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School-aged children communicate through haptics to improve motor performance

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Abstract

From rough-and-tumble play to carrying objects together, children frequently engage in physical interactions. Adults use the haptic information provided by such interations to exchange motion plans and improve individual motor performance during physically coupled tasks; but whether children possess this haptic communication ability, and how it relates to sensorimotor development, is not known. To address these questions, we developed a dedicated paradigm for school-aged children, and conducted a study with 56 children (28 dyads, 5-17 years) using a gamified wrist-tracking task while mechanically coupled via a dual robotic interface. We found that tracking error decreased with age and was further reduced when children were connected to a partner. As in adults, connecting to a more-skilled partner improved performance, whereas connecting to a less-skilled partner did not significantly degrade it. These results indicate that school-aged children can exploit haptic communication during cooperative action despite their still-developing sensorimotor skills.

Keywords: haptic communication, sensorimotor development, multisensory integration

1 Introduction

When children carry a box together, play tug-of-war, or engage in rough-and-tumble play, what do they infer about their partner from the forces they feel? In adults, partners rapidly adapt to each other's movements through the exchange of forces, a form of information transfer termed *haptic communication* (HC) [1]. HC enables physically connected adults to improve joint performance compared to the solo performance of even the more skilled partner [2]. Benefits of HC have been demonstrated across diverse tasks, including reaching [3–5], tracking [1, 2, 6], navigation over via points [7], ball-beam control [8], and beam-walking [9]. It can also facilitate motor learning [10, 11], thus motivating applications in rehabilitation and skill acquisition. Despite this evidence in adults, it is not known whether HC is already present during childhood and, if so, whether children use it differently from adults.

Children engage in social interaction from the first weeks after birth, and begin to actively contribute to joint actions during their second year, although their capabilities remain limited until around five years of age [12–14]. Effective haptic communication, as a specific form of joint action, requires partners to estimate their own body state, perceive interaction forces, and integrate these different sources of information [1] — processes that mature across childhood at different rates. It is known that infants can discriminate basic haptic properties and perform grasping actions within their first year [15, 16], while proprioceptive sensitivity and sensorimotor coordination continue to improve with age [17]. Furthermore, multisensory integration develops gradually. Although children aged 6–7 can combine uncertain sensory information with prior knowledge in simplified settings [18], integration of visual and haptic cues remains suboptimal until about 8 years, with reliance on cue recalibration strategies [19, 20]. In parallel, motor control becomes progressively more stable, where movement smoothness, variability, and adaptive learning approach adult levels only between approximately 8 and 11 years of age [21–25].

These findings indicate that the underlying mechanisms of haptic communication follow distinct developmental trajectories, making it unclear whether haptic communication is available in children and how this ability as a whole emerges during development. To investigate its development during childhood, we adapted an existing protocol previously used to study haptic communication in adult dyads [1]. Analogously, we conducted an experiment in which pairs of children (aged 5 to 17 years), connected via a virtual elastic band that provided haptic feedback, performed a gamified joint tracking task (Fig. 1). This paradigm allowed us to test a key signature of haptic communication: whether school-aged children (i) improve performance when connected with a better partner, while (ii) maintain performance with a less-skilled partner [1, 2]. It also enabled us to examine how these effects vary with partner characteristics such as age difference.

2 Results

2.1 A tracking experiment for school-age children

Fifty-six children (26 female, 30 male), aged 5–17 years (mean = 10.28, SD = 2.88), were organized into 28 dyads. The number of dyads in each age group is reported in Table 1 (Supplementary Information A). The children sat next to each other, separated by a curtain, and tracked a pseudo-random target trajectory on a monitor. They controlled an on-screen cursor via the wrist flexion/extension of their dominant arm using the Hi5 dual robotic interface [26] (Fig. 1a,b). Trials were performed either alone (*solo trial*) or while the two partners of a dyad were mechanically connected by a virtual elastic band (*connected trial*). The experiment comprised a *training phase* of 10 solo trials, followed by a *testing phase* of 40 trials in which connected and solo trials alternated (Fig. 1c). Fig. 1d displays representative trajectories during the connected and solo phases.

