Volume 28
Issue 4
August 2009

ISSN 0167-9457

Editor: P. J. Beek

HUMAN
MOVEMENT
SCIENCE

Visual and tactile action effects determine bimanual coordination performance ☆

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ARTICLE INFO

ABSTRACT

Effect-based models of motor control assign a crucial role to anticipated perceptual feedback in action planning. Two experiments were conducted to test the validity of this proposal for discrete bimanual key press responses. The results revealed that the normally observed performance advantage for the preparation of two responses with homologous rather than non-homologous fingers becomes inverted when homologous fingers produce non-identical visual effects, and non-homologous fingers produce identical visual effects. In the second experiment the finger homology effect was strongly reduced when homologous fingers produced non-identical tactile feedback. The results show that representations of to-be-produced visual and tactile action effects both contribute to action planning, though possibly to a varying degree. Implications of these results for effect-based models of motor control are considered.

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1. Introduction

The human body is to a large extent characterized by symmetry. This applies to the outer appearance as reflected in the existence of two pairs of limbs, fingers, or toes, but also to the anatomical and functional symmetry of neuronal control structures in the central nervous system. To master many of

our everyday tasks, such as when lifting a heavy object, tying a tie, playing piano, or rowing a boat, these body parts have to be used in a coordinated fashion. Experimental research on bimanual coordination has often demonstrated a bias towards symmetric movements or movements involving similar parameter values for amplitude or direction (e.g., Cohen, 1971; Kelso, 1984; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997). For example, symmetric index-finger oscillations (i.e., simultaneous inward and outward movements of the left and right index-finger) are more stable than asymmetric index-finger oscillations (i.e., one index-finger moves inward while the other moves outward): While performing these movements at low speed, both patterns are stable. However, with increasing movement speed, distinct switches from asymmetric to symmetric oscillation patterns occur, but not vice versa (Kelso, 1984).

Traditionally this superiority of symmetric movements was attributed to a tendency towards the activation of homologous muscles, which are more strongly involved in symmetric than in asymmetric body movements (Carson, Riek, Smethurst, Lison-Parraga, & Byblow, 2000; Cohen, 1971; Swinnen et al., 1998). However, recently this view was challenged by experiments demonstrating that performance in such tasks appears to be dependent on the symmetry of the perceptual *movement effects* rather than on the homology of the involved effectors (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Mechsner & Knoblich, 2004). For example, in the study by Mechsner and Knoblich (2004) different fingers from both hands (e.g., index- and middle-finger of the left hand, and middle- and ring-finger of the right hand) were combined to a bimanual-tapping task. Still, the spatially symmetrical pattern (i.e., left index-finger and right middle-finger vs. left middle-finger and right ring-finger in alternation) was more stable than the parallel pattern (i.e., left and right middle-fingers vs. left index-finger and right ring-finger in alternation). When considering the traditional account, this is most surprising, since in this case parallel patterns involve relatively more homologous muscle activations compared to symmetric patterns.

An explanation of these findings has been derived from ideo-motor theories of action control (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001; for a historical overview see Stock & Stock, 2004). The crucial assumption of this approach is that motor actions are cognitively represented by their sensory effects; that is, by codes of the perceptual effects that contingently follow certain motor actions. As a consequence, a motor action can only be accessed by recollecting codes of the sensory consequences that normally accompany this action, and serve to mentally represent it. Stated differently, there is no other way to generate a motor action than by anticipating its sensory consequences. The important implication of this approach is that all the constraints of motor control we know off, such as complexity effects (Henry & Rogers, 1960), stimulus–response compatibility (Simon, 1969), limitations in dual-task performance (Welford, 1952), or symmetry tendencies in bimanual coordination (Kelso, 1984), do not arise because of constraints inherent in the 'hardware' of the motor system, but because of constraints in the representation of the perceptual re-afferences of to-be-produced motor actions.

By now, there exist a few studies that demonstrate the bearing capacity of this idea. For example, the initiation of long responses (such as a long key press) takes usually more time than the initiation of short responses (such as a short key press). Yet, these differences can be altered by changing the duration of the contingent sensory effects following such actions. What seems to influence the initiation of the responses most is the duration of the anticipated feedback of the forthcoming action rather than the duration of the action as such (Kunde, 2003). To give another example, key presses are executed more quickly if the desired responses match a response-affording stimulus in a certain respect (such as the faster responding to stimuli that match the required response in terms of spatial location). It has been shown that not the spatial correspondence of the stimulus and response per se matters when producing key presses, but the spatial correspondence of the stimulus and the to-be-produced visual feedback of the response (Hommel, 1993).

