Motor simulation beyond the dyad: Automatic imitation of multiple actors

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Running head: Automatic imitation of multiple actors

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Abstract

A large body of research has provided evidence for the idea that individuals simulate the actions of others in their motor system. However, this research has focused almost exclusively on dyadic situations, hence ignoring the fact that social situations often require that the actions of multiple persons are simulated at the same time. In the current study, we addressed this issue by means of a widely used automatic imitation task. It is shown that individuals automatically imitate the actions of two individuals at the same time. More specifically, the results indicate that two identical observed movements produce a stronger imitation effect, whereas two different observed movements produce two imitation effects that cancel each other out. The finding that the actions of multiple agents are simultaneously represented in the motor system allows for a better understanding of social interaction beyond the dyad.

Keywords: action observation, automatic imitation, multi-actor situations

Introduction

The Ideomotor Mechanism

Social interaction often requires that individuals take into account the actions of the people they interact with. When two persons reach out to shake each other's hand, for example, the handshake will only succeed if they manage to coordinate their movements. To understand the mechanisms behind social interaction, it is therefore important to know how the actions of others are processed in the brain. According to ideomotor theory, action execution and action observation share a representational format (Greenwald, 1970; Hommel, 2009; Prinz, 1997). More specifically, it is assumed that actions are represented in the motor system in the form of their anticipated sensory consequences. Because individuals often see the actions they perform, an important implication of ideomotor theory is that observed actions should not only trigger a perceptual representation but also a motor representation.

Supporting the idea that observed actions are simulated in the motor system, research has revealed that individuals tend to automatically imitate the movements of others (reviewed in Heyes, 2011). Stimulus-response compatibility studies, for example, have consistently shown that responses to a symbolic stimulus are facilitated by a compatible observed movement and impeded by an incompatible observed movement (e.g., Bertenthal, Longo, & Kosobud, 2006; Brass, Bekkering, Wohlschläger, & Prinz, 2000; Catmur & Heyes, 2011; Liepelt, Cramon, & Brass, 2008; Stürmer, Aschersleben, & Prinz, 2000). Likewise, research on imitative tendencies in social interaction has indicated that individuals often unintentionally copy the behavior, facial expression, and posture of their interaction partner (e.g., Chartrand & Bargh, 1999; Chartrand &

van Baaren, 2009). Finally, patient studies have demonstrated that impaired inhibition due to frontal lobe damage can result in an irresistible urge to imitate the actions of others (Brass, Derrfuss, Matthes-von Cramon, & von Cramon, 2003; De Renzi, Cavalleri, & Facchini, 1996; Lhermitte, Pillon, & Serdaru, 1986; Luria, 1966).

In addition to research on automatic imitation, ideomotor theory has recently gained support from neurophysiological data (reviewed in Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). Imaging studies, for instance, have identified brain areas within the motor system that are recruited both when individuals execute an action and when they observe the same action (e.g., Dinstein, Hasson, Rubin, & Heeger, 2007; Gazzola & Keysers, 2009; Kilner, Neal, Weiskopf, Friston, & Frith, 2009). This is supported by EEG (e.g., Lepage & Théoret, 2006; Zhu, Sun, & Wang, 2013) and TMS (e.g., Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Maeda, Kleiner-Fisman, & Pascual-Leone, 2002) research in which action observation was similarly found to produce motor activation.

In summary, research from different sources has supported the idea that action observation relies on motor simulation. Interestingly, studies suggest that this intimate connection between action observation and execution may play an important role in social interaction. Motor simulation has, for instance, been related to a variety of social skills such as empathy (Chartrand & Bargh, 1999; Gazzola, Aziz-Zadeh, & Keysers, 2006; Kaplan & Iacoboni, 2006), action goal inference (Cattaneo, Caruana, Jezzini, & Rizzolatti, 2009; Hamilton & Grafton, 2006), and intention inference (Iacoboni, Molnar-Szakacs, Gallese, Buccino, & Mazziotta, 2005; Kaplan & Iacoboni, 2006). Furthermore, it has been argued that social problems in autism spectrum disorder are caused by a deficit in the ideomotor system (Williams, Whiten, Suddendorf, & Perrett, 2001) or by a deficit in the regulation of the ideomotor system (Hamilton, 2013; Spengler, Bird, & Brass, 2010). Finally, motor simulation is assumed to be important for the

execution of actions that require two or more individuals to coordinate their movements (Colling, Knoblich, & Sebanz, 2013; Knoblich & Sebanz, 2006). Specifically, it is thought that motor simulation enables individuals to anticipate the actions of their co-actor in joint action situations (Atmaca, Sebanz, & Knoblich, 2011; Kourtis, Sebanz, & Knoblich, 2013; Sebanz, Knoblich, & Prinz, 2003; Sebanz, Knoblich, Prinz, & Wascher, 2006), hence facilitating movement coordination (Kourtis et al., 2013).

The Multi-Actor Ideomotor Mechanism

However, despite the large body of research on motor simulation, most research has focused on how individuals process the actions of a single agent. This stands in contrast with the fact that individuals often engage in social interactions that involve multiple agents. When one has to move a large and heavy object, for example, this may require the cooperation of multiple persons. In order to complete such tasks without accidents, it is imperative that these different persons are able to coordinate their movements. This, in turn, requires that each person is able to monitor and anticipate the movements of the different co-actors. One possibility is that the latter relies on co-representing the movements of multiple persons in the motor system.

Indirect evidence in favor of a multi-actor ideomotor mechanism can be found in three earlier studies. In one study, Tsai and colleagues (Tsai, Sebanz, & Knoblich, 2011) investigated imitative behavior at the inter-group level. More specifically, these authors examined how imitative responses were influenced by the overlap between the number of actors and the number of imitators. The results revealed that participants were faster to imitate when the amount of imitators matched the amount of actors (e.g., two actors and two imitators) compared to when

they did not match (e.g., two actors and one imitator). This was interpreted as evidence for the idea that motor simulation is sensitive to the number of co-actors.

In two other studies, the relation between the number of actors and the probability of imitation was investigated. In an early study, Milgram, Bickman, and Berkowitz (1969) registered the behavior of pedestrians as they passed by one to fifteen people looking at a sixth floor window. The results showed that pedestrians were more likely to copy this behavior when the sample of window watchers grew in number. Similarly, in a more recent study (Herrmann, Legare, Harris, & Whitehouse, 2013) it was shown that children are more likely to imitate observed behavior when it is demonstrated by two models at the same time compared to a single model or two consecutive models. Both studies show, in other words, that the probability of imitation is larger when the observed behavior is executed by multiple persons at the same time. However, this evidence was interpreted in terms of interpretative processes rather than in terms of a multi-actor ideomotor mechanism. For example, the tendency to look up may increase with the number of window watchers because an increasing amount of window watchers also increases the odds that something interesting is happening. Nevertheless, an alternative explanation for the increased probability of imitation could be that the relevant ideomotor representation was triggered more strongly when an action was executed by multiple persons.

To summarize, previous studies have shown that imitative tendencies can be modulated by the number of observed actors. This suggests that motor simulation is sensitive to the amount of observed actors. It is, however, not yet known whether this also means that the actions of multiple observed actors can be simulated in the motor system at the same time. In the current study, we aimed to address this question by measuring automatic imitation in a situation where two observed actors are moving simultaneously. If the movements of both actors are indeed

represented in the motor system at the same time, the automatic imitation effects should reflect a combination of these movements.

Experiment 1

In order to test the above prediction, we adapted a well-known automatic imitation paradigm in which individuals are required to make a certain finger movement in response to a symbolic cue while a hand on the screen makes a compatible or an incompatible movement (Bertenthal et al., 2006; Brass et al., 2000; Catmur & Heyes, 2011; Liepelt et al., 2008). In contrast to the original paradigm, in which a single hand appears on the screen, the current adaptation included two different hands next to each other making a congruent (C), an incongruent (IC), or no (N) abduction movement with respect to the imperative cue (figure 1). Consequently, this paradigm allows us to look at the congruency effect of both the hand on the left side (LC, LN, LIC) and the hand on the right side (RC, RN, RIC) of the screen.

First, we can investigate whether the movements of both hands are represented in the motor system of the observer by testing if a congruency effect is present for each of the two hands. Importantly, a congruency effect should be present for both hands irrespective of what the other hand is doing. That is, if the ideomotor system is able to incorporate the movements of multiple actors simultaneously, the movements of each actor should result in an automatic imitation effect regardless of whether the other actor makes a movement and regardless of which movement the other actor makes.

Next, if we manage to confirm that individuals are influenced by the actions of both hands at the same time, we can use this paradigm to investigate *how* the motor system represents the actions of the hands when they make simultaneous movements. More precisely, we can use this

paradigm to examine how individuals are influenced by two identical observed movements and how they are influenced by two different observed movements. When the two hands perform an identical movement, it can be expected that the movements of both hands are mapped onto the same motor representation. This should lead to an increased activation of the corresponding motor representation and consequently to a larger congruency effect. Importantly, a larger congruency effect in the current study cannot be explained in terms of interpretative processes due to the fact that the observed movements are simple, meaningless movements that are irrelevant for the task at hand. When the two hands perform a different movement, on the other hand, the movements of the hands should trigger different motor representations. In terms of the automatic imitation task, this means that that one hand movement should activate a congruent motor representation, while the other hand movement should activate an incongruent motor representation. As a result, a facilitation and an interference effect should be present at the same time. Because these effects are opposite forces, they should subsequently cancel each other out.

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Method

Participants. 38 participants took part in the experiment (M_{age} = 22.18, SD_{age} = 2.36). All of them were right-handed females with good or corrected vision. Participants were paid 5 euro and signed an informed consent beforehand. The study was approved by the local Ethical Committee and all procedures were performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration.

Stimuli and Apparatus. The experiment was programmed in C with Tscope (Stevens, Lammertyn, Verbruggen, & Vandierendonck, 2006). Stimuli consisted of frames that were extracted from video clips (figure 1). These frames (1010 x 544 pixels) depicted two different female right hands (hand A and hand B), positioned next to each other on a blue background. The hands were positioned so they created mirror images of the participant's right hand (i.e., the response hand). To produce an illusion of movement, the hands were first presented in their neutral posture and were subsequently overwritten by a second picture of the hands in their final posture. Both hands moved independently of one another and could either not move or perform an abduction movement of the index or little finger. Two types of video clips were created: one with hand A on the left side of the screen and hand B on the right side of the screen, and one the other way around. In order to record responses, we used a custom-made response box that detects when a finger leaves a sensor.

Procedure. The experiment took about 30 minutes and consisted of two phases. To explore a possible influence of the imperative cue position, the cue was positioned at the top of the screen in one phase and at the bottom of the screen in the other phase. Each phase comprised a practice phase of 10 trials with feedback, followed by three blocks of each 90 trials without feedback. All of these blocks contained 10 trials of each condition within the left side congruency (LC, LN, LIC) x right side congruency (RC, RN, RIC) design, 5 of which were presented with W and 5 with P as imperative cue. After each block, participants had the opportunity to take a break. Trials were presented randomly, with the restriction that the same imperative cue could not appear on more than four consecutive trials. The position of the hands (left/right) and the order of the phases (cue bottom/cue top) was counterbalanced.

Before the experiment, instructions appeared on the screen. The instructions requested participants to make an abduction movement with their right hand index finger when they saw W ('wijsvinger') and to make an abduction movement with their right hand little finger when they saw P ('pink'). Participants were asked to respond as fast as possible, but without making errors.

Each trial started with a picture of both hands in their neutral posture and a fixation cross for 500 ms. This was followed by the simultaneous presentation of the imperative stimulus and the hands in their final posture for a maximum of 2000 ms or until the response. After an inter-trial interval of 1000 ms, the next trial started.

Data Analysis. All analyses were performed in R (R Development Core Team, 2013). Trials in which no response was given before the response deadline (0.34%) were excluded from all analyses. Additionally, trials with a reaction time (RT) faster than 100 ms (0.05%) were considered as action slips and excluded as well. Finally, for the RT analyses, erroneous trials (3.17%) and trials with a RT slower than 1000 ms (0.92%) were also excluded. Correlation coefficients represent Pearson product-moment correlation coefficients. *T* tests represent two-tailed paired samples *t* tests. P-values of post-hoc tests were corrected for multiple testing (p_c) according to Holm's procedure (Holm, 1979). Partial eta squared (η_p^2) and Cohen's *d* were used as measures of effect size.