Several modifications had to be carried on the protocol tested in adults [27] to ensure that the children were comfortable and engaged. First, we replaced the target and cursor with a fruit-like target and a Pac-Man–like cursor to clarify the tracking goal (see Fig. 1b), and added video-game-style background music, where both music and visuals varied between trials. A connection stiffness of $\kappa = 1.7\,\mathrm{Nm/rad}$ was selected during pilot sessions so that the children perceived interaction forces yet could not rely solely on their partner. We also reduced the number of trials, and scheduled breaks with snacks and additional activities (e.g., 3D printing, AR games). Children were permitted to speak with their partner, parents, or the experimenter, but were asked not to discuss experiment-related information. When needed, an experimenter or a parent remained near children to provide comfort while the curtain separated them from their partner. Finally, after every trial, children received a score reflecting tracking accuracy, which was found to be a critical motivator. With these modifications, all 56 children successfully completed the study, indicating that the protocol was effectively implemented and suitable to analyze haptic communication in children dyads.

2.2 How performance changes with age

We evaluated the tracking performance using the root mean square error (RMSE) between the cursor and the target, and examined how it depends on age and connection with a condition-specific quadratic mixed-effect model (Fig. 2a). We considered data during trials 37-50, i.e. after the last break, where the RMSE did not change significantly (slope of the regression line not different from 0, $\beta = -0.032$, $t(721.026) = -1.444$, $p = 0.149$, see Supplementary Information B).

The tracking error decreased with age in both the solo and connected conditions ($F(1, 33.92) = 22.038$, $p < 0.0001$), where the age-related decline was steeper in the solo condition ($F(1, 721.07) = 15.007$, $p = 0.0001$). Across ages, connected trials yielded lower errors than solo trials ($F(1, 33.92) = 22.038$, $p < 0.0001$). The performance plateaued from 13 years in the connected condition and from 12 years in solo, as indicated by regression slopes that were not significantly different from zero in these age-restricted windows (connected: $\beta = -0.044$, $t(10) = -0.118$, $p = 0.909$,

solo: $\beta = -0.332$, $t(17.94) = -1.257$, $p = 0.225$). When younger participants were included (connected: $age \leq 12$, solo: $age \leq 11$), the slope became negative, reflecting improvement with age.

As shown in Fig. 2b, movement smoothness (during trials 37-50) increased with age ($F(1, 53.91) = 11.745$, $p = 0.001$) and did not differ between the solo and connected conditions ($F(1, 722.05) = 1.228$, $p = 0.268$). This aligns with prior work in adults [28], indicating that the mechanical connection between partners did not constrain the participants' movements.

2.3 Children use haptic communication

To investigate whether the performance improvements observed in connected trials reflected haptic communication, we examined how the effects of the connection depended on the partner's ability. To avoid any positive bias from learning, we defined *improvement* as the tracking error in each connected trial minus the tracking error in the following solo trial, and plotted it (Fig. 2c) against the difference in the solo-trial error relative to the partner (*relative performance*). We then fit a linear mixed-effects model to assess the contributions of child age, partner age, and relative performance to improvement.

While age influenced solo performance (Fig. 2a), it did not significantly predict improvement in connected trials ($F(1, 25.64) = 2.001$, $p = 0.169$). By contrast, age difference ($F(1, 46.36) = 17.519$, $p = 0.0001$) and the partners' relative performance (quadratic term: $F(1, 748.63) = 12.674$, $p = 0.0004$) were robust predictors. Consistent with adults data [27], improvement as a function of relative solo performance showed a non-negative, nonlinear increasing trend (Fig. 2c), suggesting that children are also capable of haptic communication. Performance improved when paired with a better partner (Fig. 2d, ii ; $V = 395$, $p < 0.0001$, two-sided one-sample Wilcoxon test with respect to a zero baseline) and did not deteriorate significantly with a less-skilled partner (Fig. 2d, i ; $V = 241$, $p = 0.399$).

