Interpersonal interactions for haptic guidance during maximum forward reaching

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Word count: 2879

Figures: 4

Tables: 1

Acknowledgements

We acknowledge the financial support by the federal Ministry of Education and Research of Germany (BMBF;01EO1401) and by the Deutsche Forschungsgemeinschaft (DFG) through the TUM International Graduate School of Science and Engineering (IGSSE). Research support by IGSSE, TUM

Research highlights

- Deliberately light interpersonal wrist contact alters balance during maximum forward reaching
- Presence of an external object increased maximum forward reach amplitude
- Presence of an external object affected spontaneous interpersonal postural coordination
- Visual feedback available to the contact provider modified interpersonal coordination
- Visuotactile interpersonal context influenced the leader-follower relationship

Abstract

Caregiver-patient interactions rely on interpersonal coordination (IPC) involving the haptic and visual modalities. We investigated in healthy individuals spontaneous IPC during joint maximum forward reaching. A ‘contact-provider’ (CP; n=2) kept light interpersonal touch (IPT) laterally with the wrist of the extended arm of a forward reaching, blind-folded ‘contact-receiver’ (CR; n=22). Due to the stance configuration, CP was intrinsically more stable. CR received haptic feedback during forward reaching in two ways: (1) presence of a light object (OBT) at the fingertips, (2) provision of IPT. CP delivered IPT with or without vision or tracked manually with vision but without IPT. CR’s variabilities of Centre-of-Pressure velocity (CoP) and wrist velocity, interpersonal cross-correlations and time lags served as outcome variables. OBT presence increased CR’s reaching amplitude and reduced postural variability in the reach end-state. CR’s variability was lowest when CP applied IPT without vision. OBT decreased the strength of IPC. Correlation time lags indicated that CP retained a predominantly reactive mode with CR taking the lead. When CP had no vision, presumably preventing an effect of visual dominance, OBT presence made a qualitative difference: with OBT absent, CP was leading CR. This observation might indicate a switch in CR’s coordinative strategy by attending mainly to CP’s haptic ‘anchor’. Our paradigm implies that in clinical settings the sensorimotor states of both interacting partners need to be considered. We speculate that haptic guidance by a caregiver is more effective when IPT resembles the only link between both partners.

Keywords interpersonal touch; forward reach; body sway; social postural coordination

Introduction

Balance control requires successful integration of self-motion information from multiple sensory modalities [1]. The human postural control system is able to derive self-motion not only from its primary motion detectors but also from actively acquired or passively received light skin contact with the environment [2, 3]. Haptic information also stabilizes quiet stance when it originates from a non-weight-bearing contact that possesses motion dynamics of its own, i.e. another human (interpersonal touch; IPT) [4]. Deliberately light IPT is intended to involve small forces only, in order to minimize the mechanical coupling and to maximize the informational exchange[5]. Sway reductions with IPT may emerge from mechanically and informationally coupled adaptive processes and responsiveness in both partners [5].

When joint action partners coordinate their movements they may share information but also face differences in task-relevant knowledge and roles. For example, a blind person receives tactile, visual or verbal cues from the guiding partner. Spontaneous interpersonal postural coordination (IPC) has been demonstrated in diverse joint tasks [6]. For example, implicit observation of a partner in a joint precision task improved manual performance as well as IPC [7]. Verbal communication in a joint problem solving task also influences IPC regardless of whether visual information about the partner was available [8], perhaps mediated by shared speaking patterns [9]. Finally, haptic interactions provide powerful sensory cues for IPC [10]. Coordinative processes supporting goal-directed joint action can result in the emergence of spontaneous leader-follower relationships, for example in a visual, periodic collision avoidance task [11]. In situations such as quiet stance IPT, however, no clear leader-follower relationship has been reported, also not in situations with asymmetrical stance postures with one person intrinsically more stable than the partner [4, 12, 13].

A well-established clinical task to assess body balance control is the Functional Reach (FR) [14]. Maximum forward reaching (MFR) challenges the control of body sway as the body's Centre-of-Mass (CoM) approaches the physical limits of stability so that the likelihood of balance loss increases with reaching distance [15]. We assumed that joint action in an asymmetric interpersonal postural context, such as the MFR task with one partner more intrinsically stable, would be more adequate than quiet stance to investigate spontaneously emerging leader-follower relationships. According to the ecological principles of interpersonal affordances [16], we aimed to create dependencies between two individuals by asymmetries in the intrinsic postural stability and in the knowledge of the joint postural state based on the available sensory feedback. We expected that additional haptic feedback, for example as either an additional object or IPT, would increase reach distance but also stabilize body sway in the reaching person (contact-receiver; CR). Further, we anticipated that spontaneous IPC, specifically the leader-follower relationship, is altered by the haptic feedback available to CR as well as by the visual feedback available and the instructions given to the person providing IPT (contact-provider; CP). Although CR would be the main actor performing the MFR, we assumed that CR would become more dependent on CP, when CP was able to perceive the scene.