To reduce the complexity of the data pattern, we will present three separate analyses that test our three main hypotheses. First, we test whether the left and the right side hand each have an independent influence. Second, we test whether two identical observed movements produce a stronger congruency effect than a single observed movement. Finally, we investigate whether two different observed movements elicit opposing forces that cancel each other out.

Results

Simulating two observed movements simultaneously. To determine whether a congruency effect was present for both hands, RTs and error rates were subjected to a 3 (left side congruency: LC, LN, or LIC) x 3 (right side congruency: RC, RN, or RIC) x 2 (imperative cue position: bottom or top) repeated measures ANOVA combined with Greenhouse-Geisser corrected degrees of freedom for violation of sphericity. The **analysis of the reaction times** (figure 2a) revealed a main effect of left side congruency, $F(1.47, 54.38) = 46.63$, $p < 0.001$, $\eta_p^2 = 0.56$, with faster RTs in LC (439 ms) than in LN (448 ms), $t(37) = -4.84$, $p_c < 0.001$, $d = 0.79$, and faster RTs in LN than in LIC (459 ms), $t(37) = -6.85$, $p_c < 0.001$, $d = 1.11$. Similarly, there was also a main effect of right side congruency, $F(1.62, 59.86) = 31.59$, $p < 0.001$, $\eta_p^2 = 0.46$ with faster RTs in RC (438 ms) than in RN (450 ms), $t(37) = -5.83$, $p_c < 0.001$, $d = 0.95$, and faster RTs in RN than in RIC (457 ms), $t(37) = -3.39$, $p_c = 0.002$, $d = 0.55$. No main effect of imperative cue position was observed, $F(1, 37) = 2.38$, $p = 0.131$.

The analysis also revealed an interaction between left side congruency and right side congruency, $F(3.34, 123.76) = 3.36$, $p = 0.017$, $\eta_p^2 = 0.08$. This seems at odds with the hypothesis that an automatic imitation effect should be present for both hands regardless of the actions of the other hand. However, a left side congruency x right side congruency interaction does not necessarily imply that the left (right) side congruency effect is absent under certain levels of right (left) side congruency. It can, for instance, also indicate that the left (right) side congruency effect is present for all levels of right (left) side congruency but not with the same strength. To exclude the possibility that the left (right) side congruency effect was absent for certain levels of right (left) side congruency, we computed the left (right) side congruency effect (IC – C) for the different levels of right (left) side congruency. This revealed the presence of a congruency effect

for both the left side hand, all $t(37) \geq 4.15$, all $p_c < 0.001$, all $d \geq 0.67$, and the right side hand, all $t(37) \geq 5.00$, all $p_c < 0.001$, all $d \geq 0.81$, regardless of the action (C, N, IC) that was performed by the other hand[1]. No other two- or three-way interactions were observed, all $p > 0.307$.

The **analysis of the error rates** (figure 2b) revealed a similar pattern with a main effect of left side congruency, $F(1.61, 59.50) = 18.60$, $p < 0.001$, $\eta_p^2 = 0.34$, and right side congruency, $F(1.87, 69.15) = 26.78$, $p < 0.001$, $\eta_p^2 = 0.42$. Post-hoc analyses revealed that the main effect of left side congruency was due to lower error rates in LC (2.23%) than in LN (2.92%), $t(37) = -2.36$, $p_c = 0.024$, $d = 0.38$, and lower error rates in LN than in LIC (4.39%), $t(37) = -4.35$, $pc < 0.001$, $d = 0.71$. Similarly, post-hoc analyses for the main effect of right side congruency revealed lower error rates in RC (2.17%) than in RN (2.97%), $t(37) = -3.06$, $p_c = 0.004$, $d = 0.50$, and lower error rates in RN than in RIC (4.39%), $t(37) = -4.30$, $p_c < 0.001$, $d = 0.70$. There was no main effect of imperative cue position, $F < 1$.

The interaction between left side and right side congruency was near-significant, $F(3.46, 127.99) = 2.55$, $p = 0.051$, $\eta_p^2 = 0.06$ In order to exclude that this indicated the absence of a left (right) side congruency effect for certain levels of right (left) side congruency, we again computed the left (right) side congruency effect (IC – C) for the different levels of right (left) side congruency. This revealed that a congruency effect was present for both the left side hand, all $t(37) \geq 2.25$, all $p_c \leq 0.031$, all $d \geq 0.37$, and the right side hand, all $t(37) \geq 2.75$, all $p_c \leq 0.009$, all $d \geq 0.45$, irrespective of what the other hand was doing (C, N, IC)[1]. No other two- or three-way interactions were observed, all $p \geq 0.203$.

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[1] The precise pattern of the interaction is not further explored here because it is complex and not relevant to the research questions. A detailed description and interpretation of the interaction pattern can be found in appendix.

Simulating two identical observed movements. Next, in order to determine whether two identical observed movements produced a stronger congruency effect, we took the relevant conditions (IC/IC, C/C, IC/N, N/IC, C/N, and N/C)[2] and submitted the RTs and error rates to a 2 (number of hand movements: one vs. two) x 2 (congruency: IC vs. C) repeated measures ANOVA. Because the effect of imperative cue position failed to reach significance in the previous analysis, this variable was no longer considered in this analysis and further analyses. The **reaction time analysis** (figure 3a) revealed a main effect of congruency, $F(1, 37) = 65.67$, $p < 0.001$, $d = 1.32$, with RTs in IC (463 ms) being slower than RTs in C (434 ms), but no main effect of number of hand movements, $F < 1$. As predicted, the analysis also revealed an interaction between number of hand movements and congruency, $F(1, 37) = 6.91$, $p = 0.012$, $d = 0.43$, indicating that the congruency effect produced by two identical observed movements (34 ms), $t(37) = 6.97$, $p_c < 0.001$, $d = 1.13$, was stronger than the congruency effect produced by a single observed movement (24 ms), $t(37) = 7.58$, $p_c < 0.001$, $d = 1.23$.

The **analysis of the errors rates** (figure 3b) again showed a main effect of congruency, $F(1, 37) = 41.89$, $p < 0.001$, $d = 1.05$, with more errors in IC (5.16%) than in C (1.87%), but also a main effect of number of hand movements, $F(1, 37) = 6.22$, $p = 0.017$, $d = 0.41$, with more errors when two hands made a movement (3.96%) instead of one (3.07%). Importantly, the interaction between number of hand movements and congruency was again significant, $F(1, 37) = 14.02$, $p < 0.001$, $d = 0.61$, showing that the congruency effect produced by two identical observed movements (4.39%), $t(37) = 6.39$, $p_c < 0.001$, $d = 1.04$, was stronger than the

[2] Please note that these codes represent the following: MovementLeftSideHand/MovementRightSideHand. For example, IC/N means that the left side hand performed an incongruent action while the right side hand did not move.

congruency effect produced by a single observed movement (2.19%), $t(37) = 4.69$, $p_c < 0.001$, $d = 0.76$.

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Simulating two different observed movements. Finally, we investigated the effect of seeing two different movements. We reasoned that this should result in facilitation from the congruent hand movement and interference from the incongruent hand movement. Because these effects are opposing forces, we hypothesized that they should cancel each other out. To investigate this, we examined whether the RTs and error rates were different when participants observed two different movements (MEAN C/IC)[3] compared to when participants observed no movement (N/N). Both for RTs (MEAN C/IC: 447 ms vs. N/N: 450 ms), $t < 1$, and error rates (MEAN C/IC: 2.85% vs. N/N: 2.69%), $t < 1$, no difference was observed between MEAN C/IC and N/N, suggesting that the facilitation and interference effects cancelled each other out.

However, an alternative explanation for this null effect could be that it reflects an inability to process two different movements simultaneously. In order to exclude this possibility, we capitalized on the observation that some subjects were more influenced by congruent than by incongruent movements (facilitation bias), whereas other subjects were more influenced by incongruent than by congruent movements (interference bias). To rule out the alternative hypotheses that neither movements or only one movement was processed when the two hands acted differently, we then computed the correlation between the facilitation bias in the C/IC condition (N/N – C/IC) and the facilitation bias in the IC/C condition (N/N – IC/C). If neither of the movements was processed, no correlation should be observed between the two facilitation

[3] Please note that this code represents the fact that the C/IC and IC/C conditions were averaged.

biases. This is due to the fact that the movements of at least one hand have to be processed in order for a facilitation (or interference) bias to occur. Alternatively, if only one hand movement was processed, the facilitation biases should be correlated negatively. For example, if a certain participant processed only the movements of the left side hand, a facilitation bias should have been apparent in the C/IC condition (N/N – C/IC > 0), but an interference bias should have been apparent in the IC/C condition (N/N – IC/C < 0). Finally, if the movements of both hands were processed, a positive relation should emerge because a facilitation bias in the C/IC condition should still be present in the IC/C condition. The correlation analysis (figure 4) between the two facilitation biases revealed a positive correlation, $r = 0.48$, $p = 0.002$, suggesting that the movements of both hands were represented when they acted differently.

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Discussion

In the current experiment it was explored whether individuals automatically simulate the movements of multiple persons at the same time in the motor system. To this end, we investigated imitative tendencies in a situation where individuals saw two different hands making movements that were congruent or incongruent with respect to the required response. It was hypothesized that automatic imitation should occur for both hands regardless of the action that was performed by the other hand. The results indicated that both hands produced a congruency effect, but that these congruency effects were not independent of one another. Further analyses revealed that, despite the interaction between the two congruency effects, a congruency effect was always present for both hands irrespective of what the other hand did. This suggests that the

actions of each hand influenced *how* the motor system processed the actions of the other hand, but not *if* the motor system processed the actions of the other hand.

Next, it was investigated how the motor system processes two simultaneous observed movements by zooming in on two specific situations, namely the situation in which the two hands made an identical movement and the situation in which the two hands made a different movement. When the two hands made an identical movement, a larger congruency effect was found as compared to when a single hand made a movement. This suggests that the movements of the two hands were mapped onto the same motor representation, causing the motor representation to be activated more strongly. When the two hands made a different movement, one congruent and one incongruent, the results indicated the presence of a concurrent facilitation and interference effect. Specifically, the results suggested that these two opposite effects cancelled each other out. Additional analyses further corroborated this idea by excluding the alternative explanations that neither movements was processed or that only one movement was processed when the two hands acted differently. It thus appears that the actions of both hands were represented in the motor system even when they made different movements.

To summarize, the results of the current study suggest that the actions of multiple observed actors are automatically simulated in the motor system. Importantly, the results of the current study cannot be explained in terms of social facilitation (Zajonc, 1965), which is the phenomenon that individuals perform a task better or worse in the presence of others. That is, a social facilitation account would have predicted an influence of the number of observed movements independent of the content of these movements. The results of the current study, however, clearly showed that seeing two identical movements had a different effect than seeing two different movements. Moreover, a social facilitation account is not able to explain why the influence of seeing two identical movements was dependent on the congruency of the movements

with the required response. It is therefore unlikely that social facilitation caused the effects described above.

Similarly, it is unlikely that the results of the current experiment can be reduced to general features of visual processing. For example, previous research has shown that reactions to bilateral redundant targets are faster than reactions to unilateral targets (e.g., Mooshagian, Kaplan, Zaidel, & Iacoboni, 2008). A crucial difference between these studies and the current study, however, is that these previous studies have investigated the influence of redundant task-relevant stimuli, whereas the current study investigated the influence of redundant task-irrelevant stimuli. That is, in the present study it was found that perceiving two identical movements facilitates motor responses even though the perceived movements were neither relevant nor informative for response selection. For these movements to influence the response selection process, it is therefore necessary to assume a mechanism that automatically links perceived movements to motor responses.

