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Goal congruency without stimulus congruency in bimanual coordination

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Abstract Two experiments explored the role of stimulus congruency and goal congruency for the generation of object-oriented actions with two hands. Participants had to place two objects into either parallel or opposite orientations by carrying out either symmetrical or asymmetrical forearm rotations. Performance was superior when the required object orientations were identical rather than different, almost independent of the symmetry of the required arm movements. In extending previous research, goal congruency effects ensued even under conditions in which congruency of imperative response signals could not have contributed to goal congruency effects, either because only a single stimulus was used to indicate the required goals in an individual trial (Experiment 1) or such stimuli were absent at all (Experiment 2). The results thus confirm the importance of goal codes for the reconcilableness of bimanual actions, and rule out accounts in terms of stimulus-related processes.

Introduction

We often use both hands to reach a goal, for example when opening a bottle of wine, lifting a heavy object, or picking berries from a bush. It is well-known that the production of

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such bimanual actions is subject to specific constraints. For example, normally it is easier to produce symmetrical compared to asymmetrical movements (e.g., Heuer, 1993 for a review). These constraints arise at different levels of processing. Some constraints arise at peripheral stages of motor execution, such as inter-hemispheric cross-talk in efferent pathways (Franz, Eliassen, Ivry, & Gazzaniga, 1996; Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002), whereas others arise at a more central stage, such as the specification of motor parameters during movement programming (Spijkers & Heuer, 1995).

There is also evidence that the production of bimanual movements is constrained at an even more abstract level that relates to the specification and maintenance of movement goals (Mechsner, Kerzel, Knoblich, & Prinz, 2001; Mechsner & Knoblich, 2004; Weigelt, 2007; Weigelt, Rieger, Mechsner, & Prinz, 2007). To illustrate this approach consider a recent study by Kunde and Weigelt (2005). Participants in this study were asked to simultaneously reach for two objects with their left and right hand and to rotate them into a particular goal orientation. The production of these bimanual actions was faster and more accurate when the required goal orientations of the two objects (i.e., the to-be-attained object end-states) were the same rather than different. This pattern of results was essentially unaffected by movement symmetry (i.e., whether the necessary hand and arm rotations were symmetric or asymmetric). Effects of movement symmetry were only present, when the way, in which the objects had to be rotated, itself became the goal of the task (Kunde & Weigelt, 2005, Experiment 3). Such results suggest that the reconcilableness of hand and arm movements is determined by the congruency of action goals, which can refer to distal aspects (the manipulated objects) or proximal aspects (the movement trajectory) of the intended action.

The various constraints of bimanual coordination have been studied in different manners (cf. Swinnen & Wenderoth, 2004 for an overview). Research motivated by dynamical pattern theory has primarily focused on the emergent coordination in repetitive bimanual movements such as mirror-symmetric and asymmetric pendulum swinging of the hands. Research motivated by information processing theory has primarily studied discrete movements with so called bimanual reaction time tasks (e.g., Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Spijkers, Heuer, Kleinsorge, & van der Loo, 1997; Weigelt, 2007; Weigelt et al., 2007). Such tasks require the speeded production of two responses, one with the left and one with the right hand. The present study is concerned with a problem of this paradigm, which in our view, has received surprisingly little attention.

The problem relates to the way in which the required actions are usually signaled to the participants. Typically, two stimuli are presented for the bimanual action, one indicating the response for the left and one for the right hand. To give three examples: First, letter stimuli were used to signal responses, such that for example, the letters F-F signal two forward movements, whereas the letters F-S signal a forward movement with the left hand and a sideways movement with the right hand (e.g., Diedrichsen, Grafton, Albert, Hazeltine, & Ivry, 2006; Spijkers & Heuer, 1995). Second, light dots of varying color were presented on a table, and based on a particular color-response mapping for each hand, the dot colors signaled the target locations of the required movements (e.g., Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, 2003). Third, in the aforementioned object manipulation study, two symbolic objects were presented on a screen to signal bimanual actions with identical manipulatory goals, whereas different symbols signaled different goals (Kunde & Weigelt, 2005). Although the type of stimuli, the bimanual action, and level of bimanual interference addressed was quite different across these studies, their main outcome can be summarized astoundingly simply: Performance was generally superior when two identical (or at least similar) stimuli (letters, dot colors, object symbols) rather than non-identical (or dissimilar) stimuli had to be processed to determine the required responses. Thus, there was a same-stimulus advantage.