Methods

Participants

Twenty-two healthy participants (average age=26.3yrs, SD=4.1; 17 females and 5 males; all right-handed for writing) were tested. Participants with any neurological or orthopaedic indications were excluded. Two naïve, healthy young adults provided IPT to all CRs. Participants were recruited as an opportunity sample from students of the university. The study was approved by the local ethical committee and all participants gave written informed consent.

Experimental procedure

Six conditions were combined from the task requirements imposed on CR and CP. CR stood blindfolded on a force plate in bipedal stance to perform MFR with or without tactile feedback at the fingertips by touching a light object (OBT; weight=59.3g). CR was instructed to reach as far forward as possible or asked to shove OBT instead, which was placed upon a fibreglass plate (kinetic coefficient of friction=0.33). OBT could move in any direction and therefore afforded manual precision. Before the start of a trial, CR was instructed to stand in a relaxed manner, the dominant right arm extended at shoulder height to reach horizontally above a table. The table was adjusted to each individual to avoid surface contact.

CP stood orthogonally to CR in bipedal stance on a force plate placed ahead of CR in the reaching direction (Fig. 1a) and provided light IPT during CR's reach with the right extended index finger contacting CR's medial wrist (Fig. 1b). The visuotactile interpersonal context (VIC) consisted of three conditions: IPT with open or closed eyes and CP tracking the motion of CR's wrist with the extended index finger visually but without IPT. Before the start of a single trial, CP kept his contacting finger close to the wrist of CR waiting for the specific task instructions.

--- insert Figure 1 about here ---

Each condition was assessed in blocks of 10 trials for a total of 60 trials in fully randomized order. A single trial lasted 25s consisting of three phases: baseline (5s static posture), self-paced forward reaching (cued by experimenter) and reach end-state (static posture until trial end).

Two force plates (Bertec 4060H, OH, USA; 600Hz) oriented in parallel measured both individuals' six components of the ground reaction forces and moments to calculate anteroposterior (AP) and mediolateral (ML) components of the Centre-of-Pressure (CoP). In addition, a four-camera motion capture system (Qualisys, Göteborg, Sweden; 120Hz) tracked markers on both individuals at the following locations: right index finger, right wrist, left and right shoulders, 7^{th} cervical segment.

Data reduction and statistical analysis

Motion data were spline interpolated to 600Hz and subsequently merged with the kinetic data. Time series data were smoothed using a generic dual-pass, 4^{th}-order Butterworth lowpass filter (cutoff=10Hz). After differentiation, trials were segmented into three movement phases based on the AP position of CR's wrist marker (Fig. 1c). Reach onset was determined as the first frame that exceeded 4 standard deviations of wrist position within the initial 3 seconds. Stop of forward reaching was determined as the velocity zero-crossing closest to 95% of the absolute maximum reach distance. Reach performance was analysed in the horizontal plane. Average reach amplitude, direction, curvature (normalized path length=path length/straight line length) of the trajectory from baseline position to maximum reaching end-state as well as the average and standard deviation of reaching velocity were extracted. Velocity information is the predominant source for body sway control [17], therefore postural control in the maximum reach end-state was extracted as the standard deviation of CoP velocity (SD dCoP) in both directions (Fig. 1g). Similarly, standard deviation of the wrist velocity (SD dWrist) expressed reaching stability and precision in both directions. For each phase, IPC was estimated in terms of the cross-correlation function (time lag range: -/+3s) between both participants' moments as recorded by the force plates in the plane parallel to the reaching direction (Fig. 1e-f). The largest absolute cross-correlation coefficient and corresponding time lag were extracted. Coefficients were Fisher Z-transformed for statistical analysis. Two-factorial repeated measures ANOVAs with OBT (2 levels) and VIC (3 levels) as within-subject factors were calculated. Significant findings were detected at a Greenhouse-Geisser-corrected $p<0.05$.

Results

Table 1 presents the statistical results for all extracted parameters.

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Forward reaching performance

Fig. 2a shows the amplitude of CR's reach as a function of the VIC and OBT presence. Without OBT the amplitude of reaching was 37.9cm (SD=7.0). OBT increased reach distance to 38.9cm (SD=6.5). The average reach direction indicated a slight medial deviation of 5.9° (SD=7.0). Horizontal wrist velocity was reduced from 46.5mm/s (SD=19.2) to 40.9mm/s (SD=17.8) with OBT. Likewise, the variability was reduced from 54.2mm/s (SD=26.5) to 42.5mm/s (SD=14.4) with OBT. Curvature indicated a slightly curved trajectory (average=1.7, SD 0.8), which was not affected by OBT or VIC.

Postural control in the reach end-state

The reach end-state lasted on average 10.4s (SD=3.0). Separating wrist velocity into its AP and ML components resulted in an effect of OBT and an interaction between OBT and VIC on AP SD dWrist. OBT reduced AP SD dWrist in general (Fig. 2b). Post-hoc single comparisons indicated that IPT without visual feedback and without OBT resulted in a reduction compared to the other two VIC conditions (Fig. 2b).