The same basic idea seems to apply to bimanual coordination as well. As already noted above, Mechsner and Knoblich (2004) found that finger tapping was more stable when spatially symmetric rather than asymmetric fingers were involved – independent of finger homology. A similar observation was reported by Kunde and Weigelt (2005). They asked participants to turn two wooden blocks from a horizontal starting position into a specific vertical goal position in each trial. Importantly, these blocks were marked with blue on one end and the goal positions were either congruent (i.e., the color marks on both blocks were either upward or downward) or incongruent (i.e., the color mark of one

block was upward and of the other one was downward). It turned out that the congruency of the intended goal positions determined the participants' performance, irrespective of whether this required symmetric rotations (i.e., homologous muscle innervations) or asymmetric rotations (i.e., non-homologous muscle innervations) of the two hands. In both cases responses were initiated and executed faster with congruent goal positions than with incongruent goal positions. Hence, bimanual coordination is facilitated if both actions are carried out to produce similar goal states, rather than by symmetry constraints inherent in the neuromuscular-skeletal system.

Up to now, the impact of action effects in bimanual coordination has been studied with repetitive actions such as finger oscillation or tapping (Mechsner & Knoblich, 2004; Mechsner et al., 2001) or non-repetitive but continuous actions such as object manipulations (Kunde, Krauss, & Weigelt, 2009; Kunde & Weigelt, 2005; Weigelt, Kunde, & Prinz, 2006). The problem with these tasks is that planning and execution aspects of these actions are hard to disentangle. With repetitive actions the planning of the movement normally occurs while another movement is still executed. The problem with continuous actions is that they are temporally extended. For example, the object manipulations used by Kunde and Weigelt (2005) took about 800 ms to be completed. Therefore, and in accordance with previous observations on deferred programming effects in bimanual coordination (Spijkers et al., 1997), some of the action specification processes are concluded before the start of the action, while others influence action execution. This renders it somewhat ambiguous to which extent programming processes are reflected in reaction times (from stimulus to response onset; RT) or movement times (from start of the movement to its end; MT) or both. To remove this problem of distributed action specification before and after action onset, we used *discrete* bimanual responses in the present study.

To this end, participants were asked to press two response buttons simultaneously (with one finger from each hand) according to a response signal (e.g., the left and right index-finger, or the left index- and right middle-finger). Importantly, these responses required almost no time for their execution (the button is either pressed or not) and thus, they could be entirely planned in advance. Therefore, RT is the main dependent variable here, and it entails all the planning processes necessary to execute the action. Consequently, RTs in discrete bimanual tasks presumably reflect a purer measure of action planning than available from repetitive and continuous actions. The first purpose of the present study was thus to test if the impact of action effects, that has been previously observed for repetitive and continuous actions, extends to discrete bimanual responses as well.

The second purpose was to study the impact of action effects of varying remoteness. Regarding this issue already James (1890, 1981) made an interesting distinction into 'resident' and 'remote' action effects. By resident effects he denotes those body-related sensory consequences that accompany every physical activity of the body, such as the tactile and proprioceptive changes that we feel in the index-finger when bending it. These effects are resident in that they occur whenever we move a part of our body (except in rare pathological cases). In contrast to this, he referred to remote effects as those action consequences that occur outside the body. These are consequences of physical activity taken in through exteroceptive channels, such as the lightening of a lamp after pressing a light switch, or a tone after pressing a piano key. We want to pick up these intuitive plausible terms although on closer inspection it is clear that resident and remote effects differ in several respects, such as their physical distance to the body, the perceptual channel through which they are perceived, and the certainty with which they follow a certain motor output (see below). We also want to make clear that the terms resident and remote should not be confused with the terms 'proximal' and 'distal' as used in the theory of event coding (TEC; Hommel et al., 2001). According to TEC a code is distal irrespective of the sensory channel informing it if it refers to events in the world, where the body is in some sense part of the world as well. In contrast, a code is proximal irrespective of the sensory channel informing it if it refers to the specifics of the sensory transduction, that is, of how our system responds to external events. Accordingly, it simply does not matter whether fingers are perceived visually or proprioceptively: if the code refers to a finger movement as an event in the world this code is distal, it codes for a distal aspect of the event. Hence, resident and remote action effects in James' terminology would be both considered as being distal.[1]

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[1] We thank Bernhard Hommel for directing our attention to this issue.

Ideo-motor inspired research on motor control has mainly focused on remote perceptual effects, presumably because such effects can be easily controlled in the psychological lab. However, one should assume that the findings relative to motor coordination and remote effects generalize to resident effects as well. Yet, there may be good reasons to doubt this assumption. As noted above, resident and remote action effects differ in certain respects and might serve different roles in action planning. Consider, for example, that the same motor output, such as the bending of the right index-finger, can be linked to several exchangeable remote effects, such as the lightening of a desk lamp in one context, or the sound of a piano tone in another context. In contrast, resident effects are less exchangeable. Although the proprioceptive feedback of bending a finger might differ from time to time, such variability has obviously limitations. For example, it is hard to imagine that bending the finger feels like moving the leg. At least the body-related location of proprioceptive feedback from a moving effector is constant. These properties might assign different roles to remote and resident action effects in action generation. The anticipation of remote effects might activate several body movements or classes of body movements that are in principle instrumental to obtain these remote effects, whereas the anticipation of resident effects might activate very specific motor patterns. This speculation is not meant to say that we know already the different roles of resident and remote effects. We do not. It should simply illustrate that we need experimental approaches to clarify potential differences between them, and the present study is a first attempt to do so.

