

Good vibrations? Vibrotactile self-stimulation reveals anticipation of body-related action effects in motor control

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Abstract Previous research suggests that motor actions are intentionally generated by recollecting their sensory consequences. Whereas this has been shown to apply to visual or auditory consequences in the environment, surprisingly little is known about the contribution of immediate, body-related consequences, such as proprioceptive and tactile reafferences. Here, we report evidence for a contribution of vibrotactile reafferences to action selection by using a response–effect compatibility paradigm. More precisely, anticipating actions to cause spatially incompatible vibrations delayed responding to a small but reliable degree. Whereas this observation suggests functional equivalence of body-related and environment-related reafferences to action control, the future application of the described experimental procedure might reveal functional peculiarities of specific types of sensory consequences in action control.

Keywords Action control · Effect anticipations · Body-related feedback · Ideomotor theory

Introduction

“Through the free play of the will on the motoric centres, a great variety of incidental movements results

in the unborn and the newborn [...]. Each of these movements causes a sensory image (effect image) of the movement [...]. The more often the same process is repeated the more often this particular movement is executed, the wider and more passable the road [from sensory anticipation to action] becomes.” (Harleß 1861, p. 66; cf. Pfister and Janczyk 2013; Stock and Stock 2004).

Philosophers of the early nineteenth century set out to answer the question of how intentions can result in overt motor behaviour. In other words, how do mental states such as thoughts and feelings eventually result in physical activity of the muscles? A central theme of these philosophical analyses is summarized in the above quote from Emil Harleß (1861): during early ontogeny, most movements arise either due to reflexes or due to fluctuating activity in the brain. The sensory consequences of these movements are registered and associated bidirectionally with the preceding motor activity. Mental representations of upcoming, sensory consequences thus gain the power to evoke the corresponding motor patterns: anticipating the desired outcome directly triggers the appropriate action (Harleß 1861; Herbart 1825; James 1890; Lotze 1852; for historical comments, see Pfister and Janczyk 2012; Pfister et al. 2012; Stock and Stock 2004).

Ideomotor theory: from body- to environment-related effects

This so-called ideomotor mechanism provides an elegant and parsimonious philosophical answer to the question of how human agents can voluntarily produce actions that are suited to reach a given goal. Still, ideomotor theory did not gain a strong foothold among early experimental

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psychologists who questioned the empirical testability of the theory (Thorndike 1913; cf. Prinz 1990, Stock and Stock 2004). In fact, the basic assumption of bidirectional associations between motor actions and their contingent body-related sensory consequences is hard to get at empirically. The theory thus did not stimulate extensive research for more than a century following its original formulation. In the second half of the twentieth century, however, the basic idea was rediscovered (Greenwald 1970) and brought to psychologists' attention. This rediscovery, brought about a shift from body-related effects of own movements to contingent effects in the environment (e.g. Greenwald 1970; Hoffmann 1993; Hommel 1993; Hommel et al. 2001; Kunde 2001; Prinz 1992, 1997).¹

More precisely, this new approach to effect-based action control coupled different motor patterns with different visual and auditory effects as a methodological crutch to study the very mechanisms described in the philosophical formulation of ideomotor theory. If actions are indeed accessed by anticipating their sensory effects, such a mechanism might generalize to any kind of perceivable effect in the environment (e.g. Hoffmann 1993; Hommel 2009; Hommel et al. 2001; Prinz 1992, 1997; cf. Shin et al. 2010 for a recent review). Action effects in the environment were typically operationalized by coupling keypress actions with contingently following tones or visual events on a computer screen. Research on such environment-related action effects did indeed gather convincing evidence for the basic mechanisms postulated by early ideomotor theorists. For example, repeatedly experiencing an arbitrary sensory consequence resulting from one's own action seems to create an association between action and effect, and this association is bidirectional—just as claimed by early ideomotor theory (e.g. Elsner and Hommel 2001; Hoffmann et al. 2009; Wolfensteller and Ruge 2011; Nattkemper et al. 2010). Furthermore, upcoming sensory events in the environment have a systematic impact on the production of actions (e.g. Kunde 2001, 2003; Pfister et al. 2010; Shin and Proctor 2012). This finding is well compatible with the idea that effects are indeed anticipated during action planning and action initiation.