Although the color code in Fig. 2c illustrates that improvement also depended on age difference, with younger participants generally benefiting from an older partner (Fig. 2d, iv ; $V = 381$, $p < 0.0001$), this improvement is not solely driven by the partner's age. Notably, interacting with a younger partner did not significantly impair tracking (Fig. 2d, iii ; $V = 273$, $p < 0.230$), and interaction with an older partner improved tracking (Fig. 2d, iv). To assess whether younger children in our sample can use haptic communication, we examined improvement for participants aged 5, 6, and 7 years old (see colored dots in Fig. 2d). It is noted that our sample did not include 5- or 6-year-olds paired with a less skilled partner, however, six 7-year-olds did interact with less skilled partners. In this group, improvement was positive (median =0.024°, IQR = 2.54), indicating that connection to a less-skilled partner did not impair—and could benefit—performance. For 7-year-olds interacting with a better, younger, or older partner, median improvements were also positive (better: median = 0.860, IQR = 1.98; younger: median = 0.858, IQR = 2.36; older: median = 0.649, IQR = 2.48), showing that in children as young as 7 years performance improves across partners of different skill levels and ages.

2.4 Simulation Results

The experimental results suggest that pairs of interacting children use haptic communication in a manner similar to that observed in connected adults [2]. The results also reveal a clear effect of age on both solo and connected tracking performance (Fig. 2a), as well as an effect of age-difference on the partner's improvement (Fig. 2c). Are these age related effects the result of developing capability for haptic communication, or can they be explained by only considering sensorimotor development?

To investigate these questions, we simulated the experiment with 28 virtual dyads. To examine the effect of age, we matched each experimental participant's tracking error (i.e., *skill level*) with a corresponding simulated agent. We then considered two models to describe how the participants would interact with one another: i) *co-activity*, i.e. the partners are coupled mechanically but no information is exchanged over the haptic channel; and ii) that the dyads engage in *haptic communication* using the model from [27].

As can be seen in Fig. 3a, considering only the mechanical coupling between the partners and the developing sensorimotor skill cannot explain the experimental results, where the benefits of the mechanical connection decrease or increase with the partner's skill [2, 27]. However, adding the ability to interpret the interaction force of the partner as task relevant and then integrating that information into their motion plan leads to a trend in the improvement that is consistent with the experimental data (Fig. 3b): haptic communication increases the improvement of tracking performance with a more skilled partner and does not deteriorate it with a less skilled partner. These results highlight the importance of haptic communication in children. Moreover, the similar solo and combined performance (Fig. 3c) of the simulated participants suggests that sensorimotor development largely accounts for the observed age-related effects.

3 Discussion

This work investigated whether and how 28 dyads of children, aged between 5 and 17, use haptic communication. This was investigated using a gamified one-DoF tracking task that was adapted from prior work on adults [27], where children wrists flexion/extension movements were coupled together via a virtual elastic band. The results show that tracking performance improved with age in both the solo and connected conditions, and mechanical coupling reduced errors across ages. As in adults, children improved when connected to a better partner, and connection with a less-skilled partner did not impair their behavior. This yields evidence that school-aged children use haptic communication, where our sample demonstrates this for children as young as seven. Simulations that matched child skill to an established model of haptic interaction reproduced the age-related trends, suggesting that sensorimotor development can account for much of the observed age dependence without needing a separate age-specific maturation of haptic communication.

Age was found to be a strong predictor of tracking performance, with younger children exhibiting larger errors than older children (Fig. 2a). This pattern aligns with developmental literature that shows progressive refinement of sensorimotor control across childhood, with movement smoothness and accuracy approaching adult-like

levels between 8 and 11 depending on the task [23, 25]. Younger children also display greater kinematic variability and larger errors than older children and adults [21, 22, 24, 29]. Such developmental differences likely contributed to the effect of partner age difference on improvement (Fig. 2c,d), as the partner's relative error strongly correlated with age difference (but not with age).

Adapting the adult paradigm from [27] enabled us to probe haptic communication from the age of five, with the statistical evidences supporting clear HC ability from seven years upward. Whether younger children can use this ability—and whether it is innate or acquired—remains open. The observation that school-aged children can infer a partner's motion plan through haptic interaction despite elevated sensorimotor noise suggests an early-emerging capacity.

Compared with adult cohorts (e.g. in [2, 27]), children exhibited less homogeneous tracking ability within dyads. Several factors may have contributed to this broader variability. First, adapting the protocol for children (using gamified visuals and music, end-of-trial scoring, fewer trials with longer breaks, and allowing conversation with their caretaker) likely altered performance and motivation relative to the previous adult studies. In particular, the larger target/cursor from the gamified visuals likely increased tracking error, akin to adding sensory noise [30]; importantly, the experimental setup/task was the same across participants and thus unlikely to drive age-difference findings. Second, interaction roles (e.g., leader–follower dynamics [31]) may contribute to higher relative performance differences. In particular, younger children may be more passive, becoming partially guided from older siblings, as the more skilled individual tends to co-contract muscles and thus lead the interaction [32–34].

