibility that they simply originate from participants' initial surprise. Experiment 2 revealed that R–E compatibility effects were also robust, though numerically reduced, even when sufficient information (i.e., a valid cue) and sufficient time (i.e., a long SOA) are given to select the correct response in advance of stimulus onset. This suggests that R–E compatibility effects at least partly originate from response initiation. Influences of anticipated response effects were additionally observed in response execution. This influence can be described as intensity contrast: With high auditory feedback intensity, the tactile feedback intensity (i.e., PF) was reduced (and/or with low auditory intensity increased) so that the joint intensity of tactile and auditory feedback maintained a certain constant criterion for soft and forceful responses, respectively. Altogether, these findings put constraints on ideo-motor approaches of action control and compatibility theories as well, which we discuss in the following section.

Action effects in response selection

It is a basic assumption of IM theories that effect codes become activated during response selection (e.g., Greenwald, 1970; Hommel et al., 2001), and it is a basic assumption of traditional compatibility models that compatibility effects originate from a response selection stage (e.g., Kornblum, Hasbroucq, & Osman, 1990). These assumptions easily generate the prediction that R–E compatibility effects will occur during response selection, and thus the observation of R–E compatibility effects for uncued responses found in both experiments comes as no surprise.

Up to this point, R–E compatibility effects can be accounted for by very similar mechanisms as proposed in traditional S–R compatibility research. Based on common S–R activation-accumulation models, the following three assumptions are in our view necessary and sufficient to account for R–E compatibility effects in response selection (cf. Kornblum & Stevens, 2002; Stevens & Kornblum, 2000):

1. The occurrence of an external (or internal) response cue induces a gradual growth of activation of the various multimodally distributed codes of response effects over time.
2. Effect codes from different modalities interact with each other as a function of their similarity (or dimensional overlap) just like stimuli and responses interact in S–R compatibility effects. Activation of a code in a certain modality (e.g., audition) boosts the building-up of codes in other modalities (e.g., proprioception). This mutual priming is beneficial with a corresponding R–E mapping that allows for a fast building-up of code activation. Figure 3 illustrates the hypothetical rise of effect-code activation of a to-be-produced motor pattern, summed over different sensory effect modalities (mostly proprioception and audition in the present study). The solid (and dashed) lines depict the activation growth of corresponding (and noncorresponding) multimodal effect codes.
3. Mutual priming of corresponding effect codes is harmful with a noncorresponding R–E mapping. Here anticipating an auditory effect primes proprioceptive effect codes that are associated with unrequested motor patterns, whereby the recruitment of the actually requested movement is delayed.[2] At this stage the performance with mixed R–E mapping (Exp. 1) suggests that costs are much smaller than benefits, but we add a cautious note here because of the inconsistent data pattern in error rates and response times.

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[2] Dimensional overlap may be conceived as long-term memory (LTM) associations that result from extensive (mostly long-lived) preexperimental experience (Barber & O'Leary, 1997; Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). LTM associations exist between effect codes of different modalities (e.g., intensive proprioceptive effects often co-occur with intensive auditory effects) as well as between motor codes and effect codes (e.g., intensive proprioceptive effects often co-occur with forceful movements). Short-term memory (STM) associations, in contrast, exist for merely an experimental session (like the incompatible combination of soft proprioceptive feedback with a loud tone).

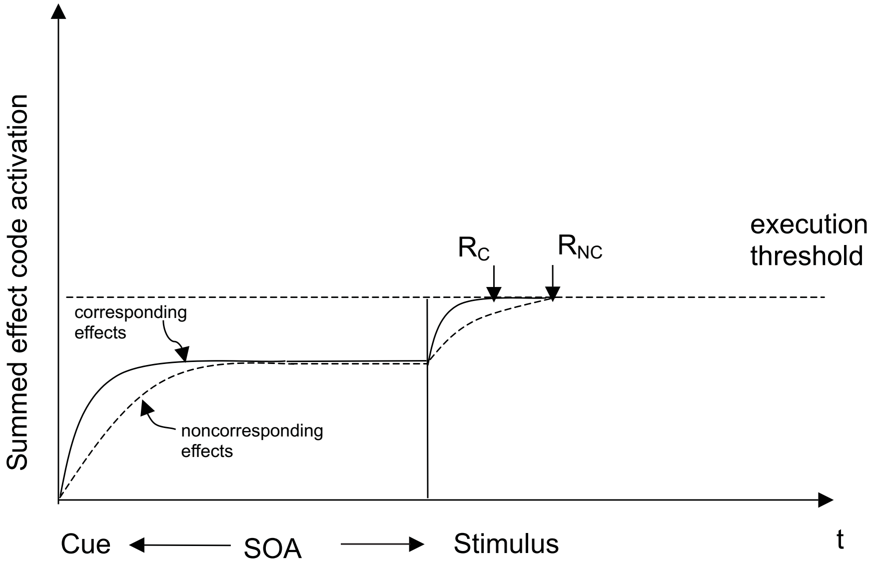

Figure 3. Hypothetical rise of effect code activation summed over different modalities as a function of preparation time and effect correspondence.

