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Motion coordination affects movement parameters in a joint pick-and-place task

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This study examined influences of social context on movement parameters in a pick-and-place task. Participants' motion trajectories were recorded while they performed sequences of natural movements either working side-by-side with a partner or alone. It was expected that movement parameters would be specifically adapted to the joint condition to overcome the difficulties arising from the requirement to coordinate with another person. To disentangle effects based on participants' effort to coordinate their movements from effects merely due to the other's presence, a condition was included where only one person performed the task while being observed by the partner. Results indicate that participants adapted their movements temporally and spatially to the joint action situation: Overall movement duration was shorter, and mean and maximum velocity was higher when actually working together than when working alone. Pick-to-place trajectories were also shifted away from the partner in spatial coordinates. The partner's presence as such did not have an impact on movement parameters. These findings are interpreted as evidence for the use of implicit strategies to facilitate movement coordination in joint action tasks.

Keywords: Joint action; Movement control; Interpersonal coordination; Social facilitation; Social cognition.

Imagine the following situation: You are, together with a group of other cooperative people, helping the host of a party to put dirty glasses into the dishwasher. Although many hands reach into the dishwasher at the same time, you do not collide with any of them, but manage well to bring the glasses to their appropriate positions. This apparently simple example of an everyday task shows how well people perform in coordinating their movements and actions with one another. However, our knowledge about the underlying mechanisms of this astonishing ability is far from complete. Activities like loading the dishwasher or shaking hands, but also more complex ones like rowing a boat together or agreeing to meet at the library entrance at 4 p.m., are called joint action tasks (Sebanz, Bekkering, & Knoblich, 2006). However, while research on the more

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cognitive aspects of joint action (e.g., Knoblich & Jordan, 2003; Sebanz, Knoblich, & Prinz, 2005) or the unconscious coordination of movements (e.g., Richardson, Marsh, & Schmidt, 2005; Schmidt, Carello, & Turvey, 1990) has flourished, relatively little experimental work has been done on how two or more humans actually coordinate their movements to perform actions in physical space and how their movement parameters are affected by the interaction (Sebanz et al., 2006).

One exception is a study by Meulenbroek and colleagues (Meulenbroek, Bosga, Hulstijn, & Miedl, 2007) that investigated whether movement kinematics are adopted from an interaction partner by simple observation. The task for pairs of participants was to one after the other grasp and transport objects of variable weight to different locations on a table. The authors assumed that the second person in the action may copy and adapt movement dynamics of the partner (e.g., the velocity) to her own lifting movements. Results showed no evidence for such a direct movement transfer although some information about the first person's grasping was indeed integrated into the partner's movement planning. This manifested in a reduced "surprise effect" in the sense that a change of object weight from one trial to the next (e.g., from heavy to light) produced a strong effect in the first person (i.e., she lifted the object too high), which occurred to a systematically lesser degree in the second person. This suggests that people are principally able to transform observed action parameters into expectations about physical object properties, but that this does not necessarily include a direct transfer of the partner's kinematics to their own movement.

A study by Castiello and colleagues (Georgiou, Becchio, Glover, & Castiello, 2007) investigated the impact of the type of social context in which a movement occurs on an individual's movement kinematics. Specifically, the influence of cooperation versus competition was compared in a reach-to-grasp movement. Two participants sat opposite each other and had to place wooden blocks in the middle of the table. In the cooperation task, this was to be achieved together in the sense that the two blocks formed a geometrical pattern. In the competitive task, the goal was to place one's own block in the middle of the table first. Results revealed that participants' kinematics of the preparatory reach-to-grasp movement (i.e., the movement prior to any interaction with the other person) were modulated by the type of social context. Movements were performed with a higher peak velocity in the competitive task than in the cooperative task. Moreover, in a follow-up experiment in which the motivation to take the other person into account was increased by instructing participants to place the wooden blocks on top instead of next to each other, high correlations between certain movement kinematics were found in the cooperative task, suggesting that participants attuned their performance to the partner.

How does such *attuning* of movements come about? Based on a variety of different theories suggesting internal processes that predict—via internal modelling (e.g., Wolpert, Doya, & Kawato, 2003), simulation (e.g., Wilson & Knoblich, 2005), or mirroring (e.g., Gallese, Keysers, & Rizzolatti, 2004; Rizzolatti & Craighero, 2004)—what the future action or action outcome of another person will be, it can be assumed that anticipating the partner's performance is crucial for smooth interaction. In order to tune one's own movements and actions to a partner, it is important to refer to the future rather than to the actually observed behaviour of the partner and to plan one's own behaviour with respect to what the partner is most likely going to do. Especially when the timing of actions is crucial, prediction might become the only way to achieve coordination because responding to the partner's actual actions will not be fast enough. Thus, own action planning and execution need to integrate predictions of what the other person will be doing before the actual action can be observed.

A study by Knoblich and Jordan (2003) supports this idea by showing that the ability to anticipate what a partner is doing can facilitate interaction and improve task performance. In their study, pairs of participants worked on a tracking task that required them to perform complementary actions. A moving target on a computer screen had to be tracked by pressing keys in order to either accelerate or decelerate the tracking cursor. The two actions were distributed between the two participants. In order to successfully track the target, participants had to work together in a narrow time window. Results indicated that participants learned to predict their partner's actions and used this information in an anticipatory control strategy to improve overall tracking performance. Further evidence for anticipatory behaviour has come from, for example, eye-tracking studies (Flanagan & Johansson, 2003).