It is well-known that stimulus identification proceeds more quickly when a display is composed of identical rather than of different stimuli, possibly because the same encoding procedures can be employed twice in close succession (e.g., Nickerson, 1965; Posner & Mitchell, 1967; Posner, 1978; Sternberg, 1998). Therefore, a problem with the finding that performance in bimanual reaction tasks is superior when identical rather than different stimuli are presented is that this advantage might at least in part be a relatively "early" perceptual phenomenon rather a "late" one

that relates to response selection, motor programming or goal specification processes as it is usually implied.

This ambiguity has not gone entirely undetected, and there have been attempts to resolve it. For example, Spijkers, Heuer, Steglich, and Kleinsorge (2000) and Spijkers et al., (1997) used a control task in which the same two stimuli as in a bimanual reaction task were presented, but only one stimulus had to be responded to. To ensure that the other stimulus was also processed by the participants, it either served as a go-signal for the second response (Spijkers et al., 1997) or had to be memorized for later report (Spijkers et al., 2000). These control tasks revealed a somewhat smaller same-stimulus advantage than the bimanual task. Still, the same stimulus advantage was significant and sometimes not even significantly smaller than in the bimanual task. What is more, changing the task requirements between stimuli might also change the perceptual processes applied to these stimuli. Therefore, control conditions exploiting different tasks for the same set of stimuli do not appear as an optimal estimate for the same-stimulus advantage observed under conditions of identical task requirements.

In a recent study by Albert, Weigelt, Hazeltine, & Ivry (2007) participants were shown two light dots on a table. In Experiment 1, the location of these dots directly determined the target locations of bimanual responses. The dots also varied in color, but color was task-irrelevant. Not surprisingly, the similarity of the dot colors did not markedly affect performance, presumably because it was not encoded at all. In two additional experiments, the dot colors had to be retained for later report (Experiment 2), or one of the colors signaled participants to withhold the responses (Experiment 3). Again, color similarity had no effect. However, stimulus color did not signal the target location of the responses here. Hence, it did not provide information about the type of response to select. Like in the abovementioned studies by Spijkers et al., color was thus processed for a different purpose than response selection, and in fact it might have been processed only after response selection had been completed (either to report the color later or to withhold an already selected response). Hence, these observations do not unambiguously rule out that stimulus similarity affects performance if these stimuli enter the same processing stream that leads to response selection.

A somewhat different approach was employed by Weigelt et al., (2007), who presented stimuli for the left and right hand in advance of an imperative go-signal which prompted the eventual execution of the responses. The assumption was that with sufficient time between stimuli and go-signal, the perceptual processing of the stimuli would be completed before the presentation of the go-signal and would thus no more contribute to reaction time (Schmidt & Lee, 1999). The results showed that the

stimulus-congruency-effect was present even with time intervals between stimulus and go-signal of up to 500 ms, which, according to the authors, renders a pure perceptual explanation of the stimulus-congruency-effect unlikely. The same approach was pursued by Kunde & Weigelt, (2005, Experiment 2), who found that performance with identical stimuli was enhanced for preparation intervals of up to 1,500 ms. Yet, there are reasons to question this procedure as well. For example, stimulus processing might not always start at stimulus onset, and it possibly continues when the RT interval has started. Moreover, there is no generally accepted consensus on the length of the time interval that would be necessary to incontrovertibly remove perceptual processes from the RT interval.

Given these possible limitations of previous research a closer examination of the role of stimulus congruency in bimanual coordination seems warranted. Apparently, the problem of stimulus congruency is a notorious one in bimanual coordination research. It would therefore be a rather ambitious research goal to unconfound possible effects of stimulus congruency from all constraints potentially affecting the coordination of bimanual movements noted in the introduction. Therefore, our more moderate purpose in the present study is to safeguard our own evidence for constraints in the specification of action goals against alternative explanations in terms of pure perceptual processing. At this point, we thus do not dispute that constraints at other levels of motor control can also affect the coordination of bimanual movements (see Heuer & Klein, 2006).