In fact, the use of action effects in the environment was so successful that the term “action effect” became synonymous with the study of environment-related effects. As a result, body-related effects are often not even included in the ideomotor equation anymore. This becomes apparent

when failures to observe bidirectional action-effect learning for environment-related effects in some conditions are taken to indicate a “far-reaching constraint” (Herwig et al. 2007, p. 1540), in terms of evidence against ideomotor theory (cf. also Herwig and Horstmann 2011; Krieghoff et al. 2009; Kühn et al. 2009). Of course, it is true that such observations do constrain ideomotor theory in terms of clarifying when environment-related action effects are included in action control and when they are not (Gaschler and Nattkemper 2012; Herwig and Waszak 2012; Pfister et al. 2010, 2011; Ruge et al. 2012). Importantly, however, an absent influence of environment-related effects does not falsify ideomotor theory. As outlined above, early formulations of the theory were not even concerned with these types of effects. This, of course, renders ideomotor theory hard to falsify, and this criticism similarly holds for its modern descendants (cf. Hommel et al. 2001; Oriet et al. 2001; Sanders 2001). Nevertheless, it should not be forgotten that early formulations of ideomotor theory were mainly concerned with body-related action effects.

The present study: anticipating body-related effects

If body-related action effects are indeed functionally equivalent to the environmental effects that are investigated typically, it should be possible to find at least some indirect evidence for this mechanism (cf. Pfister and Kunde 2013). Here, we present a series of three experiments that aim at filling this gap.

To this end, we employed an experimental design known as the response–effect (R–E) compatibility paradigm (Kunde 2001). The critical aspect of this paradigm is to manipulate arbitrary effects that follow different actions. If the employed effect shares certain features with an action in question (e.g. compatible features in terms of location, duration, or intensity), the action is initiated more quickly than if action and effect features do not match (incompatible features). Because the action effects only occur *after* action execution, i.e. when response times (RTs) have already been measured, RT differences between compatible and incompatible action-effect mappings indicate an impact of *anticipated* sensory events. This logic has been employed in various settings and using a wide range of environment-related effects in the visual and auditory modality (see also, e.g. Ansorge 2002; Pfister and Kunde 2013; Kunde et al. 2012; Janczyk et al. 2012a, b, c; Rieger 2007). Clearly, the logic behind the R–E compatibility paradigm can be applied similarly to body-related effects. While this is of course only a very coarse approximation of the mechanisms implied by ideomotor theory, we still consider it worthwhile to pursue such a strategy.

In a nutshell, we had our participants respond to arbitrary target stimuli with a right or left button press. Pressing

¹ The first explicit distinction of body-related and environment-related effects appeared under the labels of “resident” and “remote” effects (James 1890; cf. Janczyk et al. 2009; Pfister and Kunde 2013). We consider the present wording of body- vs. environment-related effects to be more intuitive, however.

a key triggered a vibration of one of the two keys, and this vibration clearly is much more of a body-related action effect than is a sound or a visual event occurring in the environment. If the location of this vibration predictably appears at a different location than the action itself, anticipating the incompatible proprioceptive signals should slow down responding.

Experiment 1

As a first, direct implementation of the described logic, we simply compared two different vibration conditions: In the compatible condition, each keypress immediately made the corresponding key vibrate for a short time. We contrasted performance in this condition with an incompatible mapping in which the opposite key vibrated instead.