It can, however, be argued that part of the results are due to the fact that two simultaneous observed movements are more salient than a single observed movement. Since earlier research has suggested that attention is an important modulator of automatic imitation (Aicken, Wilson, Williams, & Mon-Williams, 2007; Bach, Peatfield, & Tipper, 2007; Jansson, Wilson, Williams, & Mon-Williams, 2007), it is possible that the stronger congruency effect for two identical observed movements was caused by increased attentional orienting towards the hand stimuli rather than both hand movements activating the same motor representation.

Experiment 2

To rule out the possibility that the stronger congruency effect for two identical observed movements was caused by increased attentional orienting, experiment 2 tested if this effect depended on whether the hands belonged to a human agent or to a non-human agent. According to ideomotor theory, the connection between perception and action depends on the degree to which the observed agent is similar to oneself (Brass, Bekkering, & Prinz, 2001; Brass et al., 2000; Greenwald, 1972). In line with this idea, a number of studies have reported that automatic imitation is stronger for human agents than for non-human agents (Brass et al., 2001; Kilner, Paulignan, & Blakemore, 2003; Longo & Bertenthal, 2009; Press, Bird, Flach, & Heyes, 2005; Press, Gillmeister, & Heyes, 2006, 2007). Consequently, if the stronger congruency effect for two identical observed movements is the result of both movements activating the same motor representation, then this effect should be stronger for human agents than for non-human agents. On the other hand, if this effect is the result of increased attentional orienting, then it should not be different for human and non-human agents. Importantly, this is only the case if the movements of the human and non-human agents are matched on saliency. To account for this, we will compare automatic imitation of human hands with automatic imitation of wooden hands (figure 5). Because the human and wooden hands that were used in this study are highly similar, differences between the two stimulus types cannot be explained in terms of attentional orienting.

However, apart from the possibility that either motor simulation processes or attentional processes explain the stronger congruency effect for two identical observed movements, it is also conceivable that both mechanisms play a role. To address this third option, we will additionally examine whether the congruency effects produced by human and wooden hands follow a different time course. Because attentional capture is likely to operate at early time points (e.g., Klein, 2000) and motor simulation is known to operate primarily at later time points (e.g., Boyer, Longo, & Bertenthal, 2012; Brass et al., 2001; Catmur & Heyes, 2011; Cooper, Catmur, &

Heyes, 2013), this analysis allows us to better understand their contribution in construing the obtained effects.

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Method

Participants. 40 persons participated in the experiment (M_{age} = 24.52, SD_{age} = 6.36). All of them were right-handed females with good or corrected vision. Participants were paid 5 euro and signed an informed consent beforehand. The study was approved by the local Ethical Committee and all procedures were performed in accordance with the ethical standards laid down in the 1964 Helsinki Declaration.

Stimuli and Apparatus. The experiment was programmed in C with Tscope (Stevens et al., 2006). In order to ensure that the human and the wooden hands were filmed from the same angle and with the same light exposure, we created new stimuli (1010 x 544 pixels) according to the procedure of experiment 1 (figure 5). An illusion of movement was again induced by overwriting a picture of the hands in their neutral posture with a picture of the hands in their final posture. Because the abduction movement was mechanically not possible for the wooden hands, they were manipulated digitally. Note that the wooden hands were manipulated in such a way that the abduction movements were of similar magnitude as the abduction movements of the human hands.

In contrast to experiment 1, we did not use the stimuli in which the two hands made a different movement and the stimuli in which neither of the two hands made a movement. The

experiment thus included six possible final hand postures, namely C/N, N/C, IC/N, N/IC, C/C, IC/IC. In order to record responses, we used a custom-made response box that detects when a finger leaves a sensor.

Procedure. The experiment took about 20 minutes and consisted of two phases. In one phase the stimuli depicted two human hands and in the other phase the stimuli depicted two wooden hands. Each phase started with 10 practice trials with feedback, followed by three blocks of each 60 trials without feedback. Each final hand posture was shown 10 times per block, 5 times with W as imperative cue and 5 times with P as imperative cue. After each block, participants had the opportunity to take a break. Trials were presented at random, with the restriction that the same imperative cue could not appear on more than four consecutive trials. The position of the human hands (left/right), the position of the wooden hands (left/right), and the order of the phases (human hands first/wooden hands first) were counterbalanced.

Before the experiment, instructions appeared on the screen. The instructions differed slightly for the two phases. In the human hands phase, the participants were told that they would see two female hands and that these hands would make finger movements. In the wooden hands phase, the participants were told that they would see two wooden hands and that these hands were manipulated digitally to make it seem as if they made finger movements. The instructions further requested to make an abduction movement with the right hand index finger when W appeared on the screen and to make an abduction movement with the right hand little finger when P appeared on the screen. Participants were asked to respond as fast as possible, but without making errors.

Each trial started with a picture of both hands in their neutral posture and a fixation cross at the bottom of the screen for 500 ms. This was followed by the simultaneous presentation of the imperative stimulus and the hands in their final posture for a maximum of 2000 ms or until the response. After an inter-trial interval of 1000 ms, the next trial started.

Data Analysis. All analyses were performed in R (R Development Core Team, 2013). Trials in which the response deadline was exceeded (0.24%) were excluded from all analyses. Furthermore, trials with a RT faster than 100 ms (0.11%) were seen as action slips and were excluded as well. Finally, erroneous trials (4.62%) and trials with a RT slower than 1000 ms (0.59%) were excluded from the RT analysis. P-values of post-hoc tests were corrected for multiple testing (p_c) according to Holm's procedure (Holm, 1979). *T* tests correspond to two-tailed paired samples *t* tests. Partial eta squared (η_p^2) and Cohen's *d* were used as a measure of effect size.

Results

The RTs and error rates were subjected to a 2 (stimulus type: human vs. wooden hands) x 2 (number of hand movements: one vs. two) x 2 (congruency: C vs. IC) repeated measures ANOVA. The **reaction time analysis** (figure 6a, 6b) revealed a main effect of congruency, $F(1, 39) = 95.10$, $p < 0.001$, $d = 1.54$, with slower responses in IC (452 ms) than in C (419 ms). It also indicated a main effect of stimulus type, $F(1, 39) = 6.80$, $p = 0.013$, $d = 0.41$, with slower RTs for the wooden hands (440 ms) than for the human hands (431 ms). The main effect of number of hand movements, however, had no effect on the RTs, $F < 1$. The interaction of stimulus type x number of hand movements was not significant, $F(1, 39) = 1.10$, $p = 0.309$. Furthermore, no interaction of stimulus type x congruency was found, $F < 1$, indicating no difference between the congruency effect produced by the human (35 ms) and the wooden hands (32 ms). In line with experiment 1, the interaction between number of hand movements and congruency was significant, $F(1, 39) = 19.10$, $p < 0.001$, $d = 0.69$. This indicated that the congruency effect

produced by two identical observed movement (40 ms), $t(39) = 9.68$, $p_c < 0.001$, $d = 1.53$, was stronger than the congruency effect produced by a single observed movement (27 ms), $t(39) = 7.94$, $p_c < 0.001$, $d = 1.26$. Importantly, the three-way interaction stimulus type x number of hand movements x congruency was also significant, $F(1, 39) = 5.50$, $p = 0.024$, $d = 0.37$. To further explore this three-way interaction, we analyzed the number of hand movements x congruency interaction separately for the two hand types. For the human hands, a significant interaction was observed, $F(1, 39) = 28.49$, $p_c = 0.001$, $d = 0.84$. Follow-up tests showed that there was a congruency effect both when a single hand made a movement (25 ms), $t(39) = 6.53$, $p_c < 0.001$, $d = 1.03$, and when both hands made an identical movement (45 ms), $t(39) = 9.95$, $p_c < 0.001$, $d = 1.57$, but the effect was stronger when two identical movements were observed. The same interaction did not reach significance for the wooden hands, $F(1, 39) = 2.84$, $p_c = 0.100$, $d = 0.27$, although there was a trend towards a larger congruency effect for two identical observed movements (36 ms), $t(39) = 7.35$, $p_c < 0.001$, $d = 1.16$, than for a single observed movement (29 ms), $t(39) = 7.17$, $p_c < 0.001$, $d = 1.13$.

The **error analysis** (figure 6c, 6d) indicated a main effect of congruency, $F(1, 39) = 45.67$, $p < 0.001$, $d = 1.07$, with more errors in IC (7.19%) than in C (2.24%). The main effect of stimulus type and the main effect of number of hand movements, on the other hand, did not reach significance, both $F(1, 39) \leq 1.83$, both $p \geq 0.184$. The interaction between stimulus type and number of hand movements was not significant, $F(1, 39) = 2.16$, $p = 0.150$. In addition, the interaction between stimulus type and congruency did not show a difference between the congruency effect for the human (5.39%) and the wooden hands (4.52%), $F < 1$. The interaction between number of hand movements and congruency was again significant, $F(1, 39) = 15.01$, $p < 0.001$, $d = 0.61$, with a larger congruency effect when two identical movements were observed (6.30%), $t(39) = 6.98$, $p_c < 0.001$, $d = 1.10$, compared to when a single movement was observed

(3.60%), $t(39) = 5.09$, $p_c < 0.001$, $d = 0.80$. However, the three-way interaction stimulus type x number of hand movements x congruency was not significant, $F < 1$, indicating that the congruency effect for two identical observed movements was equally strong for human (2.47%) and wooden hands (2.94%).

--- Please insert figure 6 about here ---

Finally, to better understand the obtained effects, we examined their time course by means of a **quintile analysis** (Ratcliff, 1979) on the RTs (figure 7). In this analysis, RTs are evenly divided into five bins ranging from fastest to slowest separately for each condition and each participant. The congruency effects (IC – C) that resulted from this procedure were then subjected to a 2 (stimulus type) x 2 (number of hand movements) x 5 (time bin) repeated measures ANOVA combined with Greenhouse-Geisser corrected degrees of freedom for violation of sphericity. Note that we will only report on the results relating to time bin because the remaining results were already discussed above. The main effect of time bin was significant, $F(1.60, 62.31) = 45.67$, $p < 0.001$, $\eta_p^2 = 0.54$, indicating that the congruency effect increased with each quintile (table 1). The interaction between stimulus type and time bin was also significant, $F(1.82, 71.22) = 6.81$, $p = 0.003$, $\eta_p^2 = 0.15$, showing that the congruency effect increased more strongly for the human hands (table 1). The number of hand movements x time bin interaction was not significant, $F < 1$. Finally, a near-significant stimulus type x number of hand movements x time bin three-way interaction was observed, $F(1.35, 52.66) = 3.41$, $p = 0.058$, $\eta_p^2 = 0.08$. Follow-up tests revealed that this three-way interaction reflected the fact that a stimulus type x time bin interaction was present when two simultaneous movements were observed, $F(1.53, 59.76) = 7.02$, $p_c = 0.008$, $\eta_p^2 = 0.15$, but absent when a single movement was observed, $F < 1$.

Further exploration showed that the congruency effect increased with time bin both for human and for wooden hands when one hand made a movement, but not when two hands made a movement. Instead, when two hands made a movement, the congruency effect produced by human hands still increased with time bin, but the congruency effect produced by wooden hands stabilized after the first three bins (table 1). As a result of this pattern, the congruency effect evoked by two identical observed movements was larger than the congruency effect evoked by a single observed movement in all time bins except for the first when participants saw human hands, but only in the first three time bins when participants saw wooden hands (table 1).

--- Please insert table 1 and figure 7 about here ---

Discussion

Experiment 1 revealed a stronger congruency effect when individuals observed two identical movements compared to when they observed a single movement. It was argued that seeing two identical actions triggers the same motor representation and therefore produces a stronger automatic imitation effect. However, an alternative explanation is that two simultaneous observed movements are more salient than a single observed movement and hence attract more attention. To exclude the latter possibility, we conducted a second experiment in which the reported additive effect was compared for human and wooden hands. Specifically, it was reasoned that human and wooden hands are highly similar and that their movements should therefore not differ with respect to attentional capture. Following this line of reasoning, it was argued that the specified additive effect should be equally strong for the two hand types if it is driven by saliency. If it is driven by an ideomotor mechanism, however, it should be stronger for

human hands. That is, ideomotor theory states that the influence of perception on action depends on the degree to which the observed agent resembles the observer. Because wooden hands are non-intentional and non-biological agents, they are expected to produce less automatic imitation than human hands (Brass et al., 2001, 2000; Greenwald, 1972). The results of experiment 2 replicated the finding that two identical observed movements produce a stronger congruency effect than a single observed movement. Importantly, the RT additive effect was found to be present for human hands, but not for wooden hands. This finding speaks against the saliency account and instead suggests that two identical observed movements activate the corresponding motor representation more strongly than a single observed movement.