We report two experiments here. Our approach was to remove stimulus congruency right away and to assess if goal congruency effects remain nevertheless. In Experiment 1, stimulus congruency was avoided by presenting only a single stimulus in each trial, which obviously renders stimulus congruency impossible. In Experiment 2, visual stimuli were removed entirely. Participants' sight was occluded at the beginning of an experimental trial and they were instructed verbally in advance as to which goals to pursue when the to-be-manipulated objects became visible.

Experiment 1

The task was a simple object manipulation used in a previous study (Kunde & Weigelt, 2005). Participants were asked to simultaneously bring two wooden bricks from a given horizontal start orientation into a particular end orientation (cf. Fig. 1). Unlike previous experiments, where two different stimuli signaled the required object orientations, only a single letter was used. Each of the four possible combinations of left and right goal orientation (upright–upright, downwards–downwards, upright–downwards,
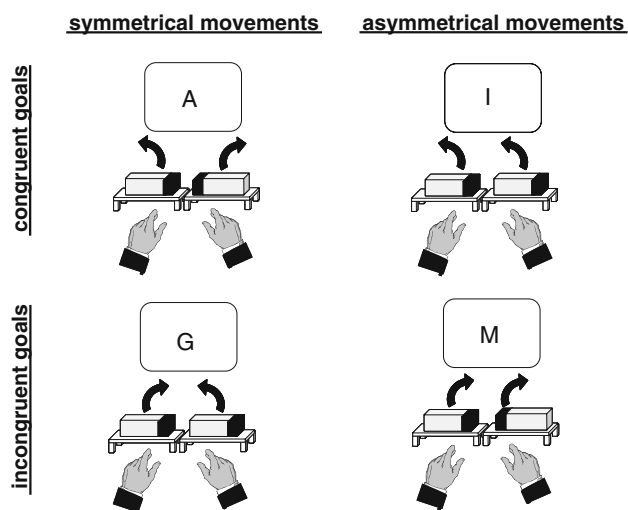
Fig. 1 Illustration of the bimanual object manipulation task in Experiment 1. Congruent or incongruent goal orientations required the execution of symmetrical or asymmetrical rotations of the hands according to a single letter stimulus

downwards–upright) was mapped to a single letter. For example, the letter "A" signaled that the left and right object would have to be aligned upright. Or the letter "M" signaled that the left object would have to be aligned upside down, whereas the right objects would have to be aligned upright and so on. If previous results were due to congruency of the stimuli there should be no effect of goal congruency under these conditions. Alternatively, if congruency of the goals matters, we should find superior performance when the intended object orientations are the same, as compared to when they are different. Previous experiments had revealed that the symmetry of the required arm movements to attain these goals (pronation and supination of forearms) had little effects on performance in this task (Kunde & Weigelt, 2005). To assess if this holds when stimulus congruency is removed, the data were analyzed as a function of movement symmetry as well.

Method

Subjects

Sixteen students from the University of Halle-Wittenberg participated for a course credit.

Apparatus and stimuli

An IBM-compatible computer with a 17 in. VGA-Display was used for stimulus presentation and response sampling. Stimuli were presented in white color on black background in a viewing distance of approximately 80 cm. The manipulated objects were two wooden building blocks (70 mm ×