We report two experiments here. In both experiments one group of participants produced identical and non-identical perceptual effects with homologous and non-homologous finger presses, respectively (congruent response–effect (R–E) mapping), while a second group produced identical effects with non-homologous and non-identical effects with homologous finger presses (incongruent R–E mapping). The crucial question was whether the normally observed advantage in RT with homologous compared to non-homologous fingers is affected (or possibly even reversed) when homologous fingers produce non-identical effects and non-homologous fingers produce identical effects (i.e., with an incongruent R–E mapping). Experiment 1 used remote (visual) effects and Experiment 2 used resident (tactile) effects.

2. Experiment 1

In Experiment 1 participants were to respond with one finger (either the index- or the middle-finger) of both hands simultaneously to the onset of a visually presented stimulus. In each trial, pressing a response button produced a visual effect. These visual effects were growing and shrinking columns that were directly located above the associated response buttons, thus representing salient remote effects (cf. Fig. 1). Importantly, these columns grew either high or low and this characteristic was varied in a way that participants in the congruent R–E mapping condition produced columns of the same height when responding with homologous fingers. In contrast, participants in the incongruent R–E mapping condition produced columns of different heights when responding with homologous fingers.

In the congruent R–E mapping condition, we should find faster responses with homologous fingers than with non-homologous fingers. However, as we suspect actions being accessed through their perceptual (in this case visual) effects, we predict that this advantage of homology should be diminished in the incongruent R–E mapping condition, where homologous fingers produce non-identical visual effects. Given this basic assumption, two scenarios appear to be possible. First, the action becomes entirely controlled by the codes of the visual effects and finger homology does not matter anymore. If this is true, we should observe faster responses with identical visual effects, independent of whether these effects are produced by homologous or non-homologous fingers. Thus, the advantage of identical over non-identical visual effects should be of the same magnitude in both congruency conditions (which would mean a full reversal of the finger homology effect with the incongruent R–E mapping). Second, the actions become controlled by codes of their visual effects, but finger homology might still play a role as well. In this case, we should find that the advantage of identical effects is somewhat smaller with the incongruent R–E mapping, where identical effects are produced by non-homologous fingers and non-identical effects are produced by homologous fingers. (Of course, it is still possible that our theoretical assumptions described above are simply wrong. In this case we should see an
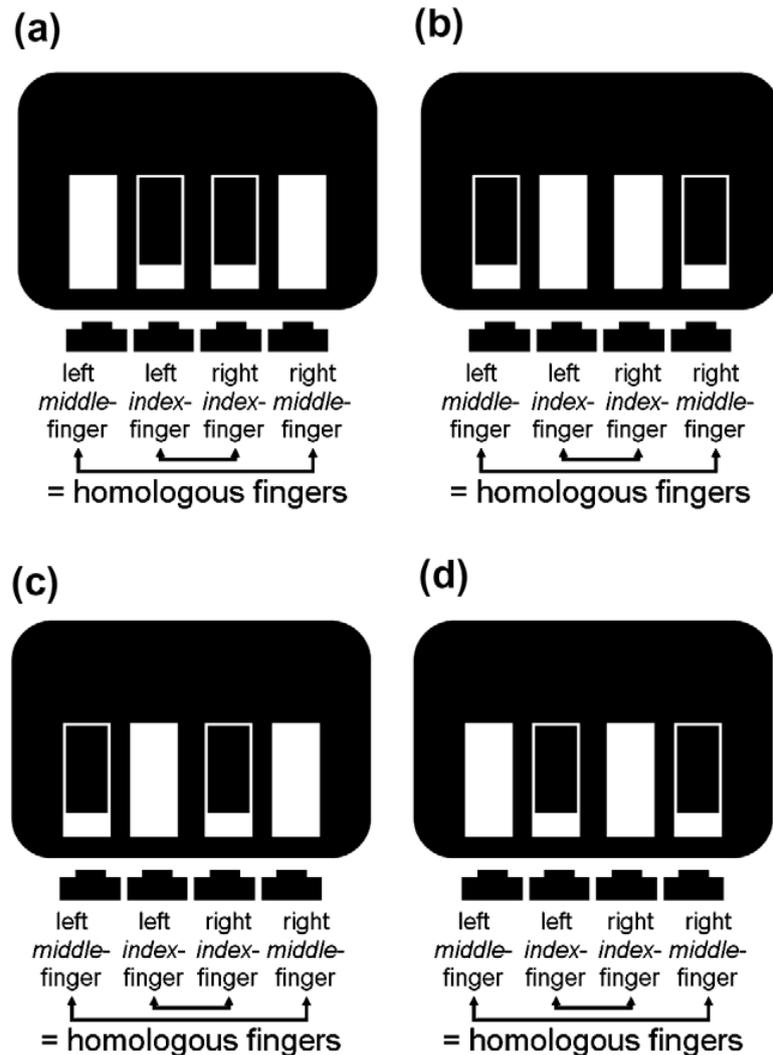
(a)