Empirically, R–E compatibility effects show up in two different statistical effects. First, RTs are expected to be higher in the incompatible than in the compatible condition. Secondly, analyses of the time course of R–E compatibility effects indicated that they emerge especially for slower responses (Kunde 2001; cf. also Keller and Koch 2006; Kunde et al. 2011). To this end, we examined R–E compatibility effects across the quintiles of the RT distribution and expected the effects to increase with quintile.

Method

Participants and apparatus

Thirty-two undergraduate students participated for course credit (mean age: 21.2 years; 6 males; 5 left-handed). All participants were naive as to the purpose of the experiment. Target stimuli were the letters X and H (24 pt, bold Arial font) presented in white colour on black background in the centre of a 19" monitor. Participants operated two custom-built response keys (inter-key distance: 18 cm) that were mounted on a pane of Plexiglas each (3 cm × 7 cm; see Fig. 1). Vibration was induced by a servomotor below the Plexiglas that rotated an unbalanced mass, causing the pane to swing up and down by circa 1 mm.

Design and procedure

Participants completed 20 blocks of 16 trials, with both stimuli occurring equally often in random order. The blocks either had a compatible R–E mapping (pressing a key made the same key vibrate) or an incompatible R–E mapping (pressing a key made the other one vibrate), and each mapping was implemented in 10 consecutive blocks. Trials began with the presentation of the target letter for 250 ms. Correct key presses within 1,500 ms after target

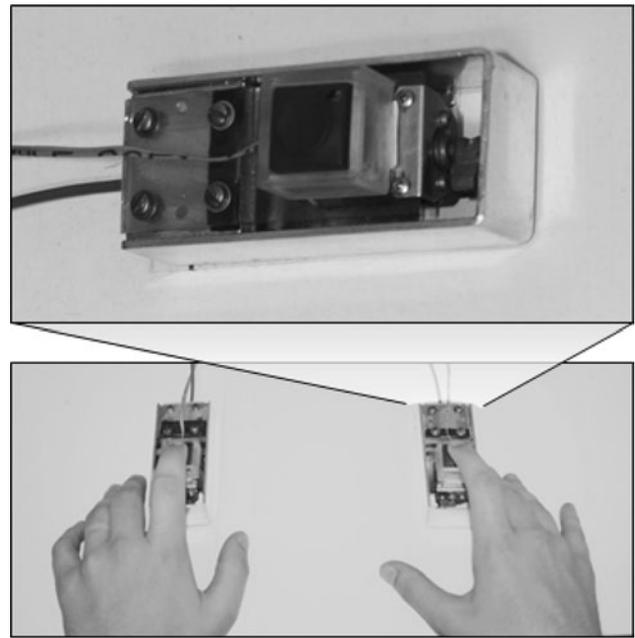


Fig. 1 Experimental set-up. Response keys were mounted on a Plexiglas pane. A servomotor below the pane rotated an unbalanced mass to make the key vibrate

onset immediately caused either the same or the other key to vibrate for 250 ms (depending on the R–E mapping). Wrong responses and response omissions did not cause any rotation but triggered visual feedback (“Fehler”; error in German) for 2,000 ms. The next trial started after 1,000 ms. The order of R–E mappings and the stimulus–response mapping were counterbalanced across participants.