40 mm × 40 mm) marked with blue color on one end (20 mm, cf. Fig. 1). The blocks lay on small racks (100 mm × 100 mm × 15 mm), which were placed 300 mm in front of the display. The racks rested on four mechanical springs, which lifted the rack by 2 mm when the block was removed and thereby opened a microswitch. At the beginning of each trial the blocks lay with their long sides on the racks. The task was to lift the blocks, to align them according to the signaled goal orientation, and to place them back on their racks. The participants were instructed to grasp the blocks at their midpoints and to manipulate the blocks with an overhand grip (i.e., holding the blocks with the thumb at the blocks' front sides and the finger tips at the blocks' backsides). Grip type was constrained to make sure that all effects of goal congruency and movement symmetry show up in temporal dependent measures (reaction time, movement time and manipulation time, see below) rather than in the type of grip itself. At the beginning of each trial, participants' index fingers rested on microswitches (20 mm × 20 mm) that were separated by 150 mm and located 150 mm in front of the blocks. Participants were seated comfortably at the front side of the table. The experimenter sat at one long side of the table, so that an inspection of the participants' responses and a proper positioning of the blocks between experimental trials were possible. If the response had been executed in a non-instructed manner (e.g., if at least one end orientation of one of the two objects was incorrect or if the objects were not grasped with an overhand grip) the experimenter entered this into the PC keyboard immediately after the trial. No distinction between types of errors was made.

At the beginning of each trial, the experimenter placed the wooden blocks in one of the 2 × 2 possible combinations of the start orientations of the objects (i.e., the head of the left and right object being oriented towards the left or right side). The starting orientation of the blocks varied from trial to trial in a random manner. The participant was told to carefully watch and realize this starting orientation of the blocks. When participants felt prepared they placed their index fingers on the home keys, and told the experimenter to start the trial. The experimenter pressed the Enter key on the PC keyboard. Two thousand milliseconds later, one of the letters A, I, G, or M was presented for 200 ms on the screen. The stimulus onset was accompanied by a 100 ms tone of 2,000 Hz. *Reaction time* was the interval between stimulus presentation and lifting of the index finger from the home key. *Approach time* was the interval between lifting the home key, and lifting the object from its rack. Approach times included thus approaching and grasping the objects as well as the initiation of their lifting. *Manipulation time* was the interval from lifting the object and placing it back on its rack. These times were measured for each hand independently. If either reaction time,

approach time, or manipulation time exceeded 1,500 ms or either of these three times differed by more than 200 ms between the hands, this was fed back by a 1,500 ms visual error message ('Too slow' or 'Too asynchronous', in German) after completion of the response. If the experimenter judged the response as being incorrect the message 'Response not properly executed!' (in German) was displayed for 1,500 ms on the screen. Then the wooden blocks were arranged for the next trial.

Procedure and design

The participants received written instructions. Each participant received a different mapping of the four stimulus letters to the 2 × 2 possible goal orientations of the blocks. They were instructed to bring the objects from the start orientation into the required end orientation as quickly as possible and to avoid errors. The experiment was run in 11 miniblocks consisting of 16 trials each. These 16 trials resulted from the orthogonal combination of 2 starting orientations of the left-hand block (leftwards or rightwards) × 2 starting orientations of the right-hand block (leftwards or rightwards) × 2 goal orientations of the left-hand block (upright or upside down) × 2 goal orientations of the right-hand block (upright or upside down). The order of trials was random. The participants had an opportunity for a brief rest after every second miniblock, where error rates and the mean reaction times of the preceding two miniblocks were displayed. The entire experiment took about 1 h.

Results

Data analysis

Trials were excluded from the analysis if either reaction time (RT), approach time (AT), or manipulation time (MANT) was below 100 ms or above 1,500 ms (0.5% of the data) or the movements were not performed simultaneously (i.e., RT, AT, or MANT for the two hands differed more than 200 ms, 2.2% of the data). In each individual trial RT, AT, and MANT were averaged over the left and right hand and served as input for the analyses of duration of these intervals.

Reaction times (RT)

A preliminary analysis of variance (ANOVA) looked for practice-related changes of the data pattern. This analysis included the variables block (1–11), movement symmetry (whether the movements were mirror symmetrical or not), and goal congruency (whether the required orientation of the blocks was the same or different) as repeated measures.

There was a general reduction of RT with block, $F(10,140) = 5,77$, $p < 0.01$; MSE = 115,172, but no interactions involving block (all $ps > 0.19$), which shows that the data pattern was stable across practice. Therefore the factor block was omitted in subsequent analysis. RTs were significantly lower with congruent rather than incongruent goals, $F(1,15) = 5.39$, $p < 0.05$; MSE = 7,677. No other effect was significant (all $ps > 0.20$). The mean RT in the orthogonal combinations of goal congruency and movements symmetry are shown in Fig. 2.