(b)

(c)

(d)

Fig. 1. Experimental setup for Experiment 1. Participants had their fingers resting on four response buttons. Right above those, four columns were displayed. Pressing a response button resulted in a high or low growing of the associated column (= remote visual effects). (a) and (b) are congruent R–E mappings (homologous finger presses result in identical effects), (c) and (d) are incongruent R–E mappings (homologous finger presses result in non-identical effects).

advantage of homologous fingers over non-homologous fingers, irrespective of the R–E congruency mapping.)

2.1. Method

2.1.1. Participants

Sixteen students (nine female) from Dortmund University of Technology participated in this experiment and were paid course credit in return. The students' mean age was 24 years 2 months and all reported normal or corrected-to-normal vision.

2.1.2. Apparatus and stimuli

An IBM-compatible personal computer with a 17-inch VGA display was used for stimulus and effect presentation, as well as for response recording. All stimuli and effects were presented in white color on a black background. Responses were collected via four custom-made response buttons (20 × 20 mm), which were connected to the computer via the parallel port. The response buttons were placed on a small black-painted box directly in front of the computer screen in an attempt to facilitate associations of the responses with the produced effects (see below for details).

Following an inter-trial interval of 1000 ms, each trial began with the presentation of a central fixation cross (250 ms). After a fixed interval of 250 ms, the imperative stimulus set on, in our case one of the digits 1, 2, 3, or 4. Each digit was associated with one combination of finger presses, where either the middle- or the index-finger of each hand was involved. Pressing a response button initiated the growing of the associated column displayed right above the response button (see Fig. 1 for an illustration). The columns grew either high (the outer columns in Fig. 1a) or low (the inner columns in Fig. 1a), stopped at their maximum for 800 ms, and then shrank back to the starting level. High growing columns grew and shrank faster than low growing columns, thus – when initiated at the same time – all four columns would reach their maximum at the same time. For each hand either the outer column could be high and the inner column low or vice versa, resulting in four different R–E conditions: two congruent R–E conditions where homologous fingers produced identical effects (congruent R–E mapping; see Figs. 1a and b), and two incongruent R–E conditions where homologous fingers produced non-identical effects (incongruent R–E mapping; see Figs. 1c and d). Four stimulus–response mappings were constructed according to a latin-square design, and each one was combined once with one of the four possible R–E conditions.

2.1.3. Procedure and design

The participants were tested in a single 1-h session. They were instructed in written form to respond to the stimuli as fast and accurate as possible. The first block of 64 trials was considered practice and no effects were displayed on the computer screen. Instead the stimuli were accompanied by down-pointing arrows indicating the two correct response buttons. The practice block was followed by six experimental blocks of 64 trials each. During each block the four stimuli occurred equally often and in a random order. Fingers' homology was varied within-participants (homologous vs. non-homologous) while congruency of the R–E mapping (congruent vs. incongruent) was a between-participants factor.

2.1.4. Data analyses

Only RTs associated with correct responses were further analyzed. A trial was counted as an error in cases of wrong responses and in cases in which the asynchrony of both fingers was more than 100 ms. RTs below 300 ms were excluded as anticipations, and RTs exceeding an individuals mean by more than 2.5 individual standard deviations (separately calculated for homologous and non-homologous finger combinations) were excluded as outliers. The remaining RTs were then averaged across both hands. Mean RTs and percentages of errors (without distinguishing different types of errors) were submitted to mixed analyses of variance (ANOVA) with finger homology (homologous vs. non-homologous) as a within-participants factor, and R–E mapping (congruent vs. incongruent) as a between-participants factor. Additional analyses were carried out by means of (one sample and two independent samples) *t*-tests.

2.2. Results

2.2.1. Error analyses

Mean percentages of errors are depicted in Fig. 2 (dotted lines). With both R–E mappings, participants committed numerically more errors when they aimed at producing non-identical effects with both fingers regardless of whether this was done by homologous or non-homologous fingers. However, neither finger homology, $F(1, 14) = 1.15$, $p = .30$, nor R–E mapping, $F(1, 14) < 1$, $p = .64$, reached significance, but the interaction only marginally failed significance, $F(1, 14) = 3.86$, $p = .07$. The error rates' difference between identical and non-identical effects was numerically slightly smaller with an incongruent R–E mapping (1%) than with a congruent R–E mapping (3.3%), $t(14) = -1.07$, $p = .30$.