Besides anticipation and motion coordination, social aspects may also affect human performance in joint action tasks. In particular, human behaviour observed in joint task performance may be influenced by so-called social facilitation effects. Social facilitation describes the finding that the presence of another person has an influence on individual performance. In easy tasks performance is often enhanced, whereas in more difficult or unlearned tasks the presence of others can lead to decreased task performance compared to when acting alone (Aiello & Douthitt, 2001; Bond & Titus, 1983). Explanations for this effect range from drive theories, which basically postulate elevated drive levels in the presence of others, which leads to the observed effects (Zajonc, 1965), to theories about the individual's concerns in a comparison situation (Cottrell, 1972), to more cognitive theories suggesting that cognitive processing capacities are influenced—for example, due to increased distraction by the other's presence (Baron, 1986). In order to account for this effect, some joint action studies include several social conditions. For example, in the above-described study by Georgiou et al. (2007), performance in a joint condition was compared to a single condition and to a condition in which an individual acted in the presence of a passive observer. As the authors did not find any significant differences between the observed and unobserved individual conditions, they concluded that the results obtained in the critical comparison between single and joint action were not based on social facilitation effects.

The present study was conducted to examine temporal and spatial adaptation to a social context during a whole sequence of naturally performed pick-and-place movements. Thus, the task stands in contrast to the frequently used motor control tasks in which only one reach-to-grasp movement is performed at a time (e.g., Meulenbroek et al., 2007). In our case, a more complex movement sequence was chosen because, first, the focus of the present study lies on the influence of the social context on actual movement execution (rather than on movement planning as in Georgiou et al., 2007) and, second, because it was intended to investigate human coordination and adaptation in an environment as natural and unconstrained as possible, while still being able to carefully control task parameters.

For this purpose, an experimental paradigm was developed (Schubö, Vesper, Wiesbeck, & Stork, 2007; Vesper, Stork, & Schubö, 2008) in which pairs of participants built a ball track (a children's game to let marbles run down a track that can be constructed in various ways) made from wooden bricks while their movement trajectories were recorded and compared in a situation when one person worked on the task alone versus when two persons performed the task together. This specific task was chosen because it required participants to cooperate and take the other person's (or, in the single conditions, other hand's) movements into account. In a pilot study using this paradigm, participants' movements were observed to be faster when working together than when working alone (Vesper et al., 2008). We suggested that this may indicate a strategy that participants used to facilitate joint action coordination.

The present study examined this finding in detail and contrasted it with an alternative explanation based on social facilitation. Three types of social context were compared: Besides a joint condition, in which two people actually worked together, and a single condition, in which one person worked on her own, a third condition was added in which one person worked alone, but was observed by the partner (single observed condition). The rationale behind this was to investigate whether differences between joint and single performance were due to social facilitation or due to an increased coordination effort in the joint action condition. In case of the former, movement performance in the joint and single observed condition should be similar, and differences between the observed and the unobserved single conditions are expected because social facilitation may be observed whenever a second person is present. If, however, the effects have their origin in the actual joint action task—that is, because participants apply strategies to facilitate movement coordination or take measures for obstacle avoidance to prevent a collision of their limbs with the partner—a different pattern is expected: In this case, we should find differences between the joint and the single observed condition, whereas performance in the single observed condition should not be different from performance in the single unobserved condition because the mere presence of another person should not modify the agent's coordination behaviour.

A variety of parameters that describe different aspects of the movement sequence were examined. In the temporal domain, overall movement time, mean velocity, and maximum velocity were compared for the three social context types in order to provide a measure of temporal adaptation. In the spatial domain, we examined whether participants would alter their trajectory paths depending on the type of social context. This was done with a measure of how much the hand path deviated from a direct path connecting object pick-and-place positions. The resulting trajectories were compared between the three conditions: joint, single observed, and single unobserved.

Method

Participants

A total of 28 volunteers (19 female) formed 14 pairs of participants. They were between 17 and 30 years old ($M = 22.39$ years) and students at Ludwig-Maximilians-University Munich. Participants of four pairs knew their partner (they rated knowing him or her with a score higher than 3 on a scale from 1 meaning "completely unknown" to 5 meaning "very well known"; $M = 2.18$). All participants were right-handed, had normal or corrected-to-normal vision, and did not suffer from any neurological dysfunctions. They gave prior informed consent and were paid for their participation (€8 per hour). The experiment was conducted in agreement with the ethical standards laid down in the Declaration of Helsinki.

Apparatus, material, and experimental set-up

Five toy ball track bricks were used in each trial (Haba, Model No. 1136). Three were of the same type with a size of 16 cm × 4 cm × 4 cm and a tilted open channel on top of which a marble could roll down. The other two bricks were cuboids with a size of 8 cm × 4 cm × 4 cm and 4 cm × 4 cm × 4 cm. Participants were sitting next to each other with the bricks lying in front of them on starting positions that were marked on the work table (see Figure 1a). The bricks had to be picked up from their initial positions and placed at their marked goal positions, which were 31 cm further in the depth plane. Two single control buttons were located left and right on the table, which had to be pressed for starting and ending a trial. Table and chair positions were kept constant throughout the experiment.

There were four possible movement types resulting from two different starting configurations and two different ball track goal positions that varied independently and were balanced across trials. Two different starting configurations resulted from the fact that either the cuboids could be assigned to the left side and the longer bricks to the right side of the table, or the assignment could be opposite. This variation allowed alternating the order in which participants (or hands) started the movement sequence. The goal position of the ball track could either be towards the right table side (with the marble running from left to right, cf. Figure 1) or towards the left table side (with the marble running from right to left). As the longer bricks had a clear "direction" due to their tilted open channel for the marble, their initial orientation in the starting configuration was fixed to match the ball track's goal position.