SD dCoP was reduced by the presence of OBT in both directions (Fig. 2d-e). A tendency of an effect of VIC was found in the AP direction. Single comparisons showed that the IPT condition with visual feedback reduced SD dCoP compared to visual tracking.

--- *insert Figure 2 about here* ---

Interpersonal coordination

Figure 3 shows the Fisher-Z-transformed coefficients and time lags of the peak cross-correlations between the wrist velocities of CR and CP in the reaching direction for the complete trial (Fig. 3a-b), the forward reaching (Fig. 3c-d) and the reach end-state (Fig. 3e-f).

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Across the complete trial, both OBT and the VIC affected the strength of IPC (Fig. 3a). Single comparisons indicated that in visual tracking, coefficients were weakest compared to the other two IPT conditions. Time lags tended close to zero (average=8ms, SD=457; Fig. 3b). In the forward reaching, coefficients were lower compared to the complete trial but affected in a similar manner (Fig. 3c). The time lags were affected by the VIC and showed an interaction with OBT. Single comparisons indicated that in the condition with IPT and visual feedback, CP tended to show a slight lead ahead of CR (average=69ms, SD=338) compared to IPT without visual feedback, where the interpersonal relationship tended to be reversed (average=41ms, SD=115). In visual tracking, OBT tended to result in CP lagging behind CR by about 263ms (SD=528; Fig. 3d) in contrast to a zero lag without OBT (average=10ms, SD=397). In the reach end-state, visual tracking resulted in the weakest IPC compared to the two conditions involving IPT (Fig. 3e). The time lags showed an effect of OBT presence with OBT resulting in zero lags (average=6ms, SD=595) compared to a lead by CR when OBT was absent (average=151 ms, SD=454; Fig. 3f).

Figure 4 shows the Fisher-Z-transformed coefficients and corresponding time lags of the peak cross-correlations between CR and CP for the moments in the plane parallel to the reaching direction across the complete trial (Fig. 4a-b), forward reaching (Fig. 4c-d) and in the reach end-state (Fig. 4e-f).

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OBT decreased the strength of IPC (Fig. 4a). Regarding the time lags, single comparisons showed that an interaction between OBT and VIC was caused by the presence of OBT to alter the interpersonal timing when CP provided IPT without vision (Fig. 4b). With OBT, CP followed CR by 286ms (SD=62), while in the absence of OBT CP was 112ms (SD=486) ahead of CR. In the other two VIC conditions time lags showed a lead of CR about 70ms (SD=400). In forward reaching, coefficients were generally lower relative to the complete trial. Similarly, OBT presence reduced the strength of IPC (Fig. 4c). Time lags indicated that CP followed CR by about 184ms (SD=614; Fig. 4d). In the maximum reach phase coefficients were still lower than during forward reaching. An effect of VIC was found (Fig. 4e). Single comparisons indicated that visual tracking showed the weakest IPC compared to the other two conditions. Overall, the time lags averaged around 155ms (SD=697; Fig. 4f).

Discussion

We aimed to understand the spontaneous IPC for balance support in maximum forward reaching and intended to modulate the leader-follower relationship by creating asymmetric interpersonal dependencies. CR, deprived of visual feedback and in the less stable postural state, was supposed to rely more strongly on CP when no alternative source of haptic information was available. On the other hand, CP's responsiveness to CR was expected to vary with the visuotactile interpersonal context in terms of visual feedback and the IPT instruction.

OBT influenced the reaching performance of CR. The precision demands (speed/accuracy) were greater with OBT as expressed by CR's reduced and less variable reaching speed. In the reach end-state, increased amplitude with OBT (Fig. 2a) coincided with reduced AP wrist and SD dCoP (Figs. 2b, 2d). Our results confirm previous observations that a target object in the FR task facilitates performance [18, 19]. Despite low friction of the fibreglass surface, the interaction with OBT could have resulted in haptic feedback at the fingertips facilitating control of balance [3] and resembling a non-rigid, haptic 'anchor' as conceptualized by Mauerberg-deCastro and colleagues [20].

Contact between the hands ought to have resulted in better interpersonal coordination and synchronization. Indeed, an increase in strength of IPC between the hands occurred in the two IPT conditions. Nevertheless, mechanical coupling between the hands is unlikely as IPT provided support to CR's arm in terms of vertical friction only. The absence of an effect of the VIC on SD dWRI in the ML direction indicates that IPT did not constrain CR's forward reaching. This is corroborated by the observation that the movement trajectories were also not influenced by IPT. In contrast in the reach end-state, both AP wrist and CoP velocity showed selectively reduced variability during IPT without visual feedback. For SD dCoP this difference was independent of the presence of OBT (Fig. 2d). It seems that the benefit of IPT appeared predominantly when CP was not able to observe CR visually. Summation of OBT and IPT should have resulted in greatest improvements in reach distance and balance stability. The lack of a summation effect of the two haptic modes [21] as observed in individual, passively received light touch [22] suggests that the two sources were not integrated. Reliability estimates or the contextual information of the two sources could have been too divergent [23]. While CR participants have experience in contacting environmental objects during stance. the social content of IPT could have made it incompatible with the OBT signal. Perhaps the variability reductions with IPT may result from social facilitation [24] with the requirement that CP attends exclusively to CR's local dynamics.