2.2.2. RT analyses

Mean RTs are displayed in Fig. 2 (solid lines). Participants with an incongruent R–E mapping responded somewhat, though non-significantly, slower than those with a congruent R–E mapping, $F(1, 14) = 3.04$, $p = .10$, and, overall, finger homology revealed no effect, $F(1, 14) < 1$, $p = .41$. However, with both R–E mappings responses were faster when they produced two identical effects, as compared
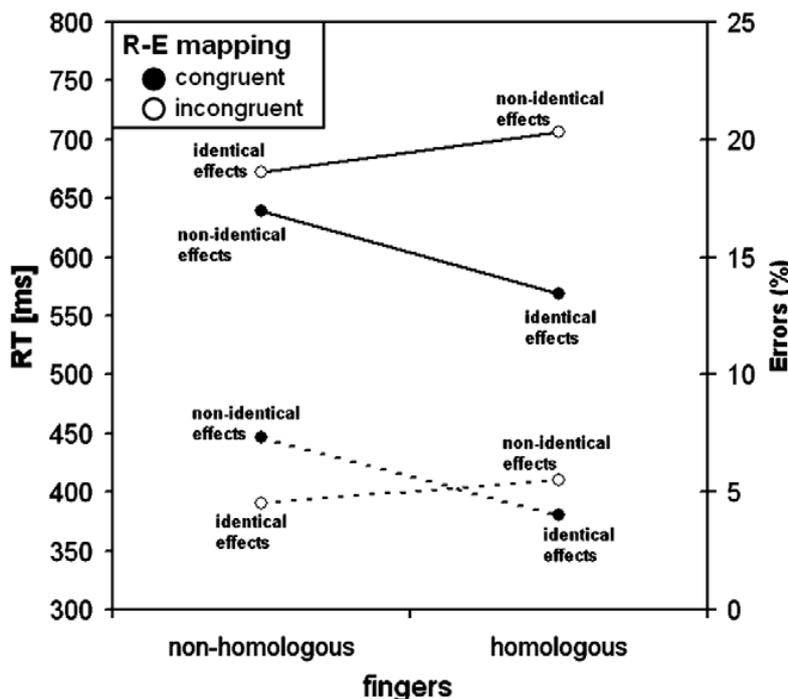
Fig. 2. Reaction times in milliseconds (solid lines) and percentages of errors (dotted lines) as a function of finger homology and response–effect mapping in Experiment 1. To facilitate interpretation it is indicated at each data point whether this particular condition resulted in identical or non-identical visual effects.

to when they produced two non-identical effects. This was confirmed by a significant interaction of finger homology and R–E mapping, $F(1, 14) = 5.97$, $p < .05$. The advantage of identical effects over non-identical effects was numerically larger with the congruent R–E mapping (71 ms), as compared to the incongruent R–E mapping (34 ms), $t(14) = -0.86$, $p = .41$.

2.2.3. Response asynchrony

Bimanual interference can also become evident through an increased asynchrony of both required responses. Thus, we determined this asynchrony and computed their means and standard deviations (see Table 1), with negative means indicating faster reactions of the right hand's finger. None of the means differed significantly from zero (one sample t-tests). The absolute mean values of asynchrony were not affected by finger homology, $F(1, 14) < 1$, $p = .50$, and R–E mapping, $F(1, 14) = 3.11$, $p = .10$, and the interaction was also not significant, $F(1, 14) = 2.38$, $p = .15$. In contrast, standard deviations of asynchronies were smaller for homologous fingers, $F(1, 14) = 20.93$, $p < .01$, and with the incongruent R–E mapping, $F(1, 14) = 9.23$, $p < .01$. The interaction was not significant, $F(1, 14) < 1$, $p = .37$.

Table 1
Mean values (M) and standard deviations (SD) for asynchronies of left and right hand responses in milliseconds.

	Experiment 1		Experiment 2	
	Congruent	Incongruent	Congruent	Incongruent
Homologous fingers				
M	1.5	3.0	1.5	1.4
SD	15.7	11.9	14.3	12.6
Non-homologous fingers				
M	−2.4	0.5	−2.1	−1.6
SD	19.5	14.4	17.4	13.9

2.3. Discussion

The results of Experiment 1 are straightforward: When homologous fingers produced identical visual effects (i.e., a congruent R–E mapping) performance was superior with homologous compared to non-homologous fingers. This finding replicates the typical homology advantage in the bimanual-tapping task (Rabbitt, Vyas, & Fearnley, 1975). Yet, with a congruent R–E mapping homology of the fingers is confounded with the assignment of identical visual effects. To disentangle the impact of finger homology and R–E congruency, the data from the incongruent R–E mapping are crucial, where homologous fingers produce non-identical effects, and non-homologous fingers produce identical effects. Here, performance was better with identical effects (non-homologous fingers) than with non-identical effects (homologous fingers). This supports the idea that the initiation of bimanual key presses is mainly influenced by the identity of the to-be-produced visual effects rather than by the homology of the fingers that are used for their production. In this respect, the experiment can be taken to show that the impact of perceptual effects on bimanual coordination, which has been reliably observed in repetitive and continuous actions, extends to the production of discrete bimanual responses. In line with an ideo-motor point of view (Hommel et al., 2001), we suggest that this pattern arises from the fact that motor actions are accessed through their anticipated perceptual consequences. Conceivably retrieving and anticipating two similar or identical effects is faster than retrieving two non-identical effects, thus resulting in faster response initiations (see also Kunde & Weigelt, 2005). The conclusions derived from the RT analyses are corroborated by the fact that the percentages of errors exhibited the same pattern (although the interaction marginally failed significance). It should be noted that non-identical effects differed in two physical features, namely the final height of the columns on the screen and their growing speed. This was done to make the effects phenomenally as different as possible, to the cost that we cannot tell apart which of the two features was most relevant here. This might be addressed by future experiments.