Approach times (AT)

Possibly, movements were initiated before the response was fully prepared, particularly so because the first segment of the responses (the hands approaching the objects) was identical in all conditions. So part of response specification may have been deferred until after response initiation. If so, we might find influences of goal congruency even in the time needed to approach the objects. In fact the analysis of approach times revealed faster ATs with goal congruency, $F(1,15) = 32.88$, MSE = 3,394.7, $p < 0.001$. The goal congruency effect was slightly more pronounced with symmetrical than with asymmetrical movements resulting in an interaction of goal congruency and movement symmetry, $F(1,15) = 4.84$. MSE = 331.89, $p < 0.05$.

Manipulation times (MANT)

The ANOVA of manipulation times replicated the influence of goal congruency, $F(1,15) = 10.44$, MSE = 2,818.76, $p < 0.01$. No other effect reached significance.

Errors

The error rate was higher with incongruent goals (13%) compared to congruent goals (3.4%), $F(1,15) = 30.01$, MSE = 49.78, $p < 0.01$. No other effect reached significance.

Discussion

The results of Experiment 1 are straightforward. Movements are initiated and carried out more quickly when congruent instead of incongruent manipulatory goals are intended. Effects of movement symmetry were present as well but not in a very consistent manner. This might appear surprising from the perspective of dynamical pattern theory, as our asymmetrical movement conditions can be considered as anti-phase coordinations which normally yield inferior performance compared to in-phase coordinations (cf. Kelso, 1995). However, such motor effects have been primarily found in simple movement tasks, where participants pursued no other goal than carrying out the movement. It is likely that these sometimes subtle motor symmetry effects are overrun in a cognitively enriched task as the present one (cf. Heuer & Klein, 2006 for this view).

More importantly, only one stimulus signaled the afforded goals, which renders it unlikely that stimulus-related processes contributed to the observed superiority of congruent goals. In terms of RTs the present goal congruency effect with a single letter stimulus amounted to 50 ms, which comes close to the 62 ms effect in a previous study that used two symbolic stimuli (Kunde & Weigelt, 2005, Experiment 1). It seems thus that stimulus congruency is of minor relevance for the present task. The goal congruency effect was not only apparent in reaction times, but also in the times to approach and manipulate the objects. This suggests that action specification was not fully completed when the movement started, but continued to some extent while the action had already started.

Still there was a stimulus. And more importantly, each stimulus was consistently coupled with a certain goal state. For example, the letter "A" which for a given participant might signal two upright object orientations was contingently followed by two upright objects (exception
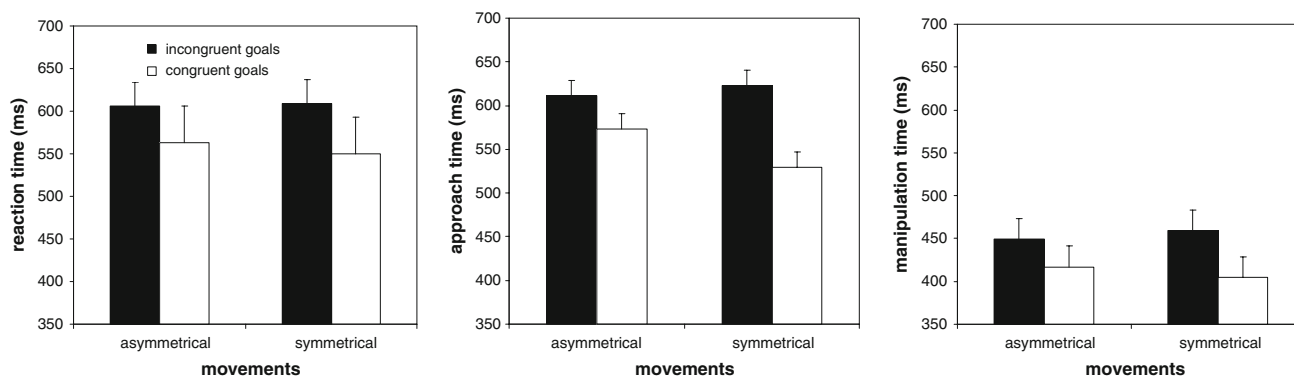
Fig. 2 Mean reaction times, approach times and manipulation times as a function of goal congruency and motor symmetry in Experiment 1. *Error bars* represent standard errors of the means