Individuals achieve joint goals by switching between symmetrical and asymmetrical modes of IPC depending on the constraints of their complementary roles. Skewes et al. [25] investigated how people trade synchronization and complementarity in a continuous joint aiming task. Interestingly, when the level of difficulty in the complementary task became too high for one partner of the dyad, this person became less adaptive to their partner's requirement thus taking the 'leader' role in the joint task. In addition, partners synchronized better with an irregular, but adaptive partner, than with a completely predictable one [25]. OBT presence and the VIC altered the strength and temporal coordination between both individuals during IPT across the complete trial and during forward reaching. OBT reduced the cross-correlation coefficients between both individuals (Figs. 3a, 3c, 4a, 4c). OBT was more relevant to CR than to CP, therefore this difference expresses CR's responsiveness to the interpersonal context. For example, being engaged in a precision task, restricted CR's adaptability, which could explain why CR was 'leader' in the majority of testing conditions.

With respect to IPC of the postural responses, CP used to follow CR's motion by up to 200 ms when visual feedback was involved (Figs. 4b, 4d). Thus, visual processing in CP's task requirements seems to have resulted in a reactive mode. While the nature of the IPT signal is local, with eyes open CP may have attended to the global scene and involuntarily experienced visual dominance [26]. Although vision dominates in bisensorial contexts, latencies to visual stimuli in these situations are typically delayed compared to touch or audition [27]. In the condition without visual feedback for CP but constant IPT, the presence of OBT made a big difference (Fig. 4b). Removing OBT, which deprived CR of a competing tactile signal, seems to have caused CR to a focus on the IPT signal, thereby turning CP into the 'leader'. During forward reaching (Fig. 4d), however, once more time lags indicated CP as the 'follower'. Naturally, the reaching phase did not contain the transition points such as initiation and stop. It is reasonable that these two events are central to successful IPC. Perhaps, in the IPT condition without visual feedback and in the absence of OBT at CR's fingertips, CR's motion onset was triggered by CP.

According to our present results, a caregiver needs to take into account the context-dependent responsiveness of a patient. If a caregiver intends to guide a patient haptically, the caregiver needs to ascertain that two prerequisites are met: the patient has no competing tactile signal available and the therapist deliberately refrains from adopting a reactive mode based on vision. This still needs to be tested in realistic patient-caregiver settings.

Conclusions

We described the effects of visual and haptic sensory information on interpersonal postural coordination in an asymmetrical maximum forward reach joint action paradigm. We observed temporal movement coordination between a ‘contact-provider’ and a ‘contact-receiver’ to depend on the presence of an external object and the visuotactile interpersonal context. Interpersonal postural coordination was strongest when deliberately light IPT was provided without the presence of an additional object at the contact-receiver’s fingertips. As the leader-follower relationship between both partners was also modified by the visuotactile interpersonal context of the contact-provider, the sensorimotor states of both partners have to be considered of equal importance. We speculate that IPT is a promising strategy for patient guidance in clinical settings. More research is needed before its implementation as a patient manual handling tool.

Conflict of Interest

There are no conflicts of interest for any of the authors.

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Tables

Table 1.
Statistical effect table. OBT: light object; IPT: interpersonal touch; ML: mediolateral; AP: anteroposterior; n.s.: not significant; Italics: marginal significance. P-values are rounded to two or three decimals respectively.

	Condition		Presence of OBT	Visuotactile interpersonal context	Interaction between OBT and visuotactile interpersonal context
	Interpersonal contact		No IPT	IPT	IPT
Trial phase	Parameter		$F_{1,21}$; p; partial η^2	$F_{2,42}$; p; partial η^2	$F_{2,42}$; p; partial η^2
Reaching performance					
Forward reaching	Horizontal amplitude		4.80; 0.04; 0.19	n.s	n.s
	Directional angle		n.s	n.s	n.s
	Horizontal velocity		19.67; 0.001; 0.48	n.s	n.s
	Variability of horizontal velocity		12.87; 0.002; 0.38	n.s	n.s
	Curvature		n.s	n.s	n.s
Control of body balance and posture					
Reach end-state	Variability of wrist velocity	ML	n.s	n.s	n.s
		AP	14.56; 0.001; 0.41	n.s	3.59; 0.04; 0.15
	Variability of CoP velocity	ML	36.50; 0.001; 0.64	n.s	n.s
		AP	13.65; 0.001; 0.39	*2.95; 0.06; 0.12*	n.s
Interpersonal postural coordination					
Complete trial	AP wrist	Coefficient	4.49; 0.05; 0.18	11.64; 0.001; 0.36	n.s
		Time lag	n.s	n.s	n.s
	AP moment	Coefficient	6.45; 0.02; 0.24	n.s	n.s
		Time lag	n.s	n.s	3.84; 0.03; 0.15
Forward reaching	AP wrist	Coefficient	6.75; 0.02; 0.24	10.40; 0.001; 0.33	n.s
		Time lag	n.s	5.34; 0.01; 0.20	3.55; 0.05; 0.15
	AP moment	Coefficient	13.21; 0.002; 0.39	n.s	n.s
		Time lag	n.s	n.s	n.s
Reach end-state	AP wrist	Coefficient	n.s	9.69; 0.001; 0.32	n.s
		Time lag	4.25; 0.05; 0.17	n.s	n.s
	AP moment	Coefficient	n.s	4.63.; 0.02; 0.18	n.s
		Time lag	n.s	n.s	n.s

Figure legends

Figure 1.