Finally, the advantage of identical over non-identical effects was still numerically (though not significantly) smaller with an incongruent R–E mapping compared to a congruent R–E mapping. This indicates some residual influence of finger homology as well, and the reasons for this are considered in Experiment 2.

3. Experiment 2

In Experiment 1 we successfully demonstrated the impact of (remote) visual effects in the bimanual-tapping task. Performance was superior when identical rather than non-identical effects were produced, independent of whether homologous or non-homologous fingers produced them. Yet, the advantage of identical over non-identical effects was numerically larger when identical effects were produced by homologous rather than by non-homologous fingers. This suggests that finger homology still played a role, and that might appear problematic for a radical model of effect-based action representation. However, we have to remember that motor actions normally produce several perceptual consequences, e.g., visual, tactile, and/or proprioceptive ones. Some of them are more remote (e.g., visual ones) and some of them are more resident (e.g., tactile ones). It seems tenable, that the normally observed finger homology advantage in bimanual coordination that occurs when remote action effects are not manipulated in a way as done in Experiment 1, might be construed as a consequence of effect congruency as well. The tactile and proprioceptive feedback, hence resident effects, which ensue with homologous fingers, might appear as more similar to each other than that of non-homologous fingers. This speculation is not easy to test, because one would have to rely on some sort of subjective measure to judge whether the resident effects of homologous fingers (e.g., both index-fingers) are experienced as more similar to each other than those of non-homologous fingers (e.g., index- and ring-finger).

A possible approach to resolve this issue is to try to directly manipulate, rather than measure, the similarity of resident action effects. In Experiment 2, we therefore manipulated the tactile effects that were linked to the effectors. To this end, the response buttons were covered with two different surfaces, a soft and fluffy surface and a surface built from nail points, respectively (cf. Fig. 3). The predictions for Experiment 2 were essentially the same as for Experiment 1. Responses with homologous

Fig. 3. Surfaces of the response buttons in Experiment 2. Two buttons were covered with a soft and fluffy material (inner buttons in the example), while the other two were covered with surface built from nail points (outer buttons in the example).

fingers should be faster than responses with non-homologous fingers in the congruent R–E mapping condition, but this advantage should be diminished (and possibly reversed) in the incongruent condition.

3.1. Method

3.1.1. Participants

Another 16 students (12 females) from Dortmund University of Technology participated in this experiment and were paid course credit in return. The students' mean age was 24 years 2 months and all reported normal or corrected-to-normal vision.

3.1.2. Apparatus and stimuli

The stimuli and apparatus were the same as in Experiment 1, with one important alternation. The remote visual effects (high and low growing columns; see Fig. 1) were replaced with tactile effects. To this end, two response buttons were covered with a soft and fluffy surface (see Fig. 3, inner responses buttons) and the other two were covered with a surface built from nail points (see Fig. 3, outer response buttons). Similar to Experiment 1, four combinations were possible, with two being congruent (homologous fingers produce identical effects; an example is given in Fig. 3) and two being incongruent (homologous fingers produce non-identical effects).

3.1.3. Procedure, design, and data analysis

The design, procedure, and data analyses were the same as in Experiment 1, with the exception that during the first (unanalyzed) practice block the tactile effects were already present (In Experiment 1 the visual effects were only introduced after this practice block.).

3.2. Results

3.2.1. Error analyses

Mean percentages of errors are shown in Fig. 4 (dotted lines). While R–E mapping did not affect mean error percentages, $F(1, 14) = 1.53$, $p = .24$, participants committed more errors when responding with non-homologous fingers than when responding with homologous fingers, $F(1, 14) = 10.66$, $p < .01$, and the interaction was also significant, $F(1, 14) = 5.73$, $p < .05$. The advantage of homologous fingers over non-homologous fingers was larger with the congruent R–E mapping (5.9%) than with the incongruent R–E mapping (0.9%), $t(14) = -2.39$, $p < .05$.