in error trials). It seems not too far-fetched that this contingency might have prompted the formation of specific stimulus–goal associations whereby the letters acquire the properties of the events that follow them. For example, the letter "A" might become a "congruent" stimulus because it signals congruent object orientations, which possibly favors its perceptual processing. This conjecture receives some support from informal reports of the participants. Some of them noted that there were two types of letters, "easy" ones (those signaling congruent goals) and "difficult" ones (those signaling incongruent goals), which afforded a closer examination. Thus, the goal congruency effect might to some extent still reflect favored encoding of stimuli that acquired the meaning of being congruent. This argument can be ruled out by removing visual stimuli from the experiment entirely. This was done in Experiment 2.

Experiment 2

In Experiment 2, we removed all visual stimuli that were consistently related to the required object orientations. To this end, participants were verbally informed in advance about the afforded object orientations, while the objects' initial orientation was occluded from sight until RT onset. Thus, whereas in Experiment 1 the start orientation was known and the goal orientation was provided at RT onset, now the goal orientation was known and the start orientation was provided at RT onset. Importantly, the start orientations of the blocks varied independently of the required goal orientation, so that there was no specific association between these "stimuli" and the required goal orientation. If goal congruency effects reside, this cannot be attributed to acquired meanings of the stimuli (i.e., particular stimulus–goal associations).

Apart from the purpose to rule out arguments that relate to the processing of the stimuli, there is a broader implication of this experiment. In all existing studies on bimanual coordination it is always the movement goal (in most studies its end point) that remains to be specified when RT begins, while the initial state of the movement (its start position) is already known. This is insurmountable when there is no goal beyond movement execution itself, because knowledge of the hands' start position is inevitable (except in rare pathological cases with loss of body sensation). The use of action goals that go beyond movement execution allowed us to test, for the first time as we believe, if goal congruency matters when the goals are known in advance whereas the movements (supination or pronation) have to be accommodated to a certain unknown initial state.

Method

Participants

Twelve students from the University of Halle-Wittenberg participated for a course credit.

Apparatus, stimuli and procedure

We only note the differences to Experiment 1 here. There were no stimuli presented on the computer monitor. Instead the participants wore shutter glasses (Elsa 3D Revalator). The glasses were controlled by a custom-made computer interface, whereby the glasses were opened or closed at a programmed point in time. At the beginning of a trial the glasses were opaque, and the participants hands rested on homekeys in front of them. The experimenter placed the objects on their racks according to a certain start orientation, and then verbally announced the afforded goal orientations of the objects (e.g., "left upwards, right upwards", "left upwards, right downwards" and so forth). When the participant signaled to be prepared, the experimenter started the trial by pressing the space bar of the PC. Two seconds later a brief warning tone followed. One thousand milliseconds after the warning tone, the glasses opened and the participant grasped the objects to put them into the required goal orientation. When the trial was completed the participant returned to the homekey and the glasses became opaque again. When the bimanual response was incorrect, too slow, or to asynchronous this was fed back verbally to the participants by the experimenter. The experiment was run in 10 miniblocks consisting of 16 trials each.

Results

Trials were excluded from the analysis if either reaction time (RT), approach time (AT), or manipulation time (MANT) was below 100 ms or above 1,500 ms (0.1% of the data) or the movements were not performed simultaneously (i.e., RT, AT, or MANT for the two hands differed more than 200 ms, 2.8% of the data). In each individual trial RT, AT, and MANT were averaged over the left and right hand and served as input for the analyses of duration of these intervals.