(A) The stance configuration of the experimental setup at the beginning of a trial. Upon a signal by the experimenter the contact receiver will start the forward reach pushing the object as far out as possible. (B) The contact provider keeping light contact with the receiver’s wrist. (C) Position of a receiver’s wrist in the reaching direction across single trial. The dashed lines indicate the beginning and end of the forward reach phase. (D) Position of a providers’s wrist in the reaching direction across the same trial. (E) Moment in the plane parallel to the reaching direction exerted by the receiver. (F) Corresponding moment exerted by the provider. (G) Receiver’s Centre-of-Pressure (CoP) velocity in the reaching direction. (H) Corresponding CoP velocity of the provider.

Figure 2.

(A) The horizontal amplitude of the contact receiver's wrist as a function of the presence of the light object (OBT) and visuotactile interpersonal context. The standard deviation of the contact receiver’s wrist velocity in the anteroposterior (B) and mediolateral (C) directions during the reach end-state. The standard deviation of the contact receiver’s CoP velocity in the anteroposterior (D) and mediolateral (E) directions during the reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p<0.05$. IPT: interpersonal touch.

Figure 3.

Left panels show the average Fisher Z-transformed cross-correlation coefficients of the wrist velocity in reaching direction as a function of the presence of the light object (OBT) and visuotactile interpersonal context in (A) the complete trial, (C) reaching phase and (E) maximum reach end-state. Right panels show the cross-correlation time lags as a function of the visuotactile interpersonal context and the object presence in (B) the complete phase , (D) reach phase, (F) and maximum reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p<0.05$. IPT: interpersonal touch.

Figure 4.

Left panels show the average Fisher Z-transformed cross-correlation coefficients of the moments in reaching direction as a function of the presence of the light object (OBT) and visuotactile interpersonal context in (A) the complete trial, (C) reaching phase and (E) maximum reach end-state. Right panels show the cross-correlation time lags as a function of the visuotactile interpersonal context and the object presence in (B) the complete phase, (D) reach phase, (F) and maximum reach end-state. Bold vertical brackets indicate an effect of OBT presence. Bold horizontal brackets indicate a single comparison between visuotactile interpersonal contact conditions averaged for the OBT factor. Thin horizontal brackets refer to a single comparison between not-averaged specific visuotactile interpersonal context conditions. Error bars indicate the between-subject standard error of the mean. The asterisk indicates $p<0.05$. IPT: interpersonal touch.

6. Table(s)

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Tables

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Complete trial	AP wrist	Coefficient	4.49; 0.05; 0.18	11.64; 0.001; 0.36	n.s
		Time lag	n.s	n.s	n.s
	AP moment	Coefficient	6.45; 0.02; 0.24	n.s	n.s
		Time lag	n.s	n.s	3.84; 0.03; 0.15
Forward reaching	AP wrist	Coefficient	6.75; 0.02; 0.24	10.40; 0.001; 0.33	n.s
		Time lag	n.s	5.34; 0.01; 0.20	3.55; 0.05; 0.15
	AP moment	Coefficient	13.21; 0.002; 0.39	n.s	n.s
		Time lag	n.s	n.s	n.s
Reach end-state	AP wrist	Coefficient	n.s	9.69; 0.001; 0.32	n.s
		Time lag	4.25; 0.05; 0.17	n.s	n.s
	AP moment	Coefficient	n.s	4.63.; 0.02; 0.18	n.s
		Time lag	n.s	n.s	n.s