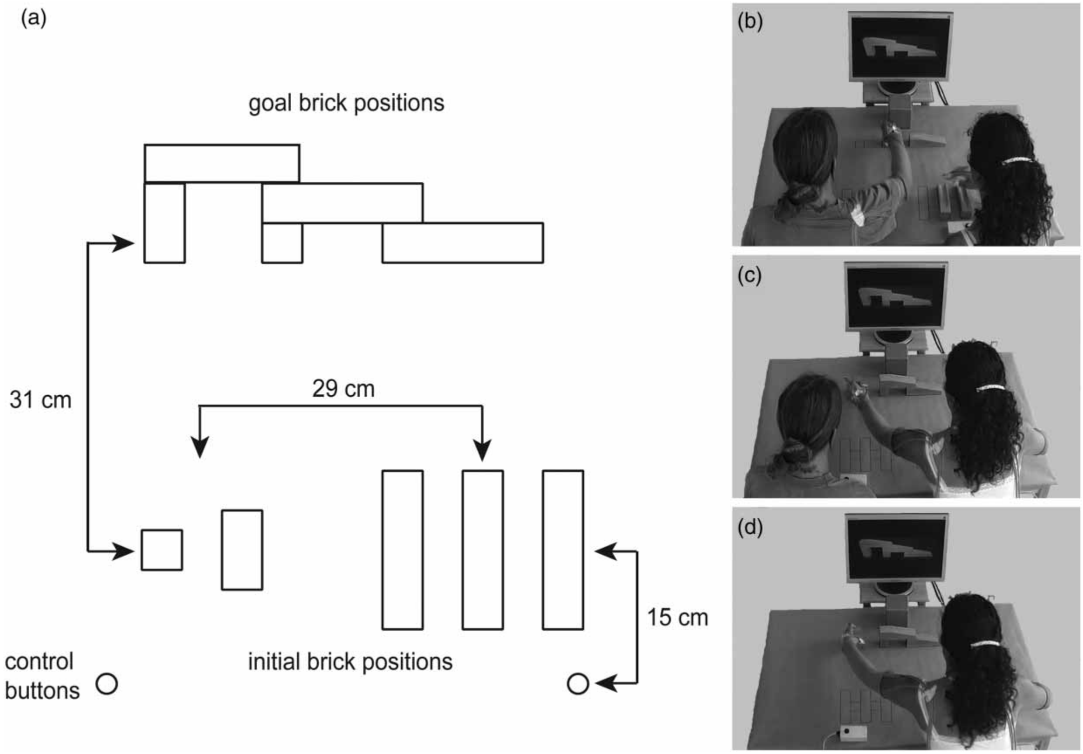

Figure 1. *Experimental design. (a) Ball track brick arrangement on the table. The starting configuration was balanced—that is, right- and left-sitting persons were assigned to each brick configuration equally often, and also the orientation of the ball track goal position was balanced across trials. Shown in this example is Movement Type 1—that is, the right-sitting person started with the long bricks, and the ball track goal orientation was to the right. (b–d) Set-up in the joint condition (b), single observed condition (c), and single unobserved condition (d).*

The following four movement types were used (from the right-sitting participant's perspective): (a) start: long bricks/goal: ball track to right; (b) start: short bricks/goal: ball track to left; (c) start: long bricks/goal: ball track to left; (d) start: short bricks/goal: ball track to right. Participants performed all four movement types with equal probability in all three experimental conditions (joint, single observed, and single unobserved).

During task performance, participants' hand movements were recorded with a Polhemus Liberty 240/8 system, a magnetic motion tracker with a six-degree-of-freedom range (*X*, *Y*, and *Z* coordinates and the three rotation angles) and a constant sampling rate of 240 Hz. Three sensors were mounted on the hands that participants were instructed to use in the task (both partners' right hands in the joint condition, the agent's left and right hand in the single conditions). The sensors were placed centrally on the back of the index finger and thumb and on the back of the hand (centred between wrist and first middle finger joint). In order to be able to exclude error trials, the movements were recorded with a video camera (Panasonic NV-GS320 with 3.1 megapixel). Experimental procedure, data collection, and preparation for statistical analyses were controlled by the program Matlab 2006b; statistical analyses were performed with SPSS.

Task and procedure

Participants had to perform a sequence of pick-and-place movements in order to build a ball track from wooden bricks. In each trial, the participants' task was to pick the wooden bricks from their initial positions and place them according to the ball track goal position. In the joint condition, participants were instructed to use their right hands and only the bricks on their side of the table, whereas in the single conditions they were to use their right hand for the right-sided bricks and their left hand for the left-sided bricks. The bricks had to be picked and placed in a fixed order: Participants had to start with the leftmost brick and then to alternate, always proceeding from relatively left to relatively right.

Each trial was started by simultaneously pressing both control buttons by the participant(s). The button-press triggered the presentation of a picture on the screen that showed one of the two starting configurations. The participant(s) had to bring the bricks into the respective configuration. As the movement data were not collected in this phase, there was no restriction in how this part had to be performed. When ready, the two buttons had to be pressed again, which brought a second picture onto the screen that depicted one of the two possible ball track goal positions. Simultaneously, motion measurement was started. Participants now had to place the bricks according to the ball track goal position and in the correct order. Having placed the last brick, both control buttons had to be pressed to indicate the end of the trial and of the data recording.

Additionally to the four possible movement types (resulting from two starting configurations and two ball track goal positions), there were three social context conditions: In the *joint* condition (J), two partners sitting next to each other worked on the task with their right hands (Figure 1b). In the *single observed* condition (SO), only the right-sitting person worked with the left and right hands, while the left-sitting partner merely watched the task (Figure 1c). In the *single unobserved* condition (SU), the left-sitting person was not in the experimental chamber, and the right-sitting person performed the task alone (Figure 1d). The three conditions J, SO, and SU were performed in separate experimental blocks. The order was counterbalanced across participant pairs.