Results and discussion

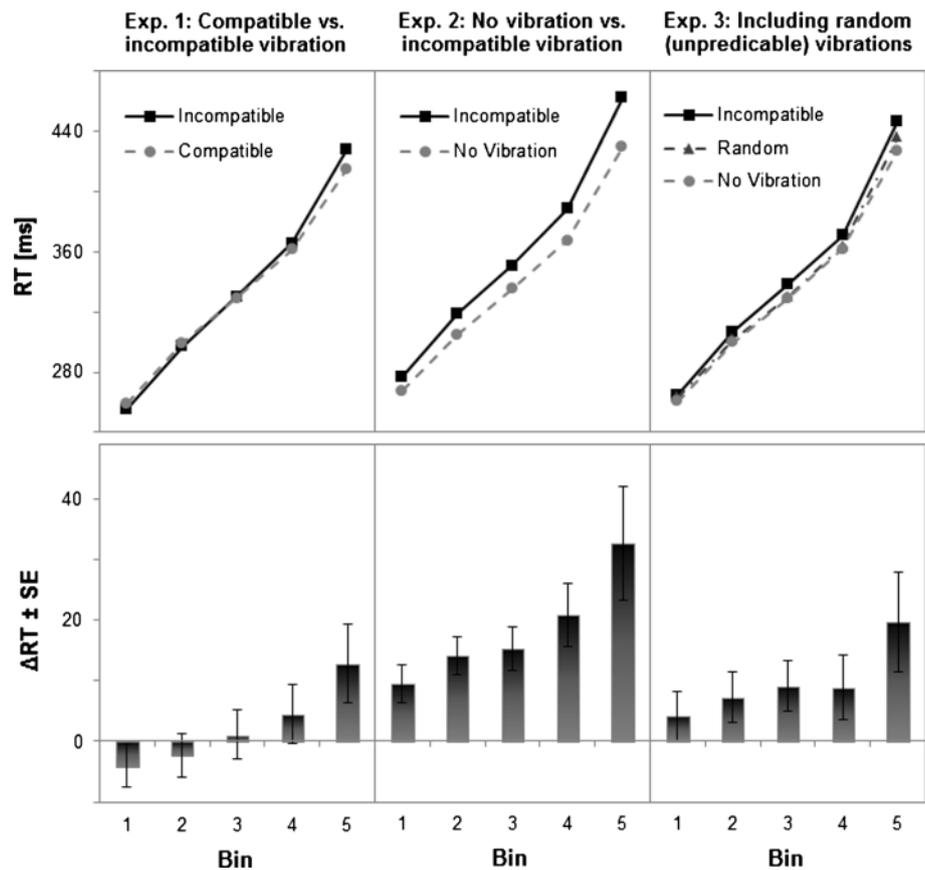
The first block of each compatibility condition was considered practice and did not enter the analyses. For the remaining blocks, errors occurred in 8.4 % of the trials and the frequency of errors did not differ between compatible (8.6 %) and incompatible trials (8.4 %), $t(31) = 0.64$, $p = .529$, $d = 0.11$. These error trials were omitted from the RT analysis and so were trials with RTs deviating more than 2.5 standard deviations from their cell mean (2.4 %), calculated separately for each participant and compatibility condition.

The data of the remaining RTs are plotted in Fig. 2 (upper-left panel) and they were analysed with a 2×5 repeated-measures ANOVA with the factors compatibility (compatible vs. incompatible) and RT distribution quintile (bin; 1–5). This analysis clearly showed the main effect of distribution quintile to be significant, $F(4, 124) = 577.52$ ($\varepsilon = .29$), $p < .001$, $\eta_p^2 = .95$. Unexpectedly, the main effect of compatibility was not significant, $F(1, 31) = 0.49$,

Fig. 2 Results for Experiments 1–3. *Upper panels* mean RTs for each experimental condition. In all three experiments, the incompatible condition employed vibrations of the key that had *not* been pressed. In Experiment 1, the compatible condition featured a vibration applied to the key that was acted on. The “compatible” conditions of Experiments 2 and 3 did not use any vibration at all. Finally, Experiment 3 introduced a random condition in which one of the keys vibrated in each trial (determined randomly).

Lower panels

R–E compatibility effects ($RT_{\text{incompatible}} - RT_{\text{compatible}}$ for Experiment 1, and, $RT_{\text{incompatible}} - RT_{\text{no vibration}}$ for Experiments 2–3) for each distribution quintile. *Error bars* show the SE_M for each individual bar (Pfister and Janczyk 2013)



$p = .489$, $\eta_p^2 = .02$, whereas a significant interaction was driven by larger compatibility effects for higher bins, $F(4, 124) = 7.18$ ($\epsilon = .32$), $p = .007$, $\eta_p^2 = .19$.