However, we were not able to replicate previous reports of an overall weaker congruency effect for non-biological compared to biological agents (e.g., Brass et al., 2001; Kilner et al., 2003; Longo & Bertenthal, 2009; Press et al., 2005, 2006, 2007). Furthermore, a discrepancy was observed between the RT additive effect and the error rate additive effect. That is, whereas the RT additive effect distinguished between human and wooden hands, this was not the case for the error rate additive effect. To better understand the obtained pattern, we therefore studied the time course of the congruency effect separately for human and wooden hands by means of a time bin analysis (Ratcliff, 1979). This analysis revealed that the time course was identical when a single movement was observed, but not when two simultaneous movements were observed. While the congruency effect evoked by seeing a single movement increased over time for both human and wooden hands, the congruency effect evoked by seeing two identical actions increased consistently only for human hands. For wooden hands, the congruency effect first increased over time but then stabilized at later stages. As a consequence of this pattern, an additive effect for two identical wooden hand movements was only observed at early time points. To summarize, the results of the time bin analysis suggest that human and wooden hand movements were processed

differently when two simultaneous movements were observed. Specifically, the time course suggests that the additive effect for two identical observed movements was related to saliency for the wooden hands, but to automatic imitation for the human hands. Indeed, previous work has shown that the deployment of attention to salient stimuli occurs very rapidly and decreases over time (e.g., Klein, 2000). Automatic imitation, on the other hand, is known to be weak at early time points and to build up over time (e.g., Boyer et al., 2012; Brass et al., 2001; Catmur & Heyes, 2011; Cooper et al., 2013).

In contrast to the congruency effect produced by multiple agents, however, the congruency effect produced by a single agent appeared to be driven by the same mechanism for biological and non-biological agents. Specifically, the finding that the congruency effect increased in strength over time is consistent with the idea that it reflected automatic imitation (e.g., Boyer et al., 2012; Brass et al., 2001; Catmur & Heyes, 2011; Cooper et al., 2013). To conclude, the results of the time course analysis suggest that human hand movements were simulated regardless of the number of movements, whereas wooden hand movements were only simulated when a single movement was observed. The fact that automatic imitation of wooden hand was unimpaired in the case of single hand movements is in line with a number of previous studies in which automatic imitation of humanlike non-biological agents was not always decreased with respect to biological agents. Press and colleagues (2006), for example, compared automatic imitation of human hand movements with automatic imitation of robot hand movements. When the robot hand was constructed as a human hand with a metal wire wrist, no difference in automatic imitation was found. When the robot hand was constructed as a gripper, however, automatic imitation was stronger for the human hand. Similarly, Longo and Bertenthal (2009) found no difference in automatic imitation of human and computer-generated hand movements unless attention was directed towards the non-biological character of the computer-

generated hand. Finally, in a study by Liepelt, Prinz, and Brass (2010) automatic imitation was stronger for a human hand than for a wooden hand only when the hand performed communicative gestures. Adding to these findings, the results of the current study suggest that differences in motor simulation between biological and humanlike non-biological agents may only become visible in complex social situations where the actions of multiple agents have to be integrated.

The question still remains, however, why the error rate additive effect was not different for human and wooden hands. A likely explanation is that this is due to differences in response time between error and correct responses. That is, errors are known to coincide with early responses (e.g., Rabbitt, 1966) as they often reflect impulsive responses delivered before the relevant stimulus was completely processed (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). In the current study, RTs of erroneous responses (398 ms) were indeed significantly faster than RTs of correct responses (439 ms), $t(39) = -5.16$, $p < 0.001$. Given that the additive effect for two identical observed movements only differentiated between human and wooden hands for later responses, it is probable that the error rate analysis was unable to detect this difference.

To conclude, the findings of experiment 2 replicate the findings of experiment 1 and show that the additive congruency effect for two identical observed actions is possibly driven by saliency on fast responses but by automatic imitation on late responses. As such, experiment 2 further supports the idea that the actions of multiple agents are automatically simulated in the motor system of the observer.

General Discussion

The aim of the current study was to investigate whether individuals automatically simulate the actions of multiple actors in their motor system. In order to address this question, we adapted a well-known automatic imitation paradigm to include two observed hands instead of one observed hand. In experiment 1, it was found that individuals automatically imitated the movements of both observed hands. In addition, it was found that two identical observed movements produced a stronger automatic imitation effect than a single observed movement and that two different observed movements produced a concurrent facilitation and interference effect that cancelled each other out.

However, an alternative explanation for the finding that two identical observed movements produced a stronger automatic imitation effect is that two simultaneous movements attracted more attention than a single movement. To exclude an explanation in terms of salience, experiment 2 examined if the additive effect for two identical observed movements differed between human and wooden hands. It was reasoned that the effect should be equally large if it was driven by salience, but smaller for the wooden hands if it was driven by an ideomotor mechanism. In line with the ideomotor explanation, the results demonstrated that the additive effect for two identical observed movements was stronger for human than for wooden hands. This supports the idea that two identical observed movements are mapped onto the same motor representation and therefore activate this representation more strongly.

Parameters of the Multi-Actor Ideomotor Mechanism

While the current study provides support for the idea that the actions of multiple individuals are simulated automatically in the motor system, important questions remain with respect to the different parameters that influence the involvement of the motor system in multi-

actor situations. For example, one important question is whether the motor system differentiates between two observed actions performed by different individuals and two observed actions performed by the same individual (e.g., bimanual actions). While this is the first study to investigate how the actions of multiple actors are processed in the motor system, two studies have already investigated the involvement of the motor system in bimanual action observation. In one study, it was compared how the brain responds to unimanual and bimanual observed actions (Heitger, Mace, Jastorff, Swinnen, & Orban, 2012). It was found that bimanual observed actions activate the motor system with the same strength as unimanual observed actions, but do so more bilaterally. In another study, weak bilateral motor activation was observed when the involvement of the motor system was measured with TMS while ignorant participants observed symmetrical bimanual language signs (Möttönen, Farmer, & Watkins, 2010). These studies thus suggest that the observation of bimanual actions affects the lateralization of the motor response rather than its strength. Given the different methods and paradigms, it is not evident to compare these results with the results of the current study. However, the finding of the current study that the strength of the motor response was dependent on the number of individuals that performed a certain action may point towards a difference in processing the actions of the same individual and the actions of different individuals. Further research should directly compare these two situations to better understand if and how the brain distinguishes between them.

Another parameter that may influence the activation in the motor system is the synchronicity of the observed movements. Herrmann and colleagues (2013), for example, observed that children have an increased tendency to imitate behavior when the behavior is demonstrated by two models compared to a single model. Interestingly, two models increased imitative tendencies both when the models performed the behavior in synchrony and when they performed the behavior consecutively, but the effect was stronger for two synchronous models.

This suggests that identical actions trigger the motor system more strongly when they are performed without delay.

Finally, the activation of the motor system may depend on the amount of observed actors. In the study of Milgram and colleagues (1969), for example, it was shown that the probability of imitation increased with the amount of observed actors. However, the degree to which an additional actor increased the probability of imitation decreased when the group of observed actors became larger. This suggests that a curvilinear relation may exist between the number of observed actors that perform an identical movement and the activation in the motor system.

Implications of the Multi-Actor Ideomotor Mechanism

The finding that individuals automatically represent the actions of multiple agents simultaneously in the motor system may have important implications for the understanding of the neurocognitive mechanisms that support social interaction. That is, while previous research has ascribed an important role to motor simulation in social interaction (e.g., Knoblich & Sebanz, 2006), its social function has so far only been investigated in dyadic situations. The findings of the current study allow us to extend the social function of motor simulation to multi-actor social situations.

An important social skill that relies on the ideomotor mechanism, for instance, is the ability to execute joint actions (e.g., Colling et al., 2013; Knoblich & Sebanz, 2006). In joint action tasks, it is imperative that individuals are able to adapt their behavior to the actions of others. In a tennis game, for example, a player can anticipate the end location of the ball by combining information about the kinematics and the strength of the opponent's shot. An efficient way to do this is to simulate the actions of the opponent in one's motor system. However, a tennis

game can also be played in team with another player. In such games, each player has to take into account the actions of three other players, namely one team member and two opponents. To decide where to run when an opponent hits the ball, it is now not only important to monitor the kinematics and strength of the opponent's shot, but also to monitor the behavior of the team member. The current study opens up the possibility that multi-actor joint action tasks, such as a doubles tennis game, depend on the ability of individuals to simulate the movements of multiple actors simultaneously in the motor system. An interesting avenue for further research is therefore to explore the involvement of the motor system in joint action tasks that exceed a dyadic structure.

In addition to the field of joint action, the current research may also have implications for imitation research. While most research on imitation has examined imitation in a context where one imitator copies the action of one agent, some studies have also started to investigate imitation in a context with multiple agents (Herrmann et al., 2013; Milgram et al., 1969; Tsai et al., 2011). In two of these studies, it was found that that the probability of imitation is related to the number of observed actors (Herrmann et al., 2013; Milgram et al., 1969). As an explanation, these studies argued that interpretative processes mediate the effect of the number of observed actors on imitative tendencies. The current study, on the other hand, suggests that these effects are not mediated by interpretative processes but by the degree to which the relevant ideomotor representation is activated. That is, in the current study the relation between the number of agents and imitative tendencies was explored in a situation where interpretative processes are unlikely to have played a role. Nevertheless, automatic imitation was found to depend on the number of agents that performed a certain movement. The current study thus suggests that an action performed by multiple people is imitated more often because this activates the corresponding ideomotor representation more strongly. This mere motor activation could then trigger

interpretative processes (e.g., "does the behavior make sense?") that determine whether the evoked action is eventually executed or inhibited. However, in this view, interpretative processes are not the antecedent but the consequence of imitative tendencies.

To conclude, the current study provides evidence for the idea that individuals automatically simulate the actions of multiple observed agents in the motor system. Given the fact that motor simulation is deeply rooted in social cognition (Knoblich & Sebanz, 2006), this finding may increase our understanding of the neurocognitive mechanisms that support multi-agent social interactions.