Reaction times

RTs were entered into an Analysis of Variance ANOVA with the variables of movement symmetry (whether the movements were mirror symmetrical or not) and goal congruency (whether the afforded orientation of the blocks was the same or different) as repeated measures. There was a

significant influence of goal congruency, $F(1,11) = 8.17$, $p < 0.05$; MSE = 686.8. No other effect was significant (all $ps > 0.20$). The corresponding means from this analysis are shown in Fig. 3.

Approach times

The hands approached the object more quickly with congruent compared to incongruent goals $F(1,11) = 30.95$, $p < 0.01$, MSE = 499.6. The goal congruency effects was slightly more pronounced with symmetrical than with asymmetrical arm movements, $F(1,11) = 8.5$, $p < 0.05$, MSE = 84.39.

Manipulation times

There were no effects in the analysis of manipulation times (all $ps > 0.13$).

Error rates

Responses were more accurate with congruent goals (8.2%) than with incongruent goals (15.2%). No other effects reached significance (all $ps > 0.11$).

Discussion

The specific purpose of Experiment 2 was to further rule out stimulus-related explanations of goal congruency observed in Experiment 1 and earlier experiments. We tested whether bimanual actions that aimed at congruent rather than incongruent object manipulations would be superior even though there was no visual stimulus that signaled the required goal orientations. Clearly this was the case. Response times and even approach times were lower with congruency of intended object orientations. We can thus be confident that the processing of stimuli linked to required goal states did not play a relevant role.

In a broader perspective the present results further previous research on bimanual coordination. Previous experiments have shown that congruent action goals benefit bimanual coordination when the start condition is known but the goal states have to be extracted from the environment. Here we have shown that congruent goals benefit bimanual coordination also when the goal state is already known but the start conditions have to be extracted from the environment. In other words, it seems to be important that actions converge to the same goal to concurrently plan them easily, irrespective of when the goals are announced. We will further address this issue in "General discussion".

General discussion

The present two experiments demonstrated that when two hands aim for different action goals in an object manipulation task, coordination costs arise, as compared to when they aim for similar action goals. These *goal coordination costs* persisted, while possible effects of stimulus congruency, that could have affected previous results (Kunde & Weigelt, 2005), were carefully ruled out in the present study. We therefore propose that the intended end-states of manual actions are powerful determinants of coordinated movement behavior. Constraints inherent to the motor system, such as muscle homology or movement symmetry, however, were not very apparent in the present data. Yet, this may well relate to the particular movement task employed (inward or outward rotations of the forearms), and we are thus reluctant to draw strong conclusions from the absence of potential motor effects here, as these have been reported to be present in other tasks.

It has been argued that processes related to the encoding of symbolic stimuli and to the translation of these stimuli into the appropriate actions brought about the movement congruency effects observed in discrete bimanual coordination (Diedrichsen et al., 2001; Hazeltine, Diedrichsen,
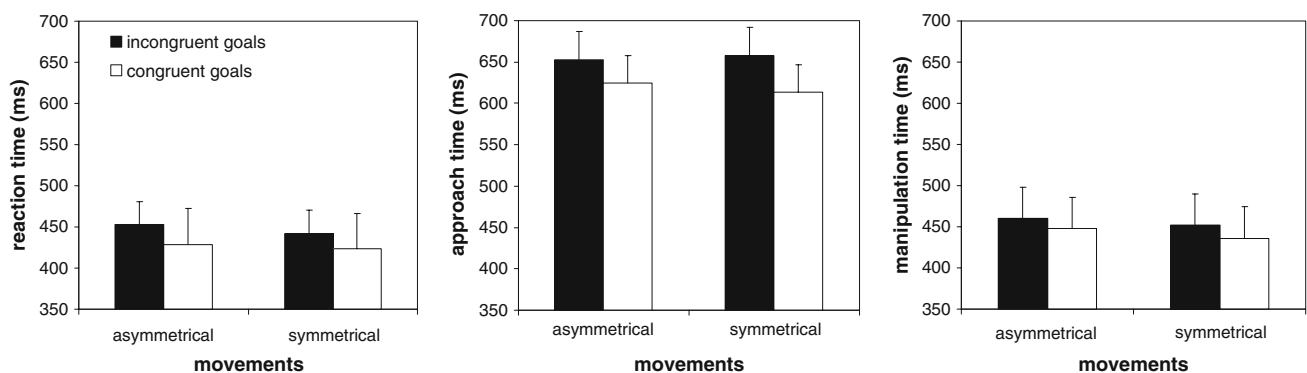
Fig. 3 Mean reaction times, approach times and manipulation times as a function of goal congruency and motor symmetry in Experiment 2. *Error bars* represent standard errors of the means