7. Figure(s)

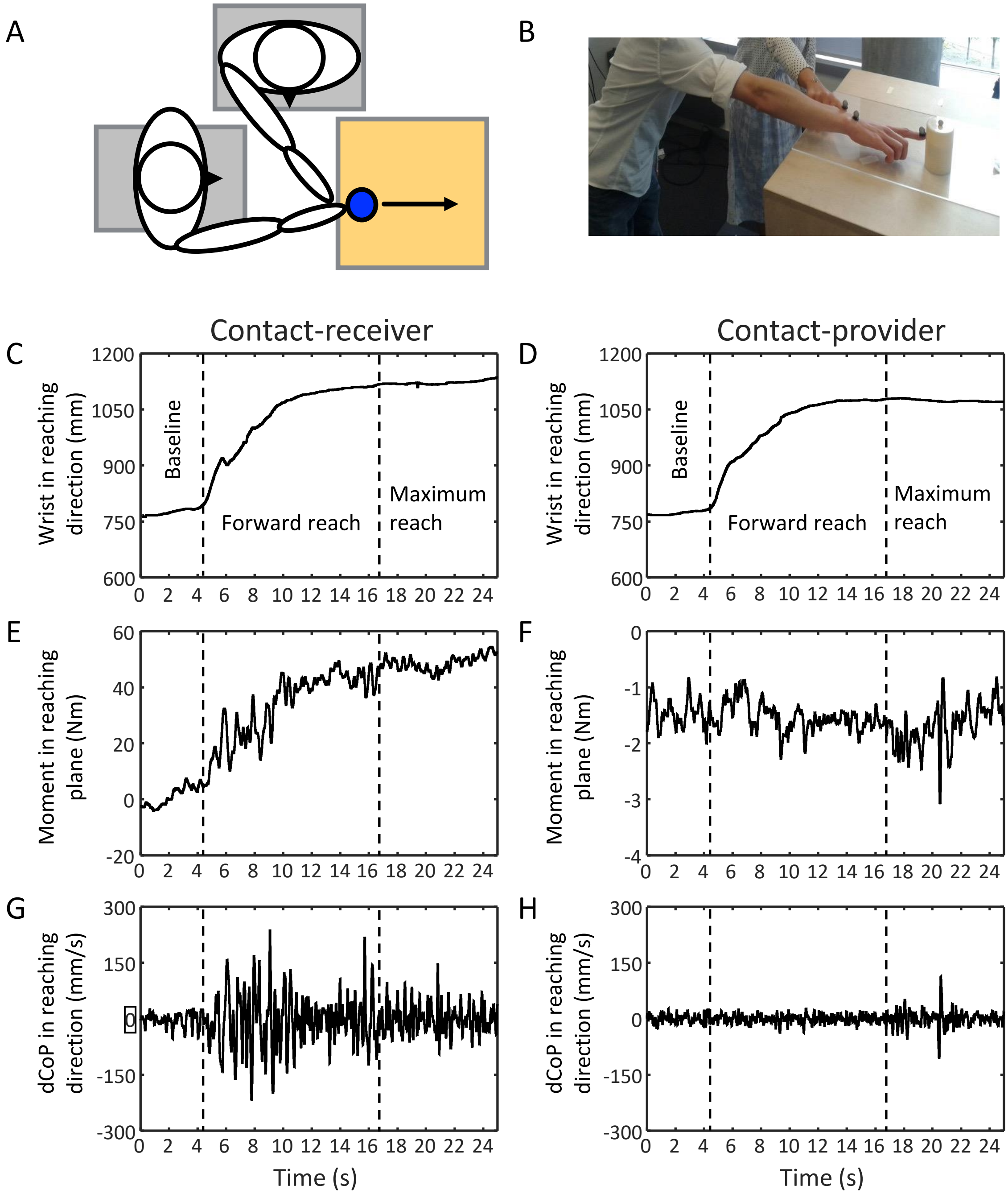

Figure 1.