At the beginning of each social context condition, 4 practice trials were performed, before four experimental blocks were run. Each block consisted of 8 trials in which the four movement types were presented twice in randomized order. This summed up to a total of 96 trials (8 trials × 4 blocks × 3 social context conditions) for the right-sitting and to 32 trials (8 trials × 4 blocks × 1 social context condition) for the left-sitting participant, as the left-sitting participant performed the joint condition only. To prevent the right-sitting person receiving special attention during task execution, participants were informed about the social aspect of the experiment only after all necessary experimental parts had been performed. (Up to this moment, the left-sitting participant still thought that it would be her turn to perform the single condition during a later part of the experiment.) As the seating positions were critical for the participant's role in the experiment, they were assigned by a randomization procedure before the experiment. The experimental session lasted about 60–75 minutes.

Data analysis

Data analysis focused on the right-hand movements of the right-sitting person. These movements allowed a direct comparison of the influence of the three social context types (J, SO, and SU); otherwise the movement of the right-sitting person's left hand would have been compared with the left-sitting person's right hand. For each trial, the movement trajectory of the right-sitting person's right hand was segmented in order to extract the task-relevant part (the movement phase proper) from the irrelevant parts. The segmentation was fully automated and based on the velocity profile of the movement: The movement phase began with the first instance of a Euclidean velocity equal to or higher than 20 cm/s, and it ended with the last instance of a Euclidean velocity value equal to or smaller than 20 cm/s. This rather high threshold was chosen to exclude smaller movements during movement planning or observation of the partner.

For the movement phase, different variables were computed that, besides the error rate, can be classified into four temporal and four spatial parameters. The error rate was calculated by manually going through the video material and marking any of three possible errors: First, the initial positions had not correctly been set up as indicated by the first picture on the screen; second, the ball track bricks were grasped in the wrong order or by the wrong person or hand; and third, the bricks were placed at a wrong goal position that did not conform with the second instruction picture. In each trial, maximally one error was marked, even if more errors had occurred, and errors were counted regardless of whether the left- or right-sitting person was responsible for them. Only valid trials were used for further statistical analyses.

Temporal parameters. Movement time (MT) was calculated as the total duration of the movement phase (defined by the velocity criterion described above). The movement onset (MO) was computed as the time between the appearance of the ball track goal picture and the time point when the velocity criterion for the onset of the movement phase was reached. For visualization purposes (cf. Figure 2a), movement patterns for all four movement types and the three context conditions were normalized in the time domain to 100 points (cf. Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987) and averaged across all participants for each experimental condition.

The velocity was calculated from the Euclidean distance between the *X*, *Y*, and *Z* coordinates of the sensor located at the participants' thumbs. A fourth-order low-pass Butterworth filter with a cut-off frequency of 10 Hz was applied; the resulting phase shift was corrected by a second application of the filter in reversed direction. The mean velocity (V_m) and maximum velocity (V_{max}) were computed for each movement type and social context condition by averaging all velocity values/taking the highest velocity value in the movement phase interval.

Spatial parameters. As a measure of how trajectories differed between the conditions J, SO, and SU in the spatial domain, the parameters transport path (TP) and return path (RP) were computed by comparing how much each transport or return trajectory (as part of the overall movement) was spatially different from the direct model path connecting starting and goal position of the single bricks. TP and RP were computed in the same way (see Figure 3a). The direct paths that served as a baseline against which the empirical trajectories could be compared were determined with linear equations from the centred pick to the centred place positions (TP, vice versa for RP). This is depicted in Figure 3a, left panel: The direct path (arrows with black segments) and the empirically measured trajectory (arrow with grey segment) both connect the same starting and the same goal position—however, possibly using different paths. From the direct path and the empirical trajectory, a segment part was taken (Figure 3a, left: thick black segment on the direct path arrow and thick grey segment on the empirical path arrow) that was defined as the distance between $Y = 10.5$ cm and $Y = 20.5$ (corresponding approximately to one third to two thirds of the distance between pick and place positions). From these segment parts, 11 points of 1 cm distance were extracted (ranging from 10.5 to 20.5 cm) for which the Euclidean distances between the direct model path and the empirical trajectory were computed. The resulting 11 distance values were averaged, providing 1 single value for the deviation of the empirical trajectory from the baseline path in the respective segment. The corresponding *X* and *Z* components of the segment paths were considered as well. Please note that in order to get a clearer picture of this deviation in horizontal and height coordinates, not absolute but directed values were used. Finally, the values for all movement segments (i.e., two or three, dependent on the movement type, Figure 3a, right panel) were averaged to form two general deviation parameters, the transport path (TP), and the return path (RP), and two specific deviation parameters for the transport path only, TP_x and TP_z. Taken together, this procedure resulted in a measure of how much participants' movement trajectories spatially deviated from a given direct path. As the same model pathways were used for all three social context types, it