The distribution analysis of Experiment 1 thus yielded a small R–E compatibility effect for body-related action effects, which was significant for the longest RTs. This finding is consistent with our predictions derived from ideomotor theory. Compared to typical effect sizes for spatial R–E compatibility effects (Kunde 2001; Pfister and Kunde 2013), the present effect sizes are small at best, however (with the largest effect of $d = 0.35$ resulting for the fifth distribution quintile).

The small effect sizes of Experiment 1 come rather unexpected because, if anything, R–E compatibility effects for body-related action effects would be expected to be larger and more robust than R–E compatibility effects for artificial consequences in the agent’s environment. One reason for the small effect size might be identified by carefully considering the experimental design: The compatible condition featured a vibration at the location that was acted on (creating a spatially compatible action effect), but a vibration occurring after a simple finger flexion is rather rare in most everyday experiences. Thus, what we used as the compatible condition unwittingly introduces some oddness to an otherwise easy finger movement. In this view,

Experiment 1 compared two incompatible R–E relations to each other—with one being slightly less incompatible than the other. An easy way to address this speculation empirically is to remove any vibration in compatible trials, and this is exactly what we did in Experiment 2.

Experiment 2

The “compatible” condition of Experiment 2 did not employ any additional action effects. Accordingly, participants simply pressed the appropriate response key and the next trial started afterwards. This condition thus included only those proprioceptive and visual action effects that would normally result from a simple finger flexion. RTs in this condition were again compared to an incompatible condition in which each keypress made the opposite key vibrate. If the above reasoning holds, R–E compatibility effects should be considerably more pronounced than in Experiment 1.

Method

We recruited thirty-two new participants (mean age: 26.4 years; 8 males; 1 left-handed). Apparatus, design, and

procedure were identical to Experiment 1 with the only exception that blocks with compatible vibrations were substituted for blocks that did not feature any key vibration. To ensure a constant timing across conditions, the programme waited for 250 ms instead of making a key vibrate in the no-vibration condition.

Results and discussion

Errors occurred in 7.3 % of the trials and the frequency of errors did not differ between no vibration (7.5 %) and incompatible trials (7.1 %), $t(31) = 0.95$, $p = .347$, $d = 0.17$. These error trials were omitted from the RT analysis, as were outliers (2.3 %).

The data of the remaining RTs are plotted in Fig. 2 (upper-central panel) and were analysed as in Experiment 1. This analysis yielded a clear main effect of compatibility with slower RTs for incompatible as compared to no-vibration trials, $F(1, 31) = 11.87$, $p = .002$, $\eta_p^2 = .28$. The main effect of distribution quintile was also significant, $F(4, 124) = 238.37$ ($\varepsilon = .27$), $p < .001$, $\eta_p^2 = .88$, and the interaction was marginally significant, $F(4, 124) = 3.29$ ($\varepsilon = .28$), $p = .074$, $\eta_p^2 = .10$, again driven by larger compatibility effects for higher bins.

Furthermore, we compared these results to the results of Experiment 1 by means of a $2 \times 2 \times 5$ split-plot ANOVA with the between-subjects factor experiment (1 vs. 2) and the two repeated-measures compatibility (compatible/no vibration vs. incompatible) and RT distribution quintile (bin). This analysis yielded a significant main effect of compatibility, $F(1, 62) = 11.46$, $p = .001$, $\eta_p^2 = .16$, and this effect was more pronounced in Experiment 2 than in Experiment 1, $F(1, 62) = 6.80$, $p = .011$, $\eta_p^2 = .10$. Additionally, the interaction of compatibility and distribution quintile was significant, $F(4, 248) = 14.82$ ($\varepsilon = .32$), $p < .001$, $\eta_p^2 = .19$, whereas the three-way interaction was not ($F < 1$).