Haptic communication requires an ability to integrate visual and haptic information into ongoing motor planning [1]. It is therefore possible that the observed age related effects in performance are caused by development in the integration of this information. While visuo-haptic and audio-haptic integration develop with age [35, 36], with evidence suggesting near-optimal visuo-haptic integration in some tasks by about 8 years [35] and later maturation [37], our simulations indicate that age-related differences in sensorimotor skill can largely explain the observed improvement patterns. Therefore, additional age-specific maturation of multisensory integration is not necessarily required to explain the experimental results, though it may still contribute to adult level tracking performance. Using dyads systematically matched in age (to reduce sensorimotor confounds) could clarify whether haptic communication ability itself strengthens with age.

From early coordinated interactions—such as between twins in utero [38] — to rough-and-tumble play and manipulating objects together, physical interaction is common throughout development, with joint action evident from about 2 years of age [12]. To our knowledge, this study provides the first clear evidence of haptic communication in children, through mutual benefits to both the less and more skilled partners. These results suggest that school-aged children not only integrate visual and haptic inputs but also incorporate partner-derived information into their motion plans. Such interactive sensorimotor models reflect an ability to infer and adapt to a partner's behavior, which may be critical for the development of social interaction. Haptic communication may constitute a basic social behavior, where the process of inferring and

adapting to a partner's behavior represents a step in developing social understanding. The paradigm developed for this study could therefore be potentially used to investigate social-interaction differences, in particular those associated with autism.

4 Methods

The experiment was granted ethical approval by the Joint Research Compliance Office at Imperial College London (reference 15IC2470). Written informed consent was obtained from participants' legal guardians, and children provided written age-appropriate assent prior to participation. It was carried out by 56 children (26 female and 30 male), aged 5-17 years old (mean = 10.28, sd = 2.88), organized into 28 dyads. Most dyads involved siblings (except for two dyads that involved school friends). The handedness of each participant was determined using the Edinburgh Handedness Inventory [39]. Their Laterality Quotient (in [-100,100]) was on average 64.9, with sd = 52.4. All participants were naïve about the experimental conditions. 46 participants reported some experience with haptic controllers such as joysticks or gaming controllers other than touchscreens, 49 reported to regularly play video games from 0.25 to 35 hours/week (mean = 7.18, sd = 7.32).

4.1 Experimental setup and procedure

Participants were tested in dyads as illustrated in Fig. 1a. They were separated by a curtain, where each participant sat in front of an individual monitor, with their dominant hand placed on one handle of the dual robotic interface Hi5 [26]. This robotic interface allows for the study of one degree-of-freedom wrist flexion/extension motions and can independently apply computer-controlled torque on each wrist. The interface was controlled at 1000 Hz, while wrist angle and torque data were recorded at 100 Hz.

The participants were asked to control a cursor visualized on the monitor as a Pac-Man-like character (Fig. 1b), whose position was controlled by their dominant wrist flexion/extension angle $q(t)$. They were instructed to move the character so that its center (displayed as a cross that moved with the character) "captured" (i.e., tracked) a fruit-shaped target "as accurately as possible". The *target's position* $q^*(t)$ (measured in degrees) changed according to a smooth pseudo-random trajectory:

$$q^*(t) = -15.6\sin(0.48\,t^*) + 3.2\sin(1.12\,t^*) + 18.8\sin(1.48\,t^*) - 21.2\sin(2.56\,t^*)\,,$$
$$t^* = t + t_0\,,\quad 0 \le t \le T, \qquad (1)$$

where t is the time in seconds, and each $T = 20\,\mathrm{s}$ long trial started from a randomly selected starting time $\{t_0 \in [0, T]\,,\ q^*(t_0) \equiv 0\}$ to minimize learning of the trajectory. The target trajectory $q(t)$ was mapped to horizontal pixel numbers x on the monitor according to $x = 5q$ as shown in Fig. 1b, so that a 1° wrist flexion corresponds to a movement of the character 2.1 mm to the left on the monitor.