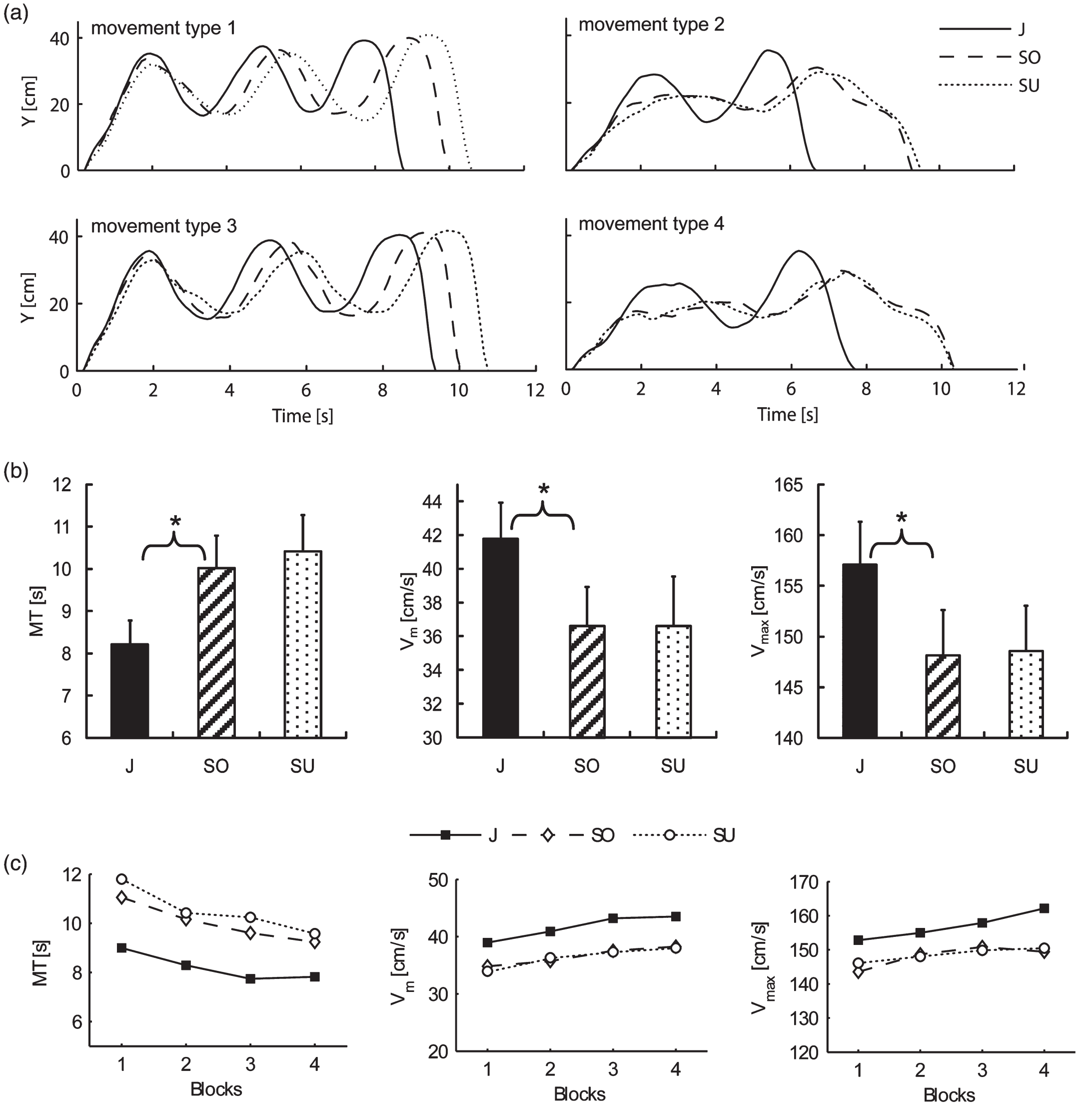

Figure 2. *Temporal parameters. (a) Grand averages (averaged across all trials and participants) of normalized trajectories for the four different movement types. Movements in* Y*-coordinates (depth plane) are shown over time. (b) Mean performance in the social context conditions (joint, J; single observed, SO; and single unobserved, SU) for the movement time MT (left), mean velocity V_m (middle), and maximum velocity V_{max} (right). (c) Mean performance for the same parameters as in (b) shown separately for the four blocks of the experiment (*x*-axis). Social contexts are indicated by different line types (solid: J; dashed: SO, dotted: SU).*

allowed comparing whether and how participants adapted their movements in space.

Statistical analyses. The error rate was analysed with a one-way repeated measures analysis of variance (ANOVA) with the within-subject factor *social context* (J versus SO versus SU). The averages of all parameters besides the error rate were analysed with 4 × 3 repeated measures ANOVAs with the within-subject factors *movement type* (2 starting configurations × 2 ball track goal positions) and *social context* (J versus SO versus SU).