These results lend additional support to the claim that anticipations of body-related action effects play a functional role in action control: Action initiation is delayed if the body is going to be affected in an atypical way. Still, the results do not necessarily imply an ideomotor explanation of the observed compatibility effects. A similarly plausible alternative explanation for the effects of Experiment 2 simply holds that the mere knowledge of some, rather unusual action consequences in incompatible trials drives the observed performance differences. For instance, this knowledge might induce some degree of avoidance motivation—a suspicion that is also in line with anecdotal reports of our participants. Avoidance motivation might, in turn, slow down responses in this condition relative to the no-vibration condition. Additionally, this knowledge might change the motor behaviour of the participants (e.g.

pressing harder to compensate for the vibration). Experiment 3 addresses this question.

Experiment 3

Experiment 3 probes for the two possible explanations for our previous findings. The *incompatible anticipations hypothesis* assumes the observed compatibility effects to depend on basic mechanisms subserving effect-based action control. Because action-contingent effects are anticipated during action initiation, anticipating body-related effects that do not match usual changes in proprioceptive reafferences should conflict with action planning, thereby increasing RTs. By contrast, the *passive knowledge hypothesis* ascribes the compatibility effects of Experiment 2 to the simple knowledge of upcoming unusual action consequences.

To pit the two hypotheses against each other, we introduced a new condition that featured a vibration in each trial (like in the incompatible condition). In contrast to the incompatible condition, however, we determined randomly which key would vibrate. This manipulation does not affect the mere knowledge of (any) upcoming, unusual action consequences. But because the location of the vibration was not predictable, the random condition does not allow for clear effect anticipations regarding the location of the vibration. The incompatible anticipations hypothesis predicts the incompatible condition to yield slower RTs than both, the no-vibration and the random condition. By contrast, the passive knowledge hypothesis predicts the random condition to yield slower RTs than the no-vibration condition because it likely implies the same motivational effects as does the incompatible condition. Of course, both hypotheses are not mutually exclusive. We therefore also analysed the RT costs of the incompatible mapping as compared to the random condition alone to determine whether the incompatible anticipation hypothesis is backed up by the data.

Method

Twenty-four new participants were recruited (mean age: 25.2 years; 3 males; 1 left-handed). Again, all participants were naive as to the purpose of the experiment. Apparatus, design, and procedure were identical to Experiment 2 with the only exception that we introduced a third block type with random R–E mapping. In such blocks, each keypress randomly triggered a vibration of either the left or the right key; the position of the vibration was thus not predictable for the participants. The number of blocks was increased to 30, and the six possible sequences of compatibility relations—no-vibration, random, and incompatible, and

permutations thereof—were counterbalanced across participants.²

Results and discussion

Errors occurred in 7.5 % of the trials and the frequency of errors did not differ between compatible (7.1 %), random (7.6 %), and incompatible trials (7.7 %), $F(2, 46) = 0.61$, $p = .545$, $\eta_p^2 = .03$. Error trials and outliers (2.3 %) were omitted from the RT analysis.

The two hypotheses presented above were tested via two planned contrasts in a 3×5 repeated-measures ANOVA with the factors compatibility (no-vibration vs. random vs. incompatible) and RT distribution quintile (bin; 1–5). The incompatible anticipations hypothesis was tested by comparing the RTs for incompatible R–E relations to the pooled data of the random and the no-vibration condition (corresponding to a contrast vector of $-1|-1|2$ for no-vibration, random, and incompatible, respectively). This contrast was significant, confirming that RTs in incompatible blocks were slower than in the other two block types, $F(1, 23) = 5.62$, $p = .026$, $\eta_p^2 = .20$ (cf. Figure 2, upper-right panel). Then, we tested the passive knowledge hypothesis by comparing the RTs for random R–E mappings to the RTs of the no-vibration condition (corresponding to a contrast vector of $-1|1|0$) and this test did not approach significance, $F(1, 23) = 0.72$, $p = .405$, $\eta_p^2 = .03$.