Video-game-style 8-bit background music was played throughout the trial. To keep the children engaged during the study, both the music track and the fruit target changed between trials. The fruits were chosen to have comparable pixel sizes on the monitor, and the music tempo was kept similar across tracks (approximately 100 beats

per minute) to minimize the potential effects of target identity or background music on the children's tracking performance.

The participants tracked the moving target either alone (*solo trial*) or while being mechanically connected to their partner through a virtual elastic band (*connected trial*). The selected stiffness $\kappa = 1.7\,\mathrm{Nm/rad}$ was chosen to ensure that interaction force could be perceived without the ability for participants to rely purely on their partner.

The experimental protocol is depicted in Fig. 1c. To familiarize participants with the interface and the task, the experiment began with a *training phase* in which they tracked the moving target for ten solo trials. This was followed by a *testing phase*, in which participants completed 40 trials alternating between solo and connected conditions, such that each connected trial was immediately followed by a solo trial.

4.2 Procedure modification for a children experiment

The experiment was originally designed as a standard controlled laboratory study using a similar, but shorter, protocol to that used with adults in [27]. However, during pilot testing, several adjustments to the protocol, procedure, and task were necessary to ensure feasibility and suitability for testing with children.

First, the tracking task used in previous studies (e.g., [27]), which required following a moving dot on a screen, was not appealing or engaging to younger participants, who often did not understand why they should be tracking the target line. Therefore, the target and cursor were replaced with a fruit and a Pac-Man-like character. Children were told that for the Pac-man to "eat" the fruit, they needed to move it so that it stayed as close to the fruit as possible.

In developing the main experiment, different stiffness levels were tested for the connected trials: $\{28.5,\ 2.9,\ 1.7,\ 0.8\}\,\mathrm{Nm/rad}$. The two more rigid levels were found to provide too much guidance to the children, where it was reported that "the robot did everything for me and I did not have to move at all." The lowest level was found to provide insufficient feedback, where many pilot participants reported that they did not notice the change between the first ten training trials and the rest. Therefore, this experiment used $1.7\,\mathrm{Nm/rad}$, which was perceived in connected trials as force feedback and allowed them flexibility in their motions.

The experiment consisted of 50 trials. Because the task was repetitive, it could become monotonous for children, leading to loss of interest or distraction. To mitigate this, five different fruit visualizations were created, and the visualization was changed from trial to trial. The background color was also varied from black to lighter greys every ten trials, creating a sense of level progression in the game. A simple music accompaniment was added to maintain attention, with themes rotated among six different melodies across trials. Across all trials, the melodies were kept to a similar tempo, complexity and timbre since it was noticed in the pilot studies that differences in the musical background were reflected in the performance/perception of the participants.

Another major adaptation to the protocol used in [27] was the introduction of breaks during the experiment. Each trial lasted 20 seconds, yielding approximately 17 minutes of robot use during the main trial block. However, children often found the task monotonous and could experience discomfort due to their hand being connected to

the robotic interface, with the forearm fixed in a constant position. Therefore, children were allowed to take short breaks for snacks and drinks. During these breaks, they were also offered a tour of the laboratory showcasing some of the latest developments and letting them try some technologies (e.g. Microsoft HoloLens 2) and even to 3D-print small souvenirs to take home. Following the pilot phase, two breaks were implemented within the main trial block and participants were encouraged to take at least 10 minutes for each break, during which they left the experimental room. The timing of these breaks was kept flexible and depended on each child's preferences and needs. Most commonly, the breaks were taken after trials 17 and 36. This procedure improved comfort for children and helped minimize fatigue effects.

Different to [27], the children were also allowed to speak with each other or with their parents during the experiment if they wished, since it was noticed that, especially for the younger participants of ages five to six, it was quite difficult to exclude communication in the unknown environment of the robotics lab. However, participants were asked not to discuss the experiment, what they felt or their score with others. When necessary, an experimenter or a parent remained near younger children to provide comfort while the curtain separated them from their partner. Moreover, in pilot sessions without performance feedback, children did not remain well focused on the task. Introducing a performance score was critical to ensure engagement and task focus. Therefore, the score—defined as the average position error between the Pac-Man's center and the fruit target—was displayed at the end of each trial.

All these factors and adjustments can potentially have an impact on the collected data, and make the comparison with the data from adults more difficult. Nonetheless, we believe that individualization of the procedure for each child, especially of different age ranges, is necessary to support participants' comfort and sustained task focus throughout the study.