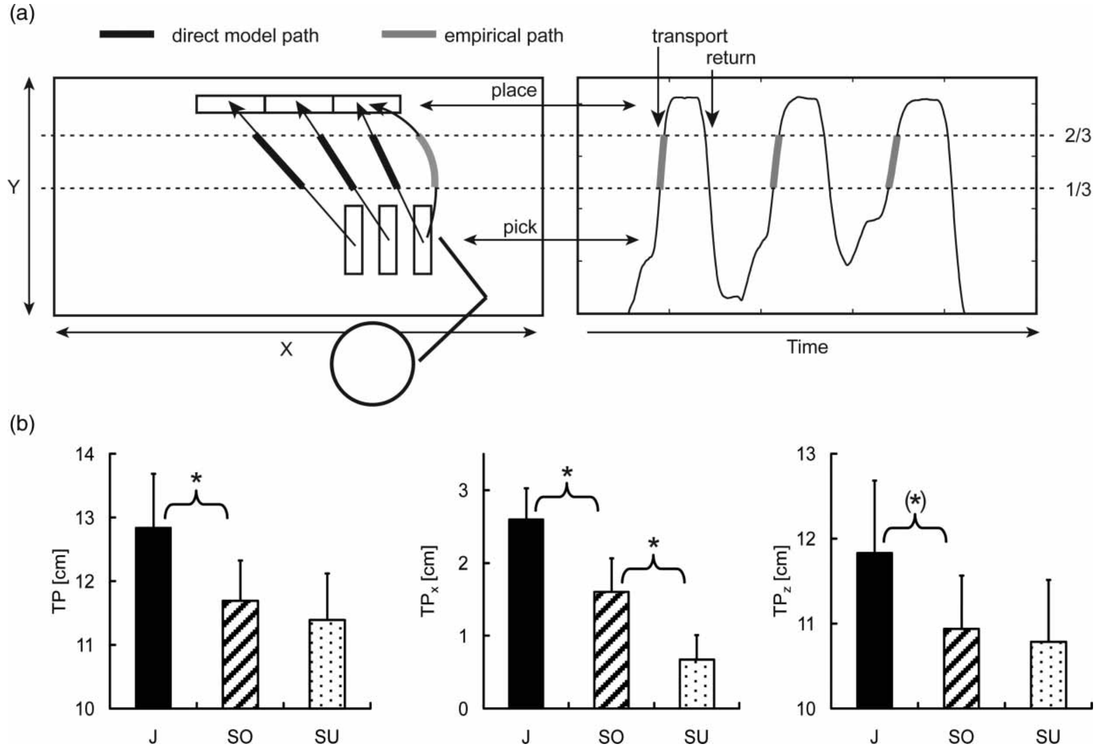

Figure 3. *Spatial parameters. (a) Schematic display indicating the calculation of the spatial parameters. Left: work table with an example starting configuration, shown with the direct model paths (arrows with black segments) and an example of an empirical path (arrow with grey segment). Only the right person's right hand is shown as only these data were included in the analyses. Right: example trajectory (*Y*-coordinate over time), demonstrating the empirical segment trajectories corresponding to the set-up shown on the left. Dashed lines show how the segments were defined. (b) Mean performance in the social context conditions for the transport path TP (left), the corresponding *X*-coordinate TP_x *(middle), and the corresponding* Z*-coordinate* TP_z *(right).*

The factor movement type was included in the analysis to account for variations caused by the use of the different movement types. As the precise differences between movements were currently not our main interest the analyses focused on the social context factor. To clarify the precise nature of social context effects, planned comparisons were performed between the factor levels J and SO and between SO and SU.

Results

Error rate

Overall, 5.36% of the trials had to be rejected due to errors. The error rate was numerically lower in the joint condition ($M = 4.46 \pm 1.26\%$) than in the observed ($M = 4.69 \pm 1.9\%$) and unobserved conditions ($M = 6.92 \pm 1.23\%$), but this difference did not reach significance, $F(2, 26) = 1.69$, $p > .2$.

Temporal coordination

Movement time and movement onset. The results of the ANOVAs for the parameters MT and MO are listed in Table 1. In Figure 2a, the averaged movement trajectories are displayed, and Figure 2b, left, shows the averaged movement times in the three social contexts. MT was influenced by the type of social context. In specific, MT was significantly shorter in the joint (J) condition ($M = 8.22 \pm 0.56$ s) than in the single observed (SO) condition ($M = 10.02 \pm 0.77$ s), $F(1, 13) = 7.32$, $p < .05$,

Table 1. *Results of the ANOVAs for temporal and spatial parameters*

Parameters		*Movement type*		*Social context*		*Movement Type × Social Context*	
Temporal	MT	$F(3, 39) = 11.02$	$p < .001$	$F(2, 26) = 5.89$	$p < .01$	$F(6, 78) = 7.61$	$p < .001$
	MO	$F(3, 39) = 20.48$	$p < .001$	$F(2, 26) = 0.77$	*ns* ($p > .4$)	$F(6, 78) = 0.38$	*ns* ($p > .7$)
	V_m	$F(3, 39) = 31.88$	$p < .001$	$F(2, 26) = 4.44$	$p < .05$	$F(6, 78) = 9.43$	$p < .001$
	V_{max}	$F(3, 39) = 30.07$	$p < .001$	$F(2, 26) = 4.0$	$p < .05$	$F(6, 78) = 3.16$	$p < .01$
Spatial	TP	$F(3, 39) = 65.28$	$p < .001$	$F(2, 26) = 5.34$	$p < .05$	$F(6, 78) = 5.96$	$p < .01$
	TP_x	$F(3, 39) = 77.84$	$p < .001$	$F(2, 26) = 16.27$	$p < .001$	$F(6, 78) = 6.75$	$p < .001$
	TP_z	$F(3, 39) = 74.84$	$p < .001$	$F(2, 26) = 3.13$	*ns* ($p = .06$)	$F(6, 78) = 6.62$	$p < .01$
	RP	$F(3, 39) = 52.24$	$p < .001$	$F(2, 26) = 2.01$	*ns* ($p > .1$)	$F(6, 78) = 0.73$	*ns* ($p > .6$)

Note: 4 (movement type) × 3 (social context) repeated measures ANOVAs (analyses of variance). MT = movement time; MO = movement onset time; V_m = mean velocity; V_{max} = maximum velocity; TP = transport path; TP_x = X component of transport path; TP_z = Z component of transport path; RP = return path.

whereas no significant difference was found between the SO and the single unobserved (SU) condition ($M = 10.42 \pm 0.86$ s), $p > .5$. Thus, participants needed less time to complete the movement sequences in the joint condition than in both single conditions with the latter being not different from each other. The parameter MO did not show any influence of the type of social context (J: $M = 1.19 \pm 0.15$ s; SO: $M = 1.36 \pm 0.26$ s; SU: $M = 1.35 \pm 0.26$ s), $p > .3$.

Mean and maximum velocity. Results for V_m and V_{max} are shown in Table 1 and in Figure 2b, middle and right. Movements in the joint condition ($M = 41.78 \pm 2.16$ cm/s) were performed with a higher mean velocity than in SO ($M = 36.62 \pm 2.31$ cm/s) and SU ($M = 36.64 \pm 2.91$ cm/s) conditions, $F(1, 13) = 8.86$, $p < .05$, for J versus SO, and $p > .9$, for SO versus SU. Similarly, the maximum velocity in the joint condition was significantly higher ($M = 157.08 \pm 4.29$ cm/s) than in SO ($M = 148.16 \pm 4.47$ cm/s), $F(1, 13) = 6.37$, $p < .05$, whereas SO and SU ($M = 148.6 \pm 4.49$ cm/s) were not significantly different, $p > .9$. Taken together, participants performed the task with higher mean velocities and reached higher maximum velocities in the joint than in both single conditions, which were basically equal.