3.2.2. RT analyses

Mean RTs are depicted in Fig. 4 (solid lines). Participants responded faster with homologous fingers compared to non-homologous fingers, $F(1, 14) = 34.00$, $p < .01$, and congruency of R–E mapping did not affect RTs, $F(1, 14) < 1$, $p = .68$. The interaction was significant, $F(1, 14) = 11.05$, $p < .01$. Similar to the pattern in mean error percentages, the advantage of homology for the congruent R–E mapping (115 ms) diminished (significantly) for the incongruent R–E mapping (31 ms), $t(14) = -3.33$, $p < .01$.
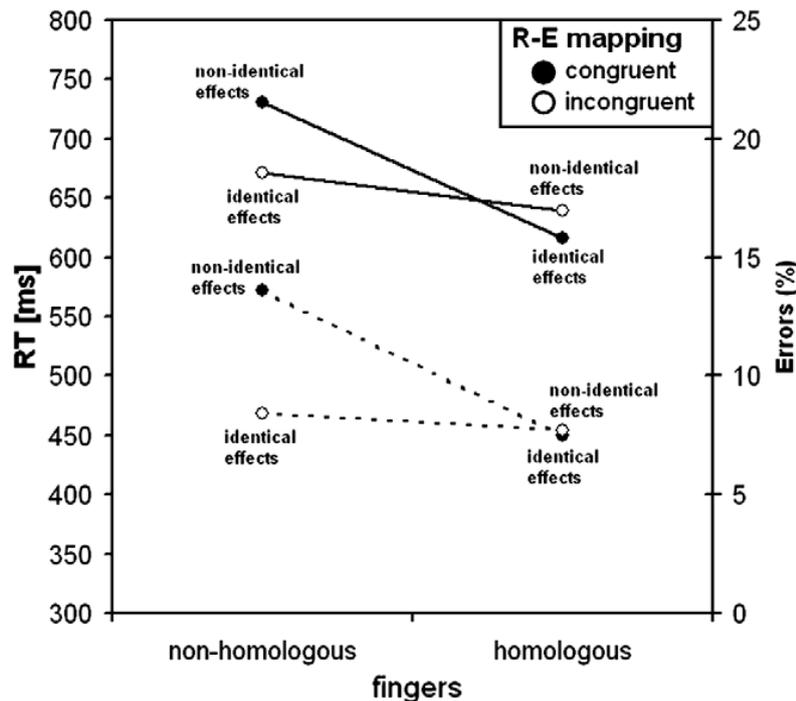
Fig. 4. Reaction times in milliseconds (solid lines) and percentages of errors (dotted lines) as a function of finger homology and response–effect mapping in Experiment 2. To facilitate interpretation it is indicated at each data point whether this particular condition resulted in identical or non-identical tactile effects.

3.2.3. Response asynchrony

As in Experiment 1, we determined mean asynchronies of both responses and calculated their mean values and standard deviations (Table 1). None of the means differed significantly from zero (one sample t-tests). The absolute mean values of asynchrony did not differ significantly between the congruent and the incongruent R–E mapping, $F(1, 14) = 1.06$, $p = .32$, but they were smaller for homologous fingers than for non-homologous fingers, $F(1, 14) = 12.83$, $p < .01$. The latter difference was numerically larger in a congruent R–E mapping (5.1 ms) than in an incongruent R–E mapping (1.7 ms), $F(1, 14) = 3.46$, $p = .08$. Standard deviations of asynchronies were smaller for homologous fingers, $F(1, 14) = 9.01$, $p < .05$, and – numerically, but non-significantly – in the incongruent R–E mapping, $F(1, 14) = 1.96$, $p = .18$. The interaction was not significant, $F(1, 14) = 1.62$, $p = .22$.

3.3. Discussion

In Experiment 2, we tested to which extent the manipulation of tactile response-feedback affects the production of bimanual responses. Most importantly, identical tactile feedback benefited performance across conditions. In congruent R–E mappings, responses with homologous fingers were about 115 ms faster when compared to responses with non-homologous fingers. However, this advantage was reduced to 31 ms in the incongruent R–E mapping, where homologous fingers resulted in the experience of very different tactile feedback. The reason for this, we suggest, is the anticipation of two different effects necessary for planning responses of homologous fingers under this condition. A similar pattern was evident in mean error percentages. Thus, the impact of perceptual effects on response planning and initiation in the bimanual finger-tapping task extends to resident effects, although it appears that their impact was not strong enough to entirely overrun and reverse the finger homology effects, as was observed in Experiment 1 with remote (visual) effects.

There are several possible explanations for this. One reason might be that the resident effects were simply not salient enough. Another reason could be that the participants had their fingers resting on the response buttons' surfaces during the experiment. Hence, they already experienced the resulting effects in parts, and the reduced necessity to mentally anticipate the effects lessened their impact on response planning and initiation. This issue is further addressed in Section 4.