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Figures

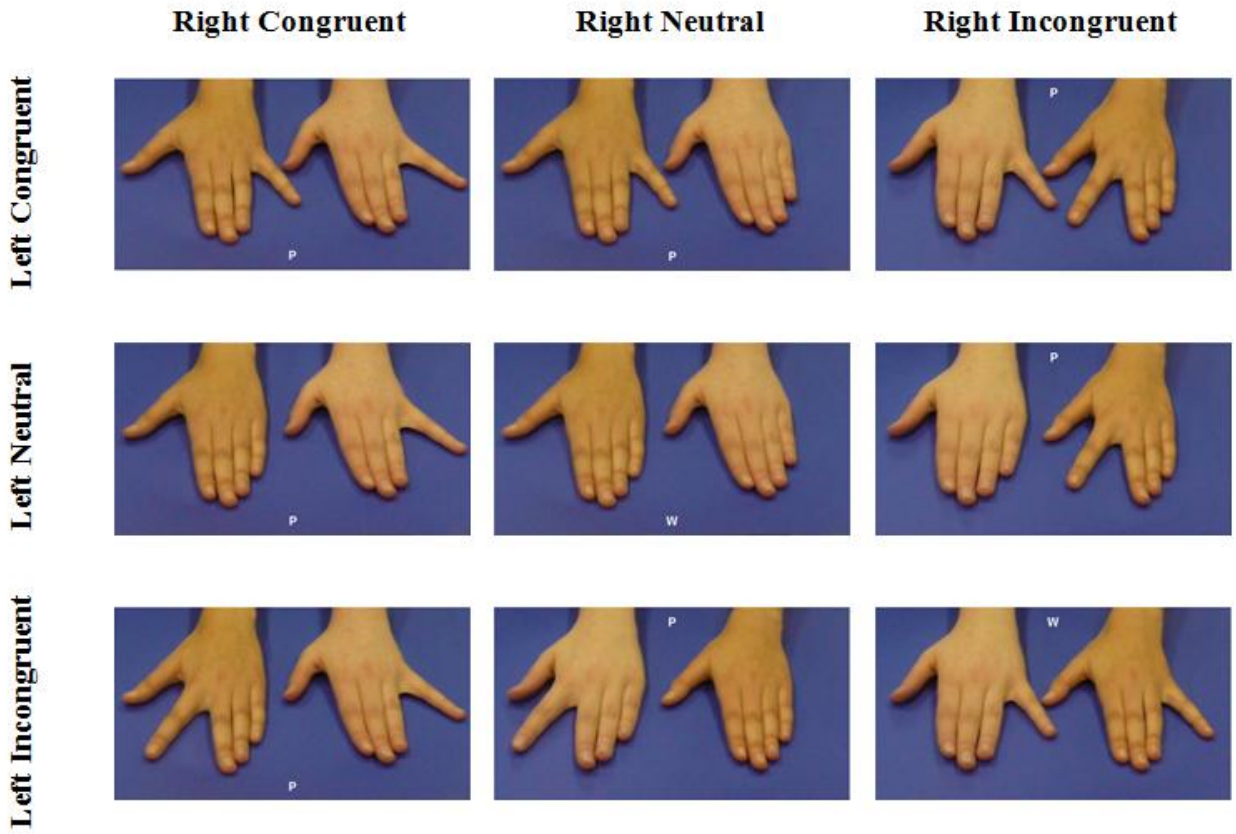

Figure 1.

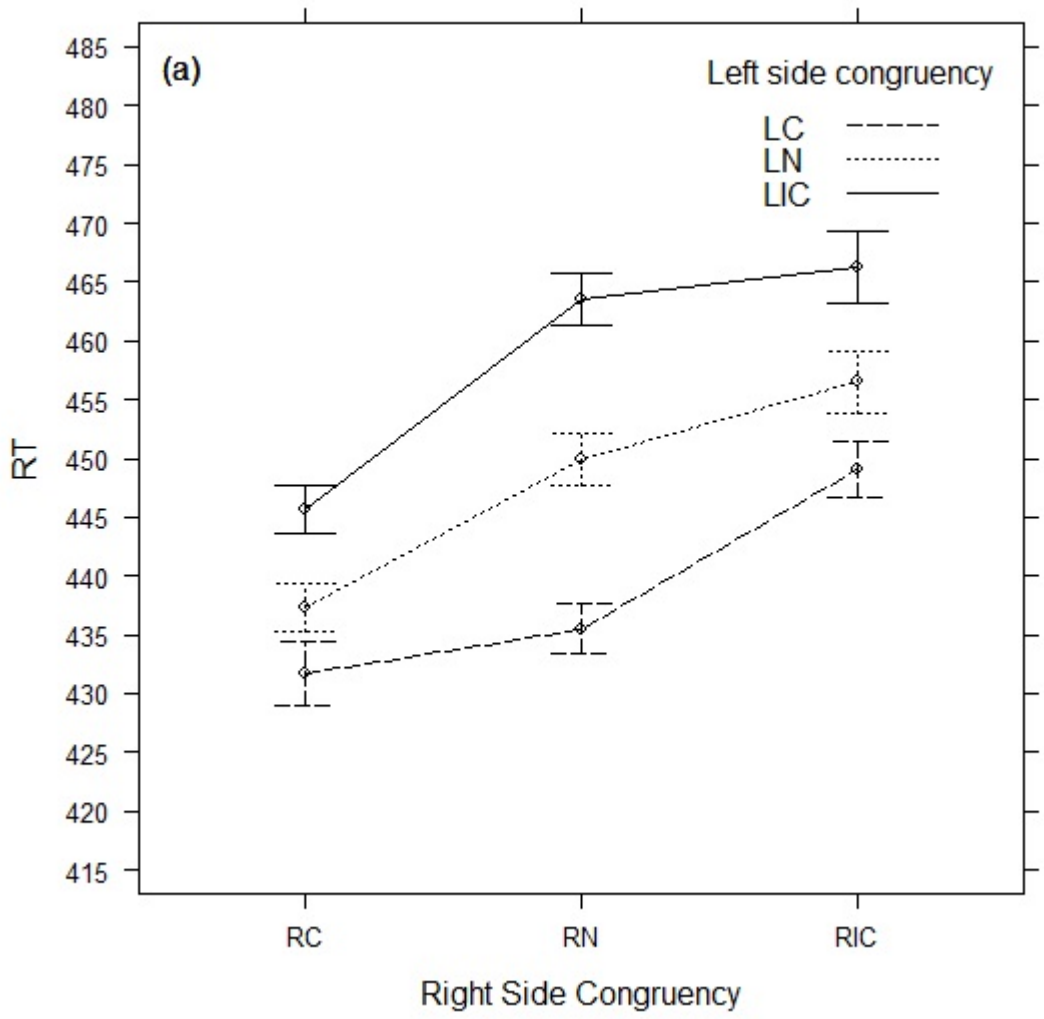
(a)
Left side congruency
LC
LN
LIC
RT
485
480
475
470
465
460
455
450
445
440
435
430
425
420
415
RC
RN
RIC
Right Side Congruency

Figure 2a.

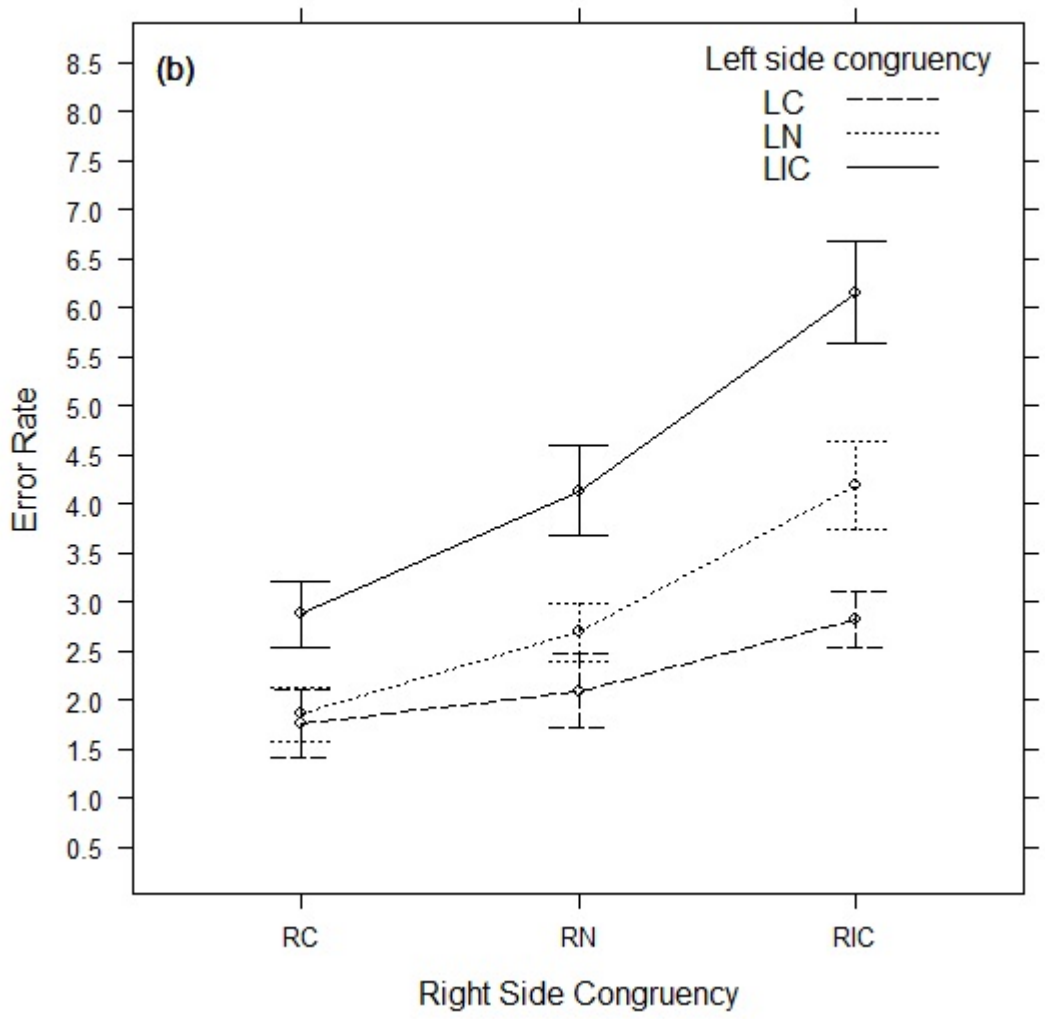
(b)
Left side congruency
LC
LN
LIC
Error Rate
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
RC
RN
RIC
Right Side Congruency

Figure 2b.

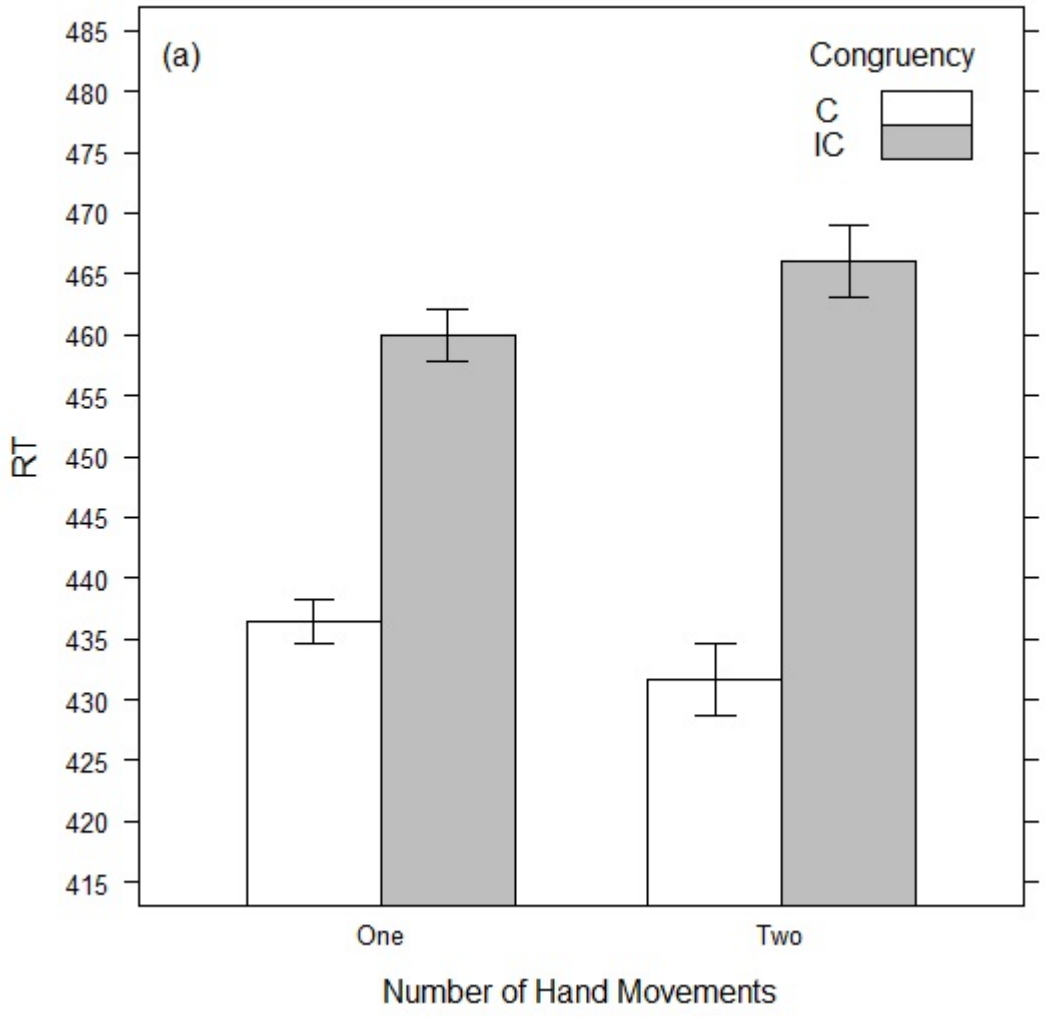
(a)
Congruency
C
IC
RT
485
480
475
470
465
460
455
450
445
440
435
430
425
420
415
One
Two
Number of Hand Movements

Figure 3a.