4.3 Data analysis

Trials were excluded from the dataset when experimenters flagged anomalies (e.g., a child looking to a parent rather than the monitor), which were subsequently confirmed via visual inspection of the tracking data. To preserve the experimental structure analysis, exclusions were applied in pairs: if a solo trial was compromised, the preceding connected trial was also removed; if a connected trial was compromised, the subsequent solo trial was removed. Through these criteria, 20 trials were removed (of altogether 1120 trials: 4 trials for 3 dyads and 2 trials for an additional 4 dyads).

We analyzed performance across connected and solo trials using the last 14 (of 50) trials, as participants on average took their final break between trials 36 and 37. We verified that there were negligible changes in these last 7 trials of each condition (see Supplementary Fig. 4; regression line slope not significantly different from 0 ($\beta = -0.032$, $t(721.026) = -1.444$, $p = 0.149$). To exclude reaction time, we omitted the first second of each trial from analysis, retaining 19 seconds of tracking data (see Fig. 1d). Participants' performance was assessed using the root mean square *tracking error* (RMSE) between the cursor (q) and target (q^*) angles as well as the spectral arc length (SPARC) *smoothness* [40].

To estimate the influence of a child's age as well as the effect of the condition (solo or connected), we fit a linear mixed-effects model on the RMSE (Fig. 2a) and motion smoothness (Fig. 2b). Here, this model incorporated fixed effects of the age (centered around its minimum value using $age_c = age - 5$), conditions and their interaction, as well as random intercepts for participants nested within dyads, such that

$$\text{RMSE} = age_c \cdot condition + (1 \,|\, ID_{dyad}/ID_{individual}), \tag{2}$$

using REML with Satterthwaite degrees of freedom. This *baseline model* was compared with a *shared-curvature model* (age_c^2 without interaction) and a *condition-specific model* ($age_c^2 \cdot condition$), each with identical random effects and estimated by maximum likelihood for comparison (see Supplementary Information C). Likelihood Ratio Tests indicated that the condition-specific quadratic model fit better than both the baseline model ($\chi^2(2) = 9.96$, $p = 0.007$) and the shared-curvature model ($\chi^2(1) = 6.17$, $p = 0.013$). For pairwise comparisons, we used tailored contrasts with Holm-Bonferroni adjustment of p-values.

We then identified the age range over which performance remains approximately constant. For this, we additionally fit a condition-specific linear mixed model

$$\text{RMSE} = age + (1 \,|\, ID_{dyad}/ID_{individual}) \tag{3}$$

with progressively expanding age windows starting from the upper tail (oldest participants). For each window, we tested the model's against zero and formed 95% confidence intervals. We defined the onset of non-plateau as the youngest age at which the slope became significantly different from zero when extending the window towards younger ages.

To examine how the connection changed performance, we computed the *improvement* score by subtracting each participant's tracking error in a connected trial from their tracking error in the following solo trial (see Fig 2c). We related this improvement to the participants' age, age difference between the partners and their relative performance (the between-partner difference in solo trial tracking error), using a linear mixed-effects model with random intercepts for participants nested within dyads (see Supplementary Information D):

$$RMSE - RMSE_c = age \cdot (age_p - age) \cdot (RMSE - RMSE_p) + (1 \,|\, ID_{dyad}/ID_{individual}). \tag{4}$$

We then compared this baseline model to one with quadratic term of relative partner performance (without interaction) keeping same random effects using Likelihood Ratio Test. Since the variance explained by the second model was higher ($\chi^2(1) = 12.33$, $p = 0.0004$), it was retained for statistical analysis.

Finally, we investigated whether participants improved with respect to a zero baseline, depending on whether their partner was (i) less skilled, (ii) better, (iii) younger or (iv) older (Fig 2d). For this, after testing for normality, we conducted four two-sided one-sample Wilcoxon tests, with Holm-Bonferroni adjustment of p-values. Additionally, to assess whether younger children in our sample could use haptic communication,

we visually examined improvement for participants aged 5, 6, and 7, and reported descriptive statistics (median and IQR) of the 7-year-olds.