In short, anticipatory effect codes presumably produce R–E compatibility effects in a similar fashion to that by which stimulus codes produce S–R compatibility effects (Lu & Proctor, 1995). The crucial difference is that effect codes in R–E compatibility become endogenously generated (because they represent the to-be-produced event), whereas stimulus codes in S–R compatibility are activated by external stimulation.

Action effects in response initiation

The theoretically most challenging outcome of the present study is the presence of R–E compatibility effects for prepared (i.e., selected) responses, found in Experiment 2. This finding deserves attention for two reasons.

First, it contributes to the ongoing debate on the functional locus of compatibility phenomena. Traditional models of S–R compatibility attribute compatibility effects to a response selection stage (e.g., Adam, 2000; Anzola, Bertolini, Buchtel, & Rizzolatti, 1977; Kornblum et al., 1990). Hence, no compatibility effects should emerge after response selection has occurred—that is, with response certainty. However, S–R compatibility effects have been found with response certainty, which suggests that stimulus-induced priming can occur at every point in time before response execution (Brass, Bekkering, & Prinz, 2001; Hommel, 1995, 1996). The present study supports and extends this conclusion by showing that anticipated effects (i.e., postresponse stimuli) also maintain their power to exert compatibility effects up to the time at which the response is actually carried out.

Second, the persisting influence of anticipated effects on already specified responses adds to our understanding of the functional role of action effects in action production.

Apparently, anticipatory effect codes do not only mediate early phases of action production (i.e., "selection") but they remain functional for making an already selected action become real (i.e., "initiation"). In other words, effect codes trigger the physical occurrence of the action—a function not, or at least not consistently, acknowledged in ideo-motor approaches to action control (cf. Greenwald, 1970; Hommel et al., 2001; Klapp et al., 1991).

Within the outlined activation–accumulation model the persisting impact of action effects can be explained by the assumption that some code activation is postponed until response initiation is allowed (cf. Figure 3). A plausible reason for this is that movements are emitted automatically when the activation of their effect codes exceeds a certain execution level (cf. Henry & Rogers, 1960; Klapp, 1995, for similar ideas). Because some residual activation is necessary to ultimately launch the action, an R–E compatibility effect is present even with prepared responses, though it is reduced because the outstanding code activation, required to push the action over its execution threshold, is smaller when some activation has already occurred, than when activation starts from rest level. In short then, response initiation can be construed as the extension, or better completion, of the same effect-code activation process that already started earlier during response selection.

Action effects in action execution

Influences of forthcoming effects on physical action execution are not the primary focus of IM theory, which is concerned with the antecedents of the physical action. Yet, empirically we saw that forthcoming action effects exerted an influence on measures of response execution in Experiment 2. Some aspects of the data suggest that this influence is independent of the processes that mediate the tones' influence on RTs. Not only were RTs and PFs statistically uncorrelated on a trial-by-trial basis, but the nature of the tones' influence on RTs and PF was different: Whereas they exerted a compatibility effect on RTs, they exerted a general contrasting bias on PF. An intermodal averaging account provides a plausible explanation for this observation: The proprioceptive feedback (reflected in response force) is adjusted so that the combined proprioceptive and auditory feedback meets a constant averaged criterion on their common intensity dimension (Aschersleben & Prinz, 1997).

Although we favour the ideo-motor framework that prompted the present study to explain our experimental results, some cautious notes on the generality of the present findings are warranted. First of all, the present study did not test the "radical" version of ideo-motor theory that effect anticipation is the one and only way of response production. Given the observation that participants can choose between different effect modalities to code their actions, this radical hypothesis might be hard to test by merely manipulating some extra experimental effects, without controlling all other potential effect modalities (Wulf et al., 1998). Our experiments show (1) that nominally task-irrelevant effects become anticipated during response production and (2) that they have the power to bias the motor system. They do not show, however, that this anticipation is mandatory. In principle the auditory effects may have served other than a response-generating function. For example, compatible effects, even though being equally informative regarding response accuracy as incompatible effects, may provide a more easy to use feedback to determine whether force has reached an intended criterion or not. The easier use of compatible feedback might allow participants to focus more on the main task than might incompatible or mixed effects. We cannot rule out this alternative explanation by the present data. We want to note, however, that R–E compatibility effects are not confined to continuous responses of the type used here, but extend well to more ballistic, discontinuous responses like spatial keypresses or vocal responses, where the use of feedback in general is unlikely (Koch & Kunde, 2002; Kunde, 2001). Moreover, the easier use of compatible feedback might explain reduced RTs; it does not explain, however, the characteristic contrast influence of effect intensity on response execution (i.e., decrease of force with high effect intensity and/or increase of force with low intensity). Nevertheless it is clear that the generality of the present finding should be tested with a different set of responses and effects to rule out this feedback-based interpretation.

In conclusion then, the present study suggests that anticipated action effects have an impact on, and are thus likely to contribute to, all phases of action production. Although the detailed mechanisms of this impact require further investigation, the present experiments provide empirical support for the widely forgotten ideo-motor principle that stresses the crucial role of anticipated action effects in action control. We think it is worthwhile to further pursue this old but fruitful idea.

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