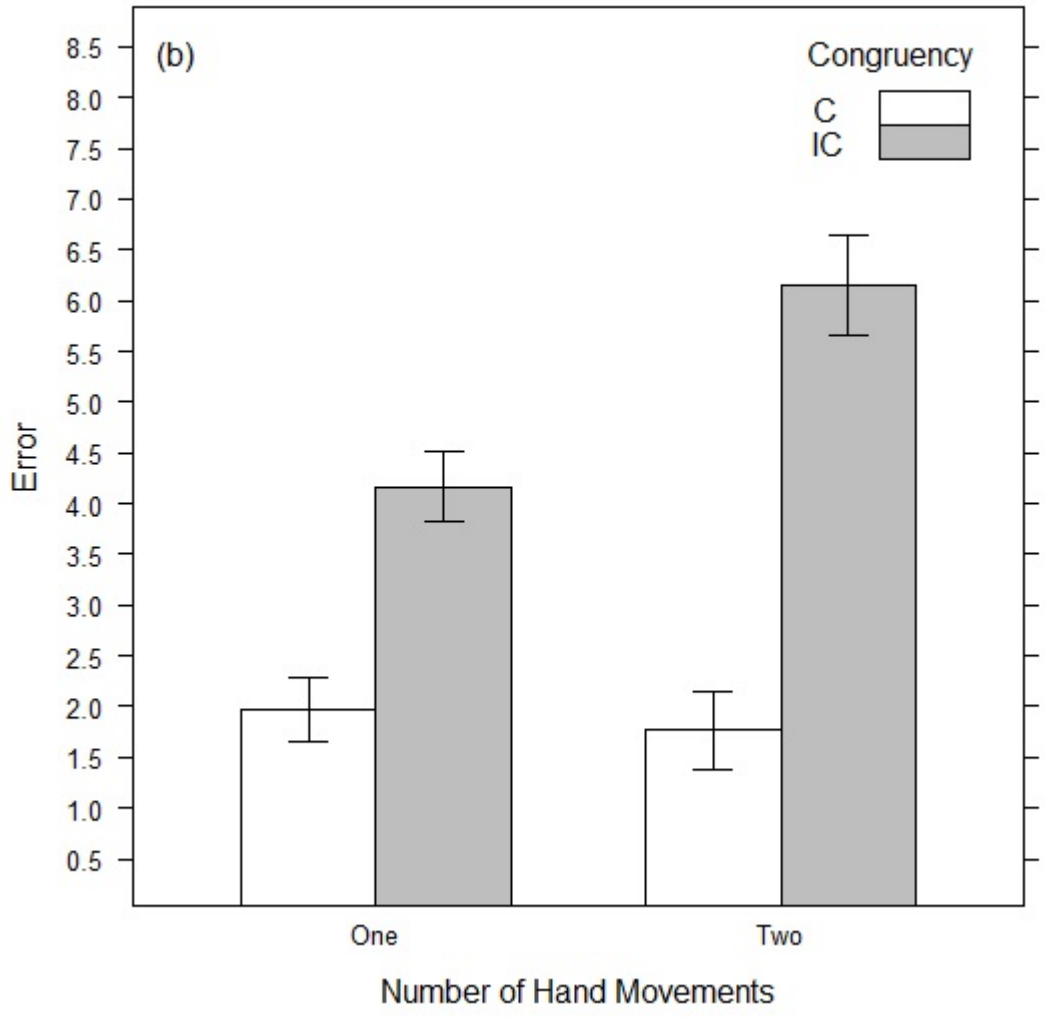
(b)
Congruency
C
IC
Error
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
One
Two
Number of Hand Movements

Figure 3b.

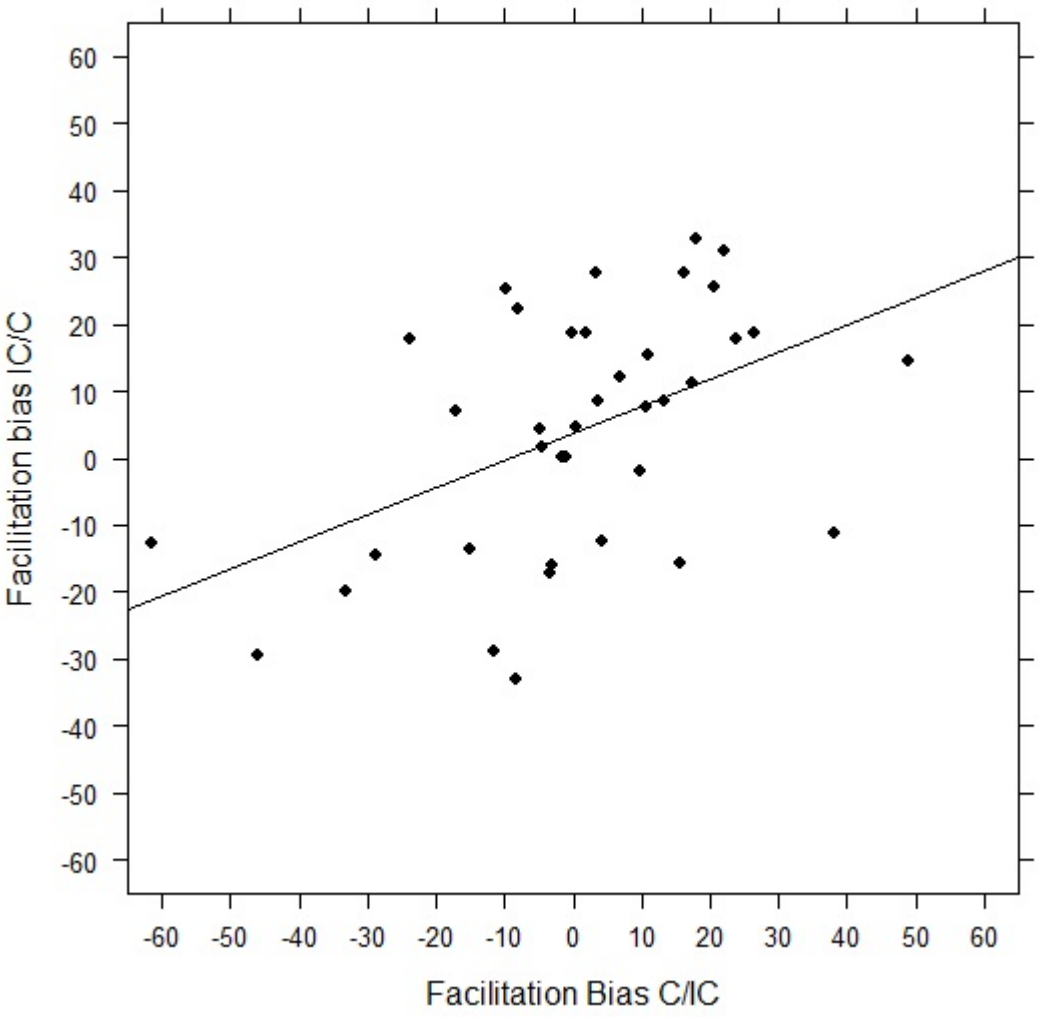
Facilitation bias IC/C
Facilitation Bias C/IC
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60

Figure 4.

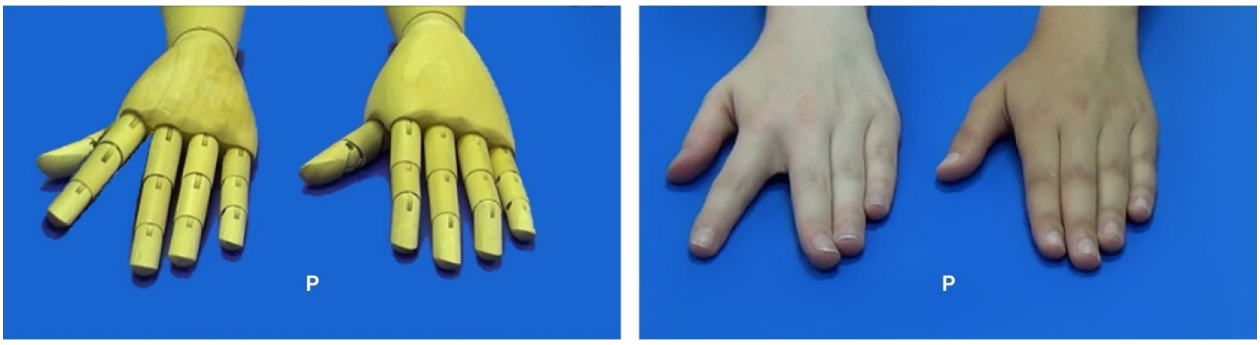

Figure 5.

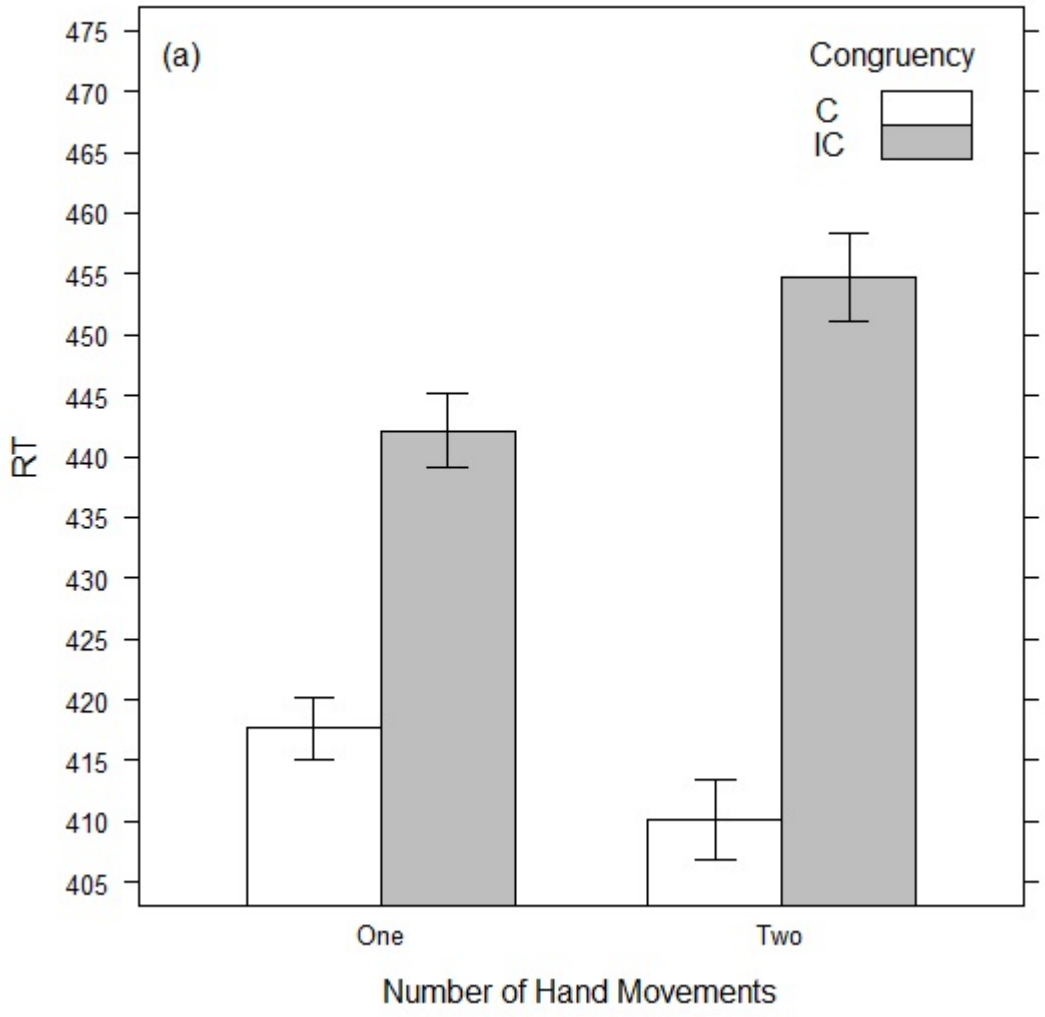
(a)
Congruency
C
IC
RT
475
470
465
460
455
450
445
440
435
430
425
420
415
410
405
One
Two
Number of Hand Movements

Figure 6a.