4. General discussion

Two experiments investigated the impact of action effects on response planning and execution in the bimanual finger-tapping task. The often observed advantage of symmetrical response patterns has frequently been ascribed to the involvement of homologous muscle portions (Carson et al., 2000; Cohen, 1971; Swinnen et al., 1998). However, recent experimentation casts doubt on this assertion by demonstrating the impact of perceptual effects rather than homology of involved effectors on the stability of continuous repetitions of movements (Mechsner & Knoblich, 2004; Mechsner et al., 2001). According to the ideo-motor hypothesis (e.g., Hommel et al., 2001) motor actions are accessed through an anticipation of their perceptual effects. In the present study, participants produced two identical or non-identical effects with a discrete response of two fingers. This allowed us to investigate whether or not these effects have an impact on the planning of bimanual responses.

Not surprisingly responses were faster and more accurate when two homologous finger presses produced the same effects. However, and in accordance with our reasoning, this familiar result became unstable when responses with homologous fingers resulted in two non-identical effects: in Experiment 2 the homology advantage was diminished by the resident tactile effects, and the pattern was even reversed by the remote visual effects in Experiment 1. Importantly, action effects in this striking latter case set on only *after* pressing the response buttons. Hence, these effects must have been cognitively represented before the response was actually carried out.

Note, that the finger homology advantage in bimanual key pressing tasks resembles to some degree the pattern arising from the response-cuing paradigm (Miller, 1982) where RTs in the 'finger-cued condition' (here: homologous fingers) are faster than RTs in the 'neither-cued condition' (here: non-homologous fingers). It has been suggested that these effects reflect processes of response grouping with Gestalt factors and inter-response dependencies mediating the formation and strength of response subgroups (for a review see Adam, Hommel, & Umiltà, 2003). From the perspective of this account identical effects can be construed as a powerful Gestalt factor that prompts response grouping and enables a quick response preparation (Wenderoth & Weigelt, 2009).

The experimental setup brought about that homologous finger presses required symmetrically located responses and were associated with symmetrically located action effects, as each response location was linked to one effect location. This might be seen as a disadvantage and (for Experiment 1) one might advocate the use of only two columns, each mapped to one hand's responses, to remove this aspect of spatial symmetry. Yet, we used four columns, and this was done in an attempt to keep both experiments reported here as comparable as possible. Trivially, in Experiment 2, each response location required its own effect location. To clarify another related point: It is true that homologous fingers always required responses at symmetrical locations and produced action effects at symmetrical locations whereas the opposite was true for non-homologous fingers. Still, this was true in both mapping conditions (the congruent and the incongruent R–E mapping) with the only difference being the identity or non-identity of the two action effects. Thus, the results show that mere midline-symmetry was not an overly important factor, but rather action effects were.

Any motor sequence is determined by a series of effects and goals that can be located on a continuum from 'very remote' to 'very resident'. If, for example, one of the authors writes a scientific article, the most remote goal might be, to communicate results to colleagues in the field. However, this remote goal can be decomposed into more resident goals or effects, such as starting the word processor, planning the intended content, and so forth. Eventually, typing a specific letter has the effect of producing this letter on the screen (Rieger, 2004) and experiencing an effect on the finger tip when touching the key on the keyboard. Most likely, the proximity of action effects is linked to the time-point in action planning when anticipatory codes of these effects come into play. Normally, the goal of an action is a remote event, and therefore must be represented in the first place. Only some time later, when it comes to the execution of specific motor patterns, more resident and movement-related effects come into play. Hence it might be that early processes of movement planning are governed by codes of remote effects, whereas later processes of movement planning are governed by more resident ones. Future research is needed to explore this issue. One way to do so would be to combine the task of the present experiments with the precuing technique (Rosenbaum, 1983). Here, it could be speculated

that the impact of remote effects disappears with long precuing intervals in which much of the early motor preparation processes are removed from the RT interval, whereas the impact of resident effects might remain.

The benefit of identical visual effects was very pronounced in Experiment 1. After all, identical visual effects were strong enough to reverse the benefit of finger homology, an otherwise very stable effect (Kelso, 1984). This raises the question of why the impact of tactile effects was less pronounced in Experiment 2. Apart from theoretically less interesting reasons such as differences in saliency and varying needs to retain these effects during the experiment, this might have to do with a common origin of benefits from similar tactile feedback and homologous fingers. Conceivably, homologous effectors produce resident feedback that is more similar to each other than that of two non-homologous effectors. Thus, any finger homology benefit might be construed as an influence of similar resident feedback from anatomically homologous effectors. While it appears to be easier to overwrite a resident representation of an action by some remote visual code, it might prove to be impossible or at least much harder to replace it by some other resident tactile code. If true, this may turn out to be an important boundary condition of effect-based action control. Motor output might become represented and controlled by arbitrary remote consequences, such as visual or auditory changes in the environment, but not by arbitrary resident consequences. This issue should be addressed in future research.

In sum, the present study demonstrates the impact of effects upon the production of discrete bimanual responses. The congruency of such action effects strongly influenced the planning of these responses, at least in parts independent of whether homologous muscle portions were involved or not. Future research should investigate the time-course of this impact as a function of remoteness of the produced effects, and the reasons for the reduced impact of resident effects.

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