Kennerley, & Ivry, 2003). This argument was supported by the work of Diedrichsen et al., (2001, 2003; Ivry, Diedrichsen, Spencer, Hazeltine, & Semjen, 2004), who demonstrated the absence of such movement congruency effects under conditions in which the target locations of bimanual movements were presented directly (i.e., on the table surface) to the actor. In these studies, the target locations (i.e., the end-points of the movements) were also the goals of the bimanual actions. The present two experiments extend these findings, showing that goal congruency effects can also be observed for actions that aim at goals related to future changes in our environment, while overcoming the stimulus congruency confounds inherent in previous studies (for a further discussion see Weigelt et al., 2007).

Ruling out explanations in terms of stimulus encoding requires one to come up with alternative explanations of the goal congruency effect. Let us first consider Experiment 1 in which the goals were provided by a stimulus, and thus some goal representation had to be created in the RT interval. It makes sense that it takes longer time to create different rather than identical goal representations for the two hands. This is particularly plausible if we assume that such goal codes are perceptual (in the present case visual) in nature, as it was originally proposed by James (1981) and recently re-advocated by Mechsner et al., (2001). There is ample evidence that it is harder to generate and to maintain an image-like representation the more different features such an image-like representation encompasses (cf. Kosslyn, Cave, Provost, & von Gierke, 1988). On top of that, different image-like representations have to be represented and assigned to the two hands in a specific manner in case of incongruent goals. Attaining this assignment of different goals to the hands is harder than with congruent goals where an assignment of goals to the individual hands is dispensable.

Technically speaking, the creation of goal representations could have occurred before the RT interval in Experiment 2, because the goal states were verbally announced in advance. This raises the question why goal-congruency effects were still observed. We see two interpretations of this outcome. First, a mere verbal description might have to be transformed into a visual format, and this transformation might occur only after visual input was available (i.e., the shutter glasses opened). This makes sense from the perspective that goals are represented in a perceptual format (Mechsner et al., 2001). One motivation for this assumption is that common codes for action planning and perception allow for an efficient comparison of motor output and re-afferent input. The creation of perceptual goal codes (visual ones in this case) might start only when visual input is available for a start-goal comparison, and thus, costs of goal incongruency showed up in RT, despite verbal pre-information. A second reason for the goal congruency

effects observed in Experiment 2 might relate to limitations in working memory. That is, irrespective of the proposed format of goal representations, participants had to retain the action goals in working memory without stimulus support. With identical goal orientations, a simple memory chunk, such as "both upright", suffices, whereas with incongruent goal orientations, upright and downward orientations must be retained separately for the left and right hand. In other words, while the same goal state can be memorized in cases of goal congruency, different states must be memorized to determine the required movements in cases of goal incongruence. The memory-based interpretation does also accord with the observation that goal congruency effects were larger in Experiment 1 than in Experiment 2. In Experiment 1 such codes had to be created at the beginning of the RT interval and maintained over the course action execution, whereas the creation of such codes could have occurred prior to the RT interval in Experiment 2. Future research is certainly warranted to determine if the costs of incongruent goals are more closely related to the creation or the maintenance of goal representations.

To conclude, the present findings provide further evidence for the notion that the production of bimanual movements is directly driven by the intended goals of the actions (i.e., some final object orientation in the present experiments). For the first time, it was possible to demonstrate that goal states influence action planning even under conditions in which the action goals were known beforehand, while information about the environmental conditions, and thus the necessary motor requirements, had to be specified thereafter. This point emphasizes the role of action goals as a constraint for action planning and expands our understanding of the limitations of our two hands in manual performance (cf. Ivry et al., 2004, for a similar view).

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