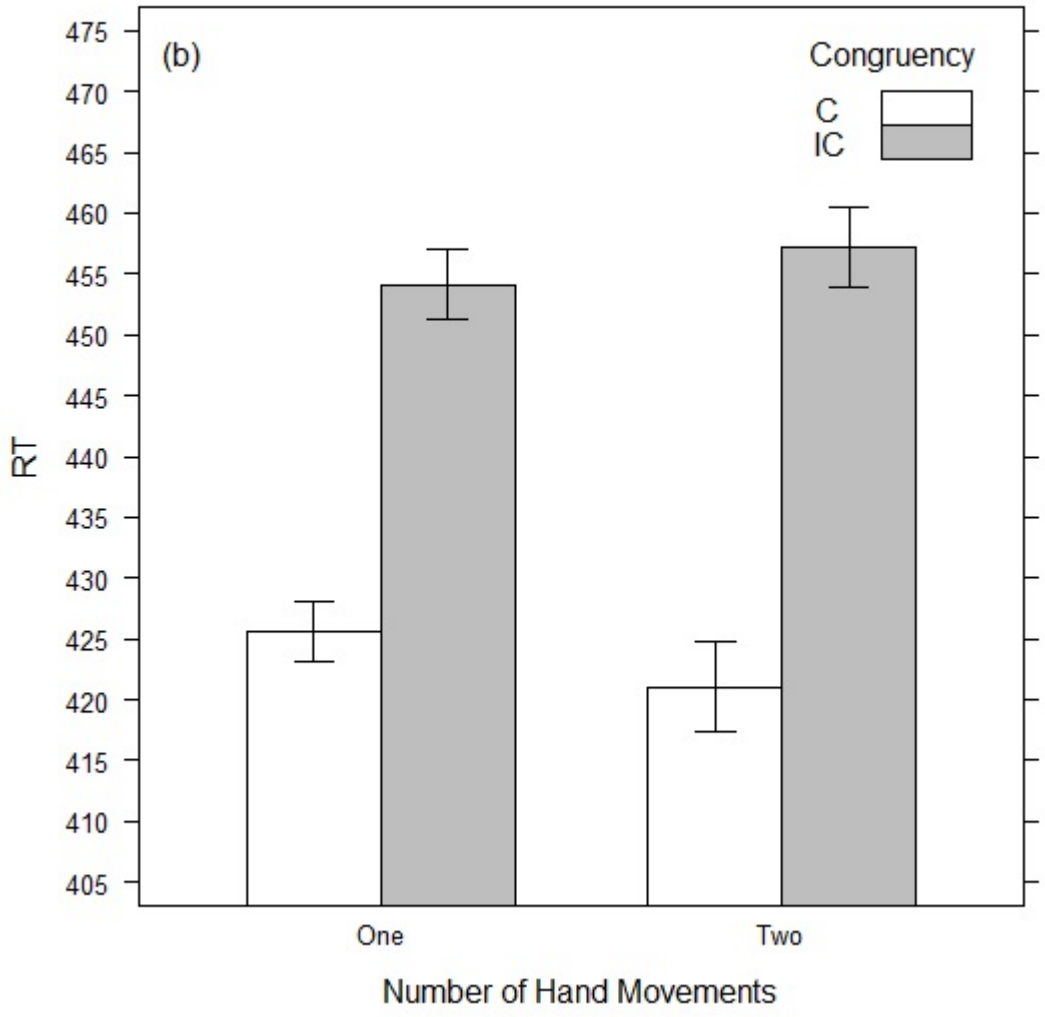
(b)
Congruency
C
IC
RT
475
470
465
460
455
450
445
440
435
430
425
420
415
410
405
One
Two
Number of Hand Movements

Figure 6b.

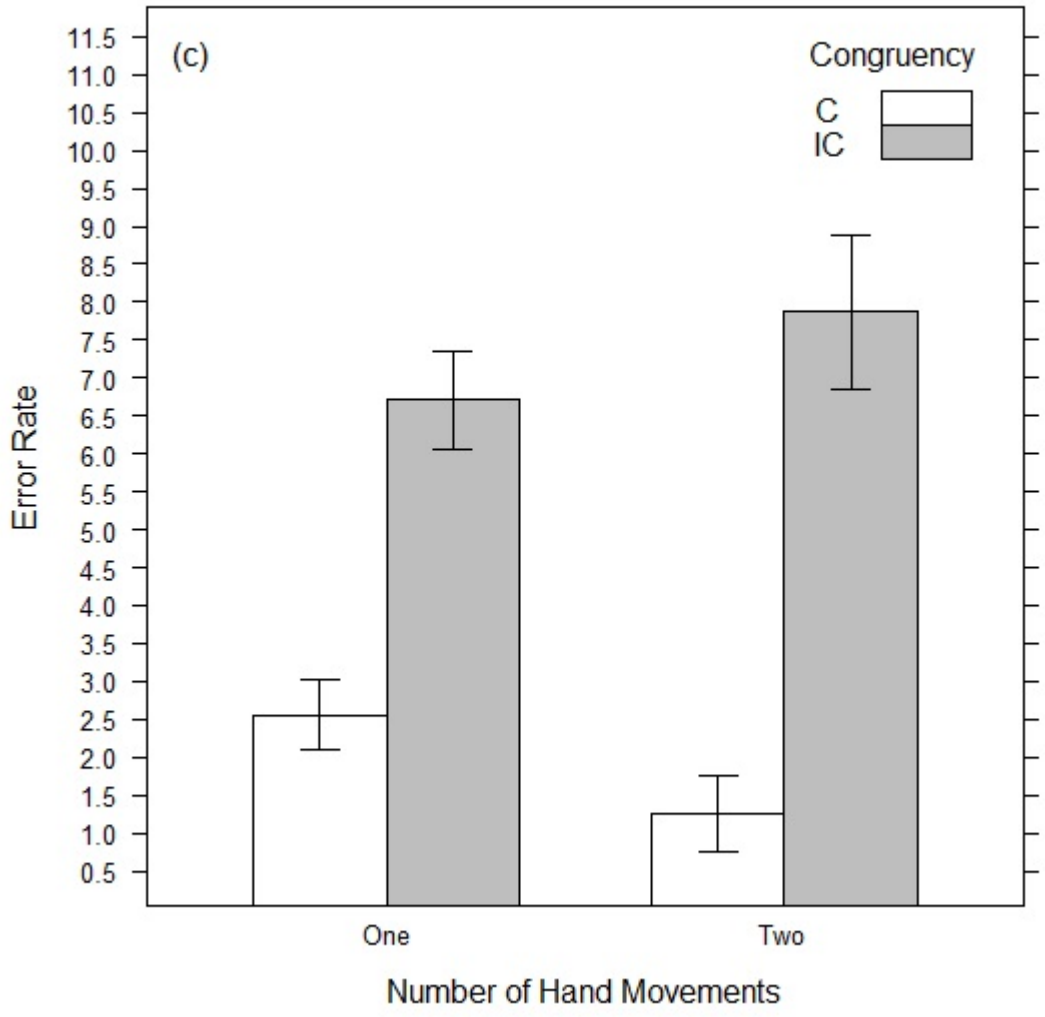
(c)
Congruency
C
IC
Error Rate
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
One
Two
Number of Hand Movements

Figure 6c.

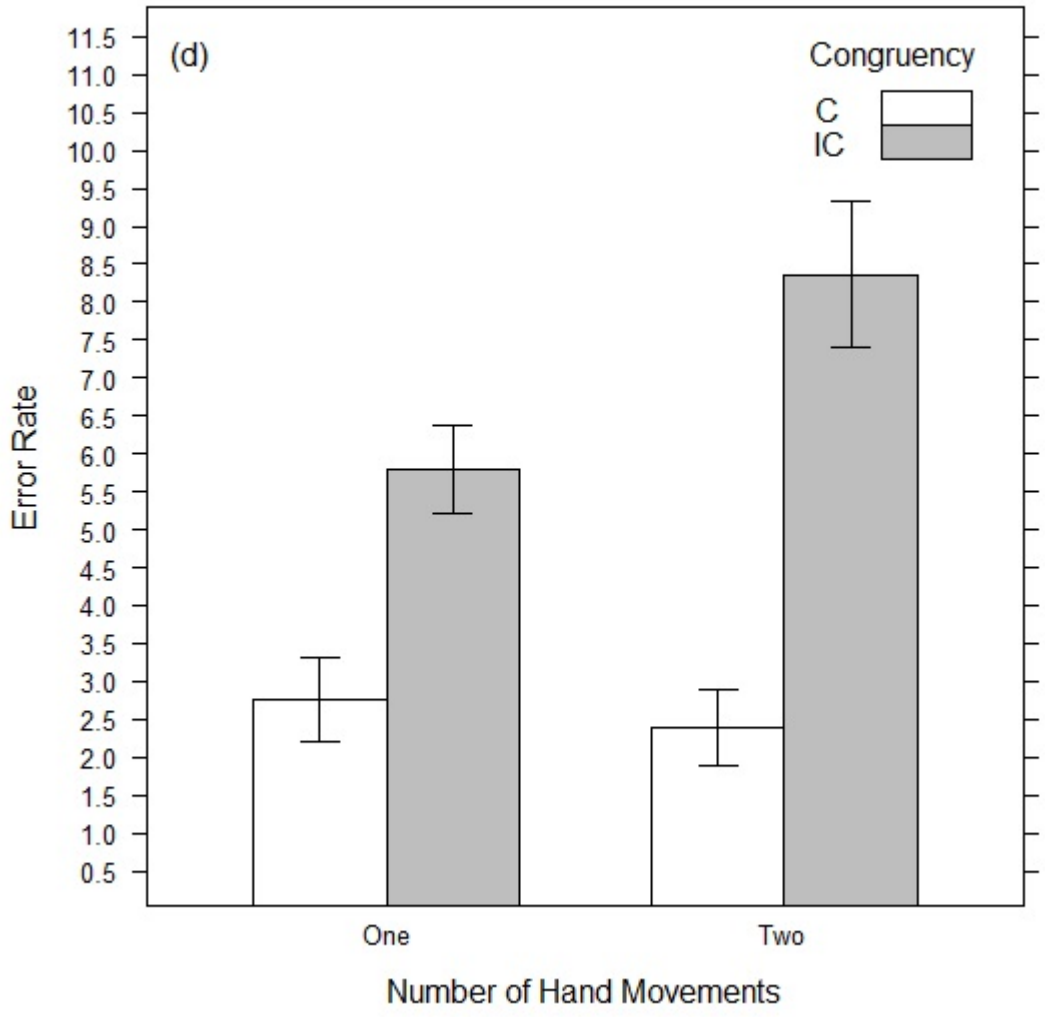
(d)
Congruency
C
IC
Error Rate
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
One
Two
Number of Hand Movements

Figure 6d.