As follow-up tests, we further conducted separate 2×5 ANOVAs to compare incompatible and compatible R–E mappings separately to the random condition (cf. Figure 3). The comparison of incompatible and random R–E mappings showed considerable costs as indicated by a significant main effect of compatibility $F(1, 23) = 4.80$, $p = .039$, $\eta_p^2 = .17$. Furthermore, the main effect of distribution quintile was significant, $F(4, 92) = 204.66$ ($\epsilon = .27$), $p < .001$, $\eta_p^2 = .90$, whereas the interaction was not, $F(4, 92) = 1.39$ ($\epsilon = .33$), $p = .258$, $\eta_p^2 = .06$. Repeating the above contrast of the passive knowledge hypothesis, the comparison of no-vibration and random mappings did not show a main effect of compatibility (see above, $F(1, 23) = 0.72$, $p = .405$, $\eta_p^2 = .03$). The main effect of distribution quintile was significant again, $F(4, 92) = 192.81$ ($\epsilon = .27$), $p < .001$, $\eta_p^2 = .89$, whereas the interaction was not, $F(4, 92) = 1.41$ ($\epsilon = .34$), $p = .254$, $\eta_p^2 = .06$.

To sum up, the data of Experiment 3 suggest the observed compatibility effects to result from ideomotor effect anticipations and not from the mere knowledge of upcoming events. This finding also reinforces our

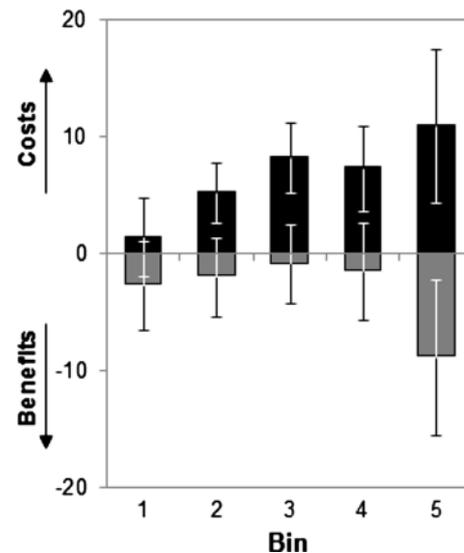


Fig. 3 Composition of the R–E compatibility effects observed in Experiment 3. Costs were computed as $RT_{\text{incompatible}} - RT_{\text{random}}$. Benefits were computed as $RT_{\text{no vibration}} - RT_{\text{random}}$. Error bars show the SE_M for each bar (cf. Pfister and Janczyk 2013)

interpretation of Experiment 2 as reflecting ideomotor effect anticipations of body-related effects.

Pooled analysis

To arrive at an optimal estimation of the effect size, we finally pooled the data of Experiment 2 and Experiment 3 (excluding random trials). We then analysed the RTs with a $2 \times 2 \times 5$ split-plot ANOVA with between-subjects factor experiment (2 vs. 3) and the repeated-measures compatibility (no-vibration vs. incompatible) and RT distribution quintile. This analysis yielded a robust main effect of compatibility, $F(1, 54) = 17.98$, $p < .001$, $\eta_p^2 = .25$, that did not differ significantly between the two experiments, $F(1, 54) = 1.70$, $p = .198$, $\eta_p^2 = .03$. Furthermore, compatibility effects were significantly larger for higher bins, $F(4, 216) = 10.08$ ($\epsilon = .32$), $p < .001$, $\eta_p^2 = .16$, whereas the three-way interaction was not significant, $F(4, 216) = 0.57$ ($\epsilon = .32$), $p = .495$, $\eta_p^2 = .01$.