Learning. Although the number of observations for each condition was not sufficient for a meaningful statistical analysis, we had a look at the development of the three important temporal parameters MT, V_m, and V_{max} over the course of the experiment. In Figure 2c, the respective means over the four experimental blocks are shown. Overall, performance improved in all three parameters and in all three social context types over time—that is, in later trials participants needed less time to complete the movement and performed it on average faster and with a higher maximum velocity than in earlier trials. Most important, however, the advantage for the joint condition is in all cases present already from the beginning of the experiment. These findings indicate that participants improved their performance, but that this improvement was not modulated by the type of social context.

Spatial coordination

Transport path. The statistical results are shown in Table 1. The parameter TP revealed that the social context had an impact also on participants' hand trajectories during the transport phases (Figure 3b, left). Planned comparisons indicated that trajectories in the joint condition ($M = 12.84 \pm 0.81$ cm) deviated to a larger extent from the direct path than in the SO condition ($M = 11.7 \pm 0.64$ cm), $F(1, 13) = 5.16$, $p < .05$. The difference between SO and SU ($M = 11.4 \pm 0.69$ cm) did not reach significance, $p > .5$. A separate analysis of the X and Z

components revealed that participants moved more to the right side of the workspace in the joint condition ($M = 2.6 \pm 0.43$ cm) than in SO ($M = 1.61 \pm 0.46$ cm), $F(1, 13) = 8.48$, $p < .05$, and that movements in SU ($M = 0.67 \pm 0.34$ cm) deviated least to the right, $F(1, 13) = 6.28$, $p < .05$. Although the effect failed to reach significance for the Z component, $p > .06$, participants' movements were also higher above the work table in the joint ($M = 11.83 \pm 0.86$ cm) than in the SO condition ($M = 10.94 \pm 0.63$ cm) and in SU ($M = 10.79 \pm 0.73$ cm). The results of both X and Z components are displayed in Figure 3b, middle and right.

Return path. There was no significant effect for social context in the return path, $p > .1$ (J: $M = 13.14 \pm 0.74$ cm; SO: $M = 13.72 \pm 0.53$ cm; SU: $M = 14.13 \pm 0.52$ cm; see Table 1). Thus, the difference observed in the transport movement segments was not present in the return movement segments.

Discussion

The aim of the present investigation was to differentiate between the influence of coordination effort and social presence on movement performance in a joint coordination task. Single and joint performance were compared in a pick-and-place task; a third experimental condition also allowed comparing the performance of an individual who was observed by her partner. Thereby, effects that are primarily related to the effort of both persons to coordinate their actions could be disentangled from effects that have their basis in the mere presence of the partner, as postulated by social facilitation theories (e.g., Aiello & Douthitt, 2001).

Coordination in time

With respect to temporal movement parameters, it was found that the time to perform the movement was shorter in joint than in single performance. Also higher mean and maximum velocities were obtained when people worked together on the task. For all parameters, the differences between joint and single performance were significant, but not those between the single observed and unobserved conditions. Thus, simple social presence affected individual performance far less than the real interaction with the partner did so that an explanation based on social facilitation can be excluded. Rather, the joint action task—that is, the effort to coordinate one's own movements with another person's movements—led to the observed faster performance.

Such adaptation of movements to the interaction situation can be interpreted as a (probably unconscious) strategy employed by the participants to facilitate coordination with the partner. In order to avoid the same limited workspace in which both persons have to place their ball track bricks being occupied by their own hand at that point in time when the partner also places a brick, it seems to be a useful strategy to leave this common workspace as fast as possible. To do so, participants in the joint condition may increase the speed of their movements as observed in the current experiment. This behaviour effectively prevents the same area being occupied by both persons at the same time and minimizes the danger of collision. Further evidence for a strategic adaptation of own temporal movement kinematics is provided by the fact that only the movement phase itself was speeded, whereas the movement onset did not differ between joint and single conditions. It might thus be possible that participants needed the same amount of time to process the visual stimuli, plan their movement sequence, and so on in all three social context types and that they speeded up their performance specifically during the movement execution phase.

Another interesting finding in the current study relates to the improvement of coordination performance over the course of the experiment. Participants decreased the duration of the movement sequence and increased mean and maximum velocity over experimental blocks in all three conditions. This improvement, however, was observed independent of the type of social context, meaning that the temporal advantage of the joint condition is present right from the start of the experiment. This suggests that the strategies employed to facilitate interpersonal coordination do not need to be learned over a longer period of trials, but can already be used at the beginning of the interaction.

Coordination in space

The parameters transport path and return path were analysed to examine how movement trajectories were spatially modulated by the type of social context. During the transport part of the movement, participants moved away furthest from a direct path when working together with another person compared to both single conditions. More specifically, movement trajectories during object transport were expanded more to the right side of the common workspace (i.e., away from the partner's position as only the right-sitting person's right hand was analysed) and were executed slightly higher above the work table in the joint than in the two single conditions. This suggests that participants aimed at moving away from the partner and her workspace side. Similar to the pattern found in the temporal domain, this spatial adaptation was generally strongest in the joint condition compared to single performance. Therefore, the deviation of the movement trajectory also seems to be a direct adaptation to working with a partner, which is not based on mere social presence effects (e.g., Aiello & Douthitt, 2001).

Similar to the temporal domain, spatial adaptation in the joint condition may also have the function to avoid collisions of the two partners' limbs. Changing the movement path, as was observed during the transport part of the movement in the joint condition where participants drew aside both in the horizontal and in the height plane, provides one effective strategy to prevent collisions with the partner. Specifically, these path deviations can be considered to aim at avoiding physical interference with the partner and as a strategy to avoid using too much of the common workspace. Interestingly, for the return path parameter, no significant social context effect was observed. This suggests that during return movements strategic adaptation to the partner was no longer necessary. Spatial adaptation to the partner is required during movements towards the shared goal positions—that is, the position where the ball track is set up by both partners—but not during the movements back to the own private starting positions from which the new bricks need to be taken. It is thus likely that the degree to which the workspace is shared with another person directly influences the requirement to adapt one's own movement parameters.