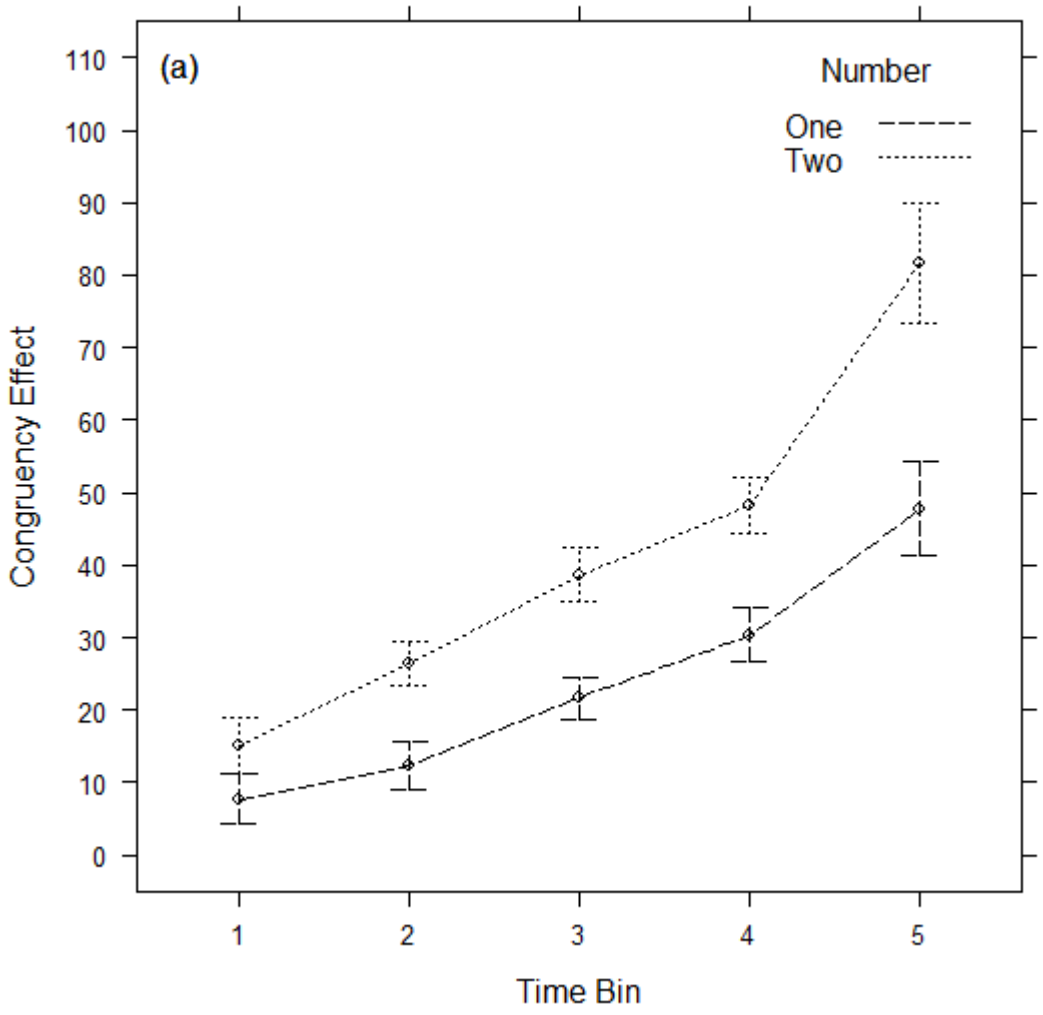
(a)
Number
One
Two
Congruency Effect
Time Bin
0
10
20
30
40
50
60
70
80
90
100
110
1
2
3
4
5

Figure 7a.

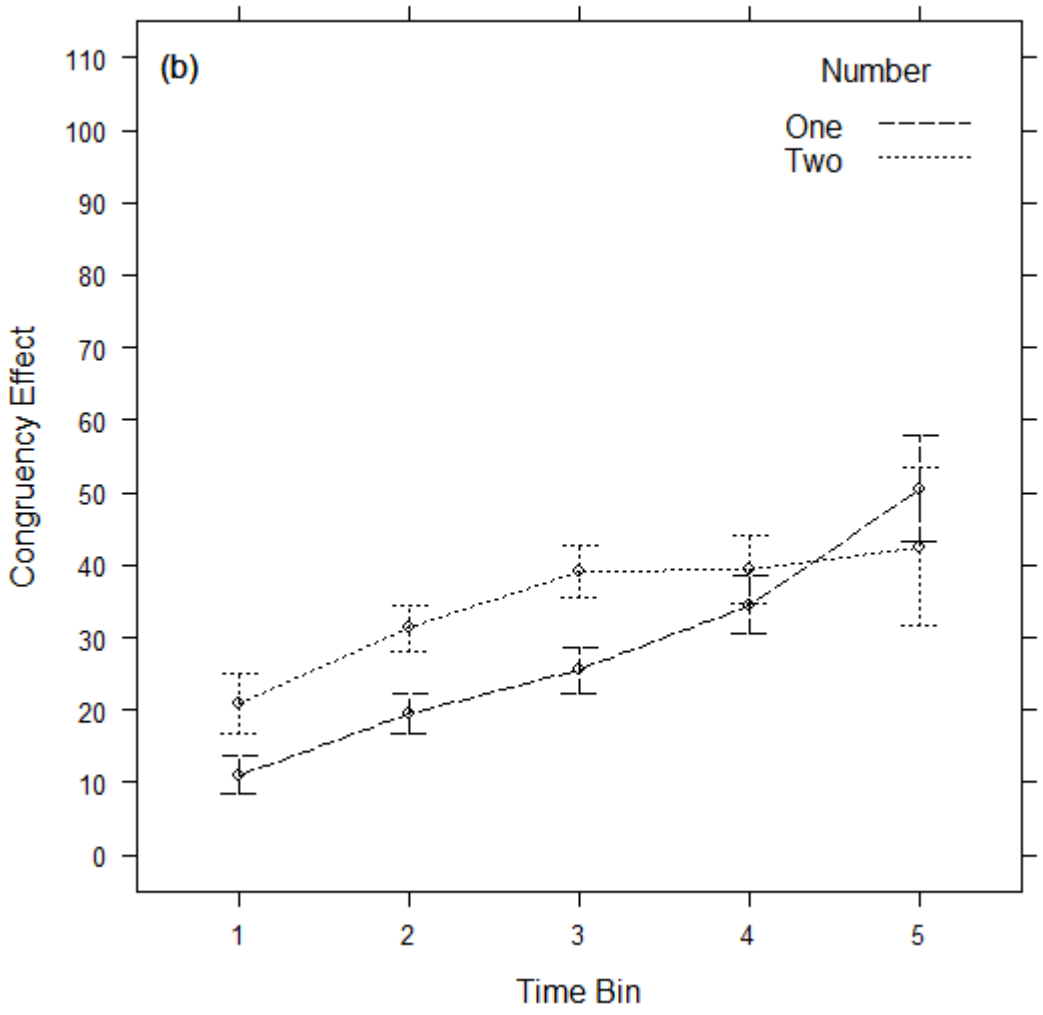
(b)
Number
One
Two
Congruency Effect
Time Bin
0
10
20
30
40
50
60
70
80
90
100
110
1
2
3
4
5

Figure 7b.

Figure Captions

Figure 1. The design of experiment 1. Each cell contains an example stimulus for the corresponding condition.

Figure 2. Experiment 1 reaction times (a) and error rates (b) of the left side congruency x right side congruency analysis. Error bars represent standard errors of the mean (SEMs) corrected for within-subject designs according to Morey (2008).

Figure 3. Experiment 1 reaction times (a) and error rates (b) of the number of hand movements x congruency analysis. Error bars depict SEMs corrected for within-subject designs according to Morey (2008).

Figure 4. Experiment 1 correlation between the facilitation bias in the C/IC condition and the IC/C condition. The line represents a linear regression fit line.

Figure 5. Example stimuli of experiment 2.

Figure 6. Experiment 2 reaction times (a) and error rates (b) for the human hands and experiment 2 reaction times (c) and error rates (d) for the wooden hands. Error bars depict SEMs corrected for within-subject designs according to Morey (2008).

Figure 7. Experiment 2 reaction time congruency effects (IC – C) for the human hands (a) and for the wooden hands (b) separately for time bin. Error bars depict SEMs corrected for within-subject designs according to Morey (2008).

Tables

Table 1.

Results of the quintile analysis.

	Bin 1		**Bin 2**		**Bin 3**		**Bin 4**		**Bin 5**
Human Hands									
One	7.78	†	12.27	***	21.69	**	30.41	**	47.79
			**		**		**		**
Two	15.12	**	26.50	**	38.68	**	48.32	***	81.64
Wooden Hands									
One	11.10	**	19.51	*	25.50	***	34.53	*	50.55
	†		*		*				
Two	20.94	*	31.28	**	39.10		39.34		42.53

Note. Each cell displays the mean congruency effect (IC – C) in ms. In between the cells is shown whether the respective conditions differ significantly after applying Holm's correction for multiple testing (Holm, 1979). Significance is denoted as follows: †$p < 0.10$, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Appendix: Left Side Congruency x Right side Congruency Interaction (Experiment 1)

In this appendix, we will explore the left side congruency x right side congruency effect reported in experiment 1 separately for RTs and error rates. In addition, we will provide an interpretation for the obtained pattern.

Reaction Times

With regard to RTs, it appears from figure 2a that the interaction was driven by a stronger congruency effect under RN than under RC or RIC. This was supported by post-hoc analyses that showed a stronger left side congruency effect (LIC – LC) under RN (28 ms) than under RC (14 ms), $t(37) = 3.58$, $p_c = 0.003$, $d = 0.58$, and a trend towards a stronger left side congruency effect under RN than under RIC (17 ms), $t(37) = 2.14$, $p_c = 0.078$, $d = 0.35$, but no difference between the left side congruency effect under RC and under RIC, $t(37) < 1$.

Error Rates

With regard to error rates, figure 2b suggests that the left side congruency effect was stronger under RIC than under RC or RN and that the right side congruency effect was stronger under LIC than under LC or LN. Follow-up tests for the left-side congruency effect supported this visual analysis by showing a stronger left side congruency effect (LIC – LC) under RIC (3.33%) than under RC (1.11%), $t(37) = 3.34$, $p_c = 0.006$, $d = 0.54$. However, no stronger left side congruency effect was found under RIC than under RN (2.03%), $t(37) = 1.93$, $p_c = 0.122$, $d = 0.31$. Likewise, the left side congruency effect did not differ between RC and RN, $t(37) = 1.24$, p_c

= 0.225, d = 0.20. Similar to pattern for left side congruency, follow-up tests for the right side congruency effect revealed that the right side congruency effect (RIC – RC) was stronger under LIC (3.27%) than under LC (1.06%), $t(37) = 3.34$, $p_c = 0.006$, $d = 0.54$, but not stronger than under LN (2.34%), $t(37) = 1.23$, $p_c = 0.226$, $d = 0.20$. No difference was observed between the right side congruency effect under LC and under LN, $t(37) = -1.87$, $p_c = 0.139$, $d = 0.30$.

Interpretation

A possible explanation for the RT interaction pattern could be that there was a processing bias for the right side hand. That is, it was found that the left side congruency effect was strongest when the right side hand did not move. This suggests that the actions of the right side hand hindered the processing of the left side hand. One reason for such a right side hand bias could be that the right side hand was more similar to the response hand (i.e., the right hand). This could have caused the actions of the right side hand to attract more attention than the actions of the left side hand, leading to a reduced left side congruency effect when the right side hand moved.

This interpretation can, however, not easily explain the interaction pattern for the error rates. That is, for the error rates we found a stronger congruency effect when the other hand performed an incongruent action. A look at figure 2b suggests that this was mainly driven by an imbalance in the additive effect for two identical observed movements (see also figure 3b). That is, while there was a strong additive effect for two identical incongruent actions (IC/IC) compared to a single incongruent action (IC/N or N/IC), $t(37) = 3.60$, $p < 0.001$, $d = 0.58$, there was virtually no additive effect for two identical congruent actions (C/C) compared to a single congruent action (C/N or N/C), $t < 1$. A likely explanation for this finding is that there was a floor

effect: two congruent actions may not have decreased the error rate because it was already very low for a single congruent action.

The interaction thus appears to have a different cause for RTs and error rates. While the RT interaction seems to reflect a right side hand bias, the error rate interaction seems to reflect an imbalance in the additive effect for two identical observed movements.