7. Figure(s)

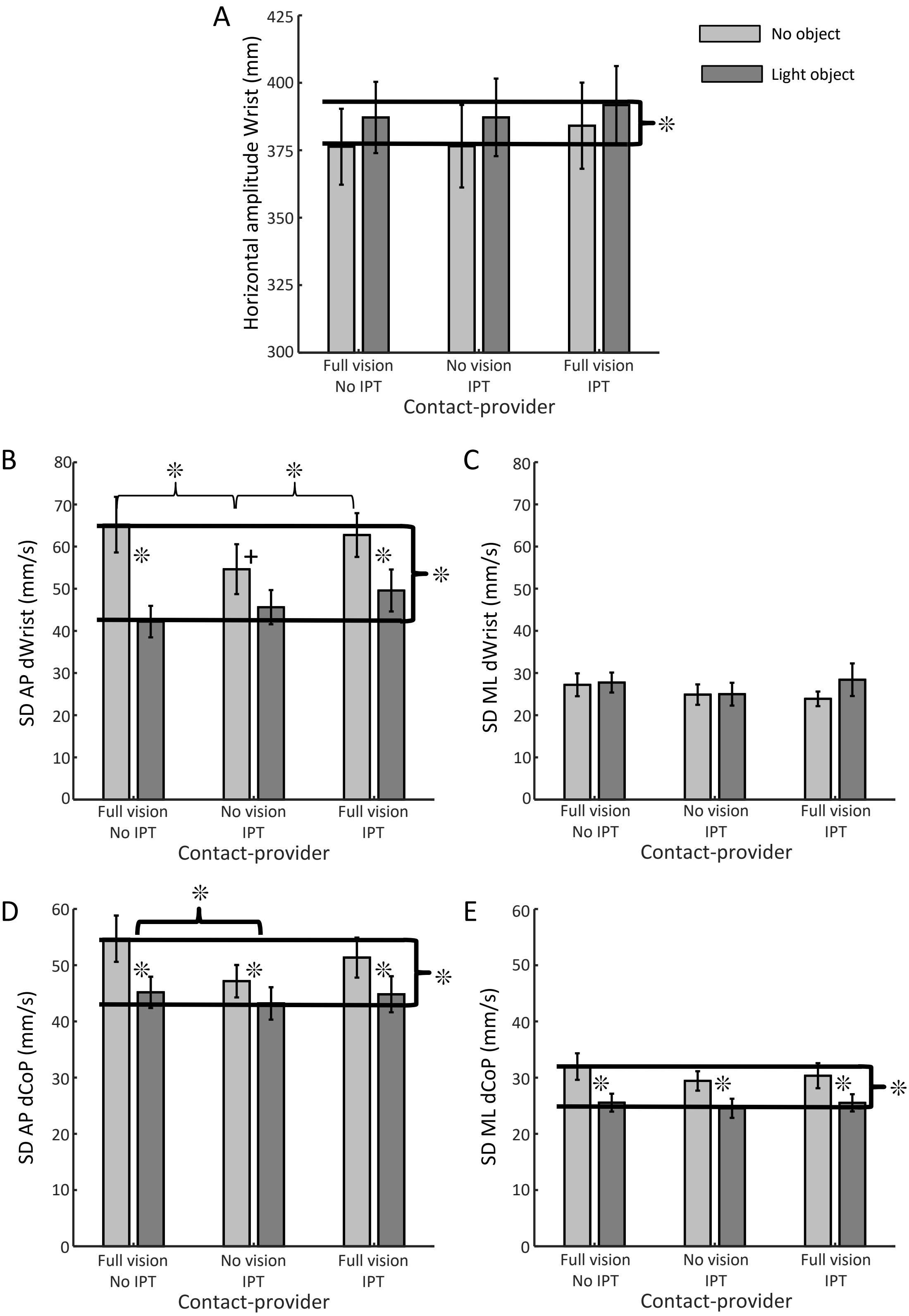

Figure 2.

7. Figure(s)

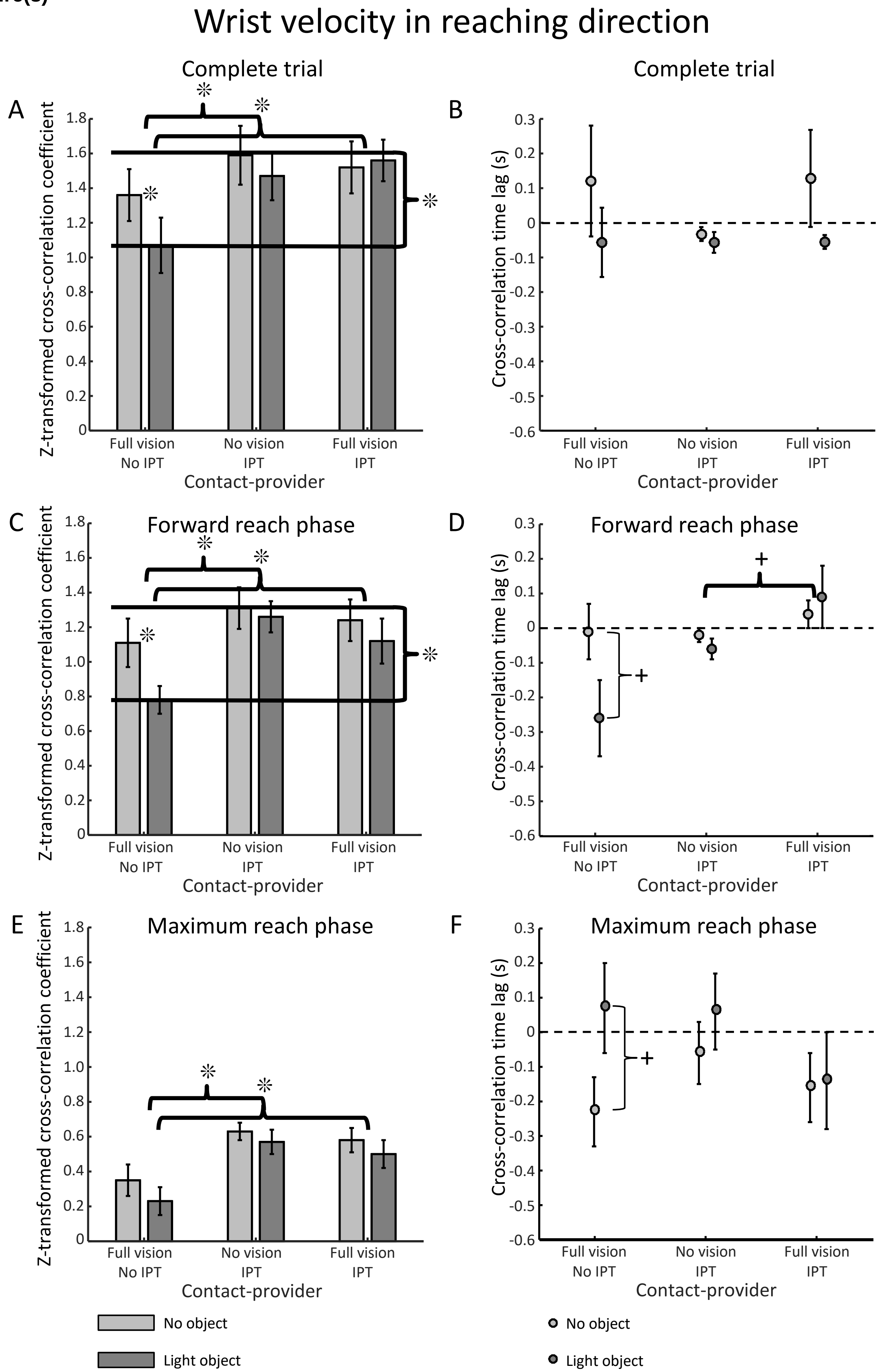

Figure 3.