Besides minimizing the danger of limb collisions, the observed adaptive behaviour may also serve an alternative function. In particular, it can ensure that both partners maintain as much visual information about the current state of the workspace as possible. In other words, by shifting own movements away from the central work area it is more likely that initial and goal brick positions are not occluded by a hand or an arm, and, therefore, joint task performance might be facilitated. However, this alternative account does not explain why no effects of spatial adaptation were found for the return movements: As movements of both partners had to be performed alternately, joint visual control should have been required throughout the whole task.

Motion coordination and adaptation strategies

To summarize, the current findings imply that social facilitation effects (e.g., Aiello & Douthitt, 2001) are influencing the movement kinematics only to a minor extent. Instead, the joint performance effects observed in temporal and spatial movement parameters have their basis in the effort to coordinate movements with the partner and in the attempt to achieve the common action goal of building a ball track. In particular, the present results showed that, first, participants speeded up during joint performance, thereby optimizing the time constraints for the partner, and, second, they adapted their movement paths to the interaction situation by moving away from the partner's side, thus optimizing the spatial constraints for the partner in joint performance.

Interestingly, participants in our study did thus not fully comply with the isochrony principle, a general principle of motor control stating that movements of different lengths are often performed at different velocities, so that the movement duration is roughly kept constant (e.g., Viviani & McCollum, 1983; Viviani & Schneider, 1991). Common examples of isochrony stem from handwriting or drawing research. Isochrony is considered a compensatory increase of movement speed that is observed when the agent intends to execute a motor task in a standardized manner although the movement path lengths vary. In the present experiment, one may assume that the speed increase observed in the joint condition may simply result from the agent's intention to compensate for the increase in path length. However, from the fact that we found not only an increase in speed but at the same time a decrease in movement time it can convincingly be inferred that the speeding up in the joint condition was not only a side-effect resulting from elongated movement paths, but a strategic adaptation to the joint task.

Based on these findings, one can say that participants put extra effort into the task during joint action in the sense that they perform the task at higher velocities while at the same time moving on slightly longer paths. This finding is especially astonishing as it is widely acknowledged that interpersonal coordination is principally more difficult than intrapersonal coordination because the flow of information from the limbs is more indirect in the former (Knoblich & Jordan, 2003; Wolpert et al., 2003). In particular, during a joint action task, the partner's movement dynamics need to be inferred from observed behaviour, and predictions of subsequent actions require a translation of the observed parameters into a suitable predictive model. In single action, such an internal model for prediction can be more accurate—for example, because data coming from the own limbs are less noisy and faster available (Wolpert et al.).

Our finding of extra coordination effort in the joint situation is consistent with the results obtained by Georgiou et al. (2007) where an increase of movement speed was found for the preparatory movement in both the cooperative and the competitive joint action task. There is, thus, accumulating evidence that participants work harder in interaction situations in order to overcome the difficulties arising from the fact that they need to observe, interpret, and predict their partners' external behaviour. We suggest that this extra effort comes in the form of implicit strategies, which have been described above. It is noteworthy that these strategic adaptations seem to be concerned mainly with preventing collisions of the two partners' limbs. Such collision avoidance is a basic requirement of action coordination, especially in situations where movements target at a narrow commonly shared work area (just as in the example of loading a dishwasher). In the current task, this is specifically the case during placing the bricks to the goal location, which shows the largest effects of adaptation behaviour.

It remains to be examined in detail whether such adaptive strategies are generally employed to joint action situations and to what extent participants adapt their movements online to the specific action of the partner. In other words, is the increase in speed and the adaptation of the movement path a general preventive measure that is employed whenever two or more people need to share a common work area or do the effects reflect trial-by-trial online adaptation to the actual movement of the partner? In the study by Meulenbroek et al. (2007), no automatic transfer of observed movement dynamics among partners was found, suggesting that movement parameters were not automatically adapted via a direct action observation/action execution matching system (e.g., Rizzolatti & Craighero, 2004). Although highly speculative at this point, it might be that their task did not require an adaptation of participants' movement parameters to the same extent as the present task or the task by Georgiou et al. (2007) in which effective strategies were needed to reduce the risk of limb collisions. In contrast, in these latter tasks participants seem to have adapted their movements on a general level because, first, movements were adapted also before the actual interaction took place (Georgiou et al.), and, second, movement execution was speeded in the joint condition right from the beginning of the experiment as is suggested by the present results.

Another aspect to be further examined is whether and to what extent anticipation of the partner's movements is required (as, e.g., in Knoblich & Jordan, 2003). The present results indicated adaptive changes of motion parameters for the interaction situation but it cannot be clearly determined whether this adaptation is done in a rather reactive manner—that is, as a reaction to what is observed from the partner's actions—or in a predictive way, anticipating into the near future of the partner's behaviour. Investigations into this topic seem promising for revealing more insights into the complex mechanisms of interpersonal coordination of movements.

Finally, it would also be worth examining how changes with respect to the set-up could affect the current findings. Most of all, it is possible that the side-by-side seating arrangement constituted an especially high risk of limb collisions. A different set-up in which, for example, participants sit face to face to each other might thus produce weaker or no effects of spatial workspace adaptation compared to the results of the current study. Similarly, giving participants even more freedom to choose how to solve the task—for example, by not instructing them which hand to use for each brick or by leaving open the order of placing the bricks—might also affect results. In particular, participants might come up with a different set of adaptation strategies that could include components such as a within-person transfer of bricks from one hand to the other.

Taken together, the current study showed performance differences between single and joint action on a motor level. Participants performed the same movements faster and varied their spatial position when interacting with a partner to achieve a common goal. These effects were found to be due to the participants' increased effort to coordinate during the interaction, whereas social facilitation was not found to play a role.

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