General discussion

The present experiments aimed at studying effect-based action control with body-related action effects (cf. also Janczyk et al. 2009; Pfister and Kunde 2013). In line with early formulations of ideomotor theory, we found R–E compatibility effects for body-related, vibrotactile consequences of own actions as induced by vibrating

² Condition order had a rather pronounced impact on the RT data in this experiment. All reported effects, however, are significant (and slightly more pronounced) when controlling for order by including it as an additional between-subjects factor in the reported ANOVAs.

response keys. To our knowledge, this is the first empirical demonstration of anticipations in the R–E compatibility paradigm that clearly pertain to body-related action effects. In the light of these findings, environment- and body-related effects appear to be functionally equivalent and likely contribute to action selection and production in a similar way. Even though our results are certainly anticipated by previous findings with visual or auditory effects, we consider the present demonstration to be an important step in the empirical investigation of ideomotor action control.

Equal functionality of both kinds of effects is corroborated by recent reports on distractor–response bindings for tactile (i.e. body-related) distractors (Frings et al. 2011; Moeller and Frings 2011). In general, such distractor–response bindings are transient short-term associations between irrelevant features of stimuli and corresponding responses that arise on a trial-to-trial basis. They are assumed to draw on the very same mechanisms as short-term associations between responses and their ensuing effects (Frings et al. 2007; Frings et al. 2013a; b; Giesen and Rothermund 2011), even though such action-effect bindings have only been studied with auditory effects to date (e.g. Dutzi and Hommel 2009; Herwig and Waszak 2012; Janczyk et al. 2012a, b, c).

The present vibrotactile stimulations are certainly not the ideal manipulation of body-related effects that probably contribute to normal motor control. Conceivably, these effects relate to natural tactile and proprioceptive reafferences of moving limbs. To manipulate compatibility of such effects, one would need to exchange the feeling of, say, moving the right index finger with that of lifting the left foot. Obviously, this is hard to achieve for the tactile and proprioceptive sensory channel. These methodological drawbacks might explain the small effect size of the present manipulation. Similarly, compared to the previous results for spatial R–E compatibility effects in the visual domain (Kunde, 2001; Pfister and Kunde, 2013), vibrotactile effects might not give rise to a strong spatial coding, which might also explain the smaller effect size in Experiment 1 as compared to Experiments 2 and 3.

The present manipulation still might suffice to reveal peculiarities of body-related versus environment-related consequences in human action control. A particularly interesting question seems to be the time point in action production at which action effects kick in (cf. Kunde et al. 2004; Shin and Proctor 2012). This time course might differ between environment-related and body-related effects: whereas environment-related effects might be more relevant in early phases of action selection and body-related action effects might be more relevant for action initiation later on. The present set-up could be easily extended to address this issue.

It is important to note, however, that the present demonstration is not meant to draw empirical research on effect-based action control back to the (body-related) roots of ideomotor theory. For a clearer understanding of human action control, more complex actions and different types of action effects are certainly more relevant than focusing on immediate, body-related effects of circumscribed actions (cf. also Herbolt and Butz 2012). For one, this comprises object-oriented actions such as in tool use and the question of whether tool transformations can be understood in the same framework as other action effects (Janczyk et al. 2012a, b, c; Kunde et al. 2012; Ladwig et al. 2012). For another, abstract action effects need to be considered in addition to physical R–E relations (e.g. Badets et al. 2013; Hubbard et al. 2011; Koch and Kunde 2002). Finally, actions that aim at changing the social environment clearly need to be addressed more thoroughly in the framework of effect-based action control (for a first step in this direction, see Kunde et al. 2011; Pfister et al. 2013).

These different lines of research offer promising approaches to extend the empirical validity of ideomotor theory while at the same time this research may uncover important constraints for effect-based action control. In any case, it should not be forgotten that ideomotor theory was initially mainly concerned with instant changes relating to the agent's own body, as also demonstrated by the present results.

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