7. Figure(s)

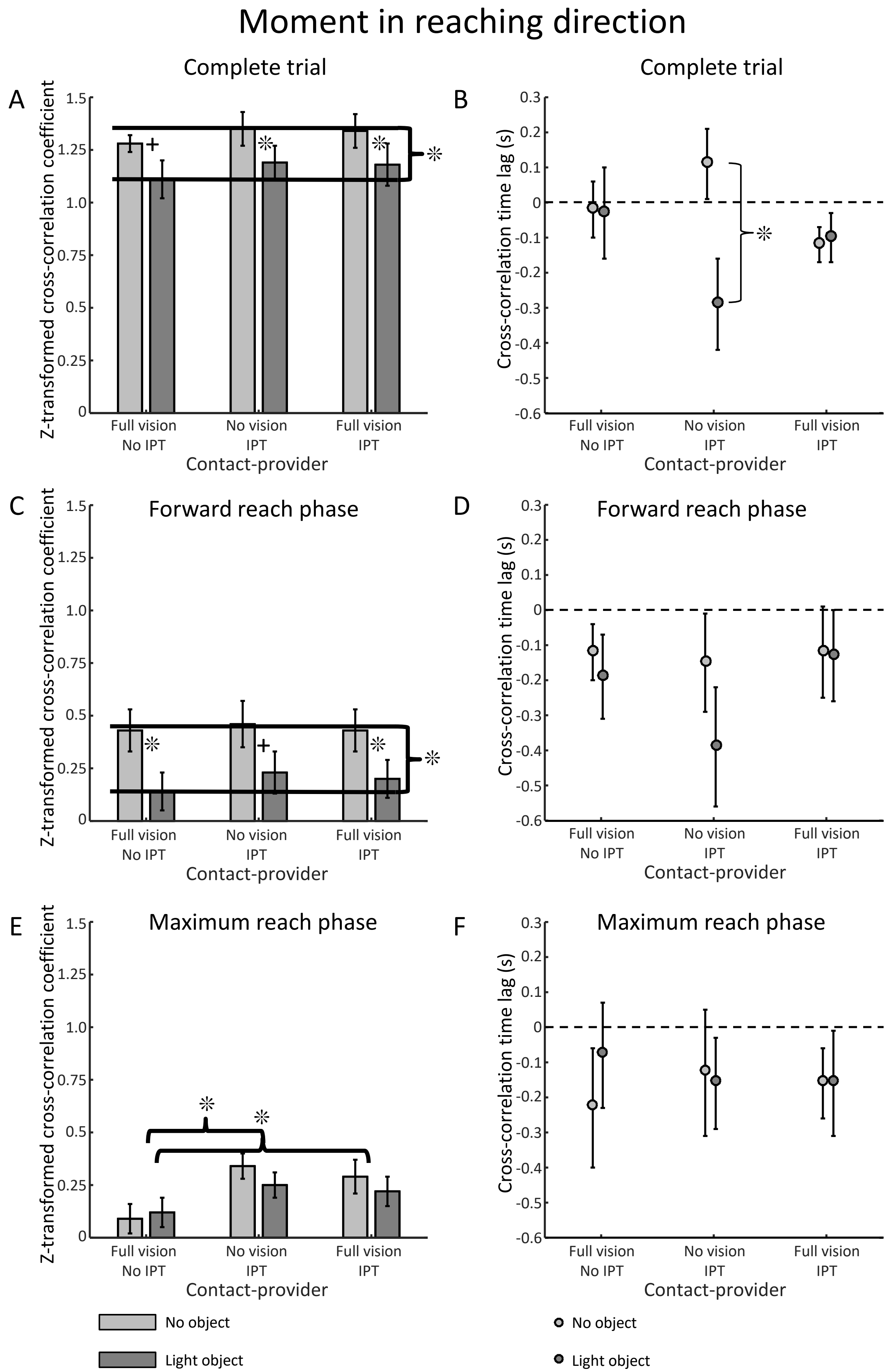

Figure 4.

*Research Highligts

Interpersonal interactions for haptic guidance

Research highlights

- Deliberately light interpersonal wrist contact alters balance during maximum forward reaching
- Presence of an external object increased maximum forward reach amplitude
- Presence of an external object affected spontaneous interpersonal postural coordination
- Visual feedback available to the contact provider modified interpersonal coordination
- Visuotactile interpersonal context influenced the leader-follower relationship