4.4 Simulation

We evaluated the effect of age on the participants using 56 simulated participants (grouped in 28 dyads). As in [27], wrist control was modeled as a discrete-time linear controller acting on a double-integrator system describing the wrist flexion/extension angle q. The state-space dynamics at time step k were given by

$$\mathbf{q}_{k+1} = \mathbf{A}\mathbf{q}_k + \mathbf{B}(u_k + \tau_k), \quad \mathbf{q}_k \equiv \begin{bmatrix} q_k \\ \dot{q}_k \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} 1 & dt \\ 0 & 1 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 0 \\ dt/I \end{bmatrix}, \tag{5}$$

where $\mathbf{A}$ and $\mathbf{B}$ denote the state and input matrices, dt is the time step and $I = 0.002$ kg m^2 the wrist's moment of inertia (as defined for experiments with the Hi5 robot in [27]). The simulated control input was computed via the linear feedback control law

$$u_k = -L_p\left(q_k - \widehat{q}_k^*\right) + L_v\left(\dot{q}_k - \widehat{\dot{q}}_k^*\right), \tag{6}$$

where L_p and L_v are the proportional and derivative gains determined to minimize a physiological quadratic cost function of error and effort [41], and $\widehat{q}_k^*$ denotes the simulated participant's trajectory estimate. In solo trials $\tau_k \equiv 0$. In connected trials

$$\tau_k = 1.7q_k + 0.0286\,\dot{q}_k\,. \tag{7}$$

with fixed stiffness (in Nm/rad) and damping (in Nm/rad s).

Two different models were used to consider how partner's interacted with one another. In the *co-activity* model, the simulated participant was modeled as linear quadratic estimation (LQE), in which the measurement $\mathbf{z}_k$ was given by

$$\mathbf{z}_k = q_k - q_k^* + \mu, \tag{8}$$

where $\mu \in N(0, \Sigma_v)$ characterizes the visual noise naturally present in the participant's tracking. In this model, haptic interaction was modeled as only an input force due to the mechanical coupling.

In contrast, in the *haptic communication* model, haptic interaction was modeled as both an input force that can assist target tracking and as augmented sensory information that can improve the participant's estimate of the current task state. In this model, the partner estimate $\widehat{q}^*$ integrates visual feedback with haptic information from the interaction. Specifically, the participant's own target (from vision) is fused with the partner's target estimate $\widehat{\widehat{q}}^*$ inferred from the haptic interaction. Here, $\mathbf{z}_k$ was given by

$$\mathbf{z}_k = \begin{bmatrix} q_k - q_k^* \\ q_k - \widehat{\widehat{q}}_k^* \end{bmatrix} + \begin{bmatrix} \mu \\ \tilde{\mu} \end{bmatrix}. \tag{9}$$

$\tilde{\mu} \in N(0, \Sigma_h)$ characterizes the haptic noise, which is composed of the partner's visual noise $\Sigma_{\tilde{v}}$ and additional noise resulting from the viscoelasticiy of the virtual band Σ_κ, such that $\Sigma_h = \Sigma_{\tilde{v}} + \Sigma_\kappa$.

The effect of age was incorporated into this simulation model through the variance Σ_v. Participants were simulated using the above interaction model, where Σ_v (which represented the participants sensorimotor skill) was determined by mapping each participant's solo trial performance to an equivalent skill level, consistent with the relationship between skill level and visual noise identified in [30]. Here, this mapping followed the method in [27], with an additional scaling factor (obtained as the best fit between the two datasets) to account for differences in trajectories and cursor types.

Data availability

Data can be provided on request.

Code availability

The code used for analysis can be provided on request.

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Author Contributions

All authors conceived and designed the study; E.I. and J.E. prepared the experimental setup; E.I. and N.P.P. performed the experiments; J.E. carried out the simulations; All authors analyzed the data, interpreted the results, prepared the figures, wrote the manuscript and agree with its content.

Competing Interests

No conflicts of interest, financial or otherwise, are declared by the authors.

Additional Information

Supplementary information. Can be found in pages 19-23.

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Supplementary Information

A Number of dyads per participant age

Age	5	6	7	8	9	10	11	12	13	14	15	16	17
5	-	-	2	-	-	-	-	-	-	-	-	-	-
6		-	-	-	-	-	2	1	-	-	-	-	-
7			3	-	1	-	1	-	1	-	-	-	-
8				-	-	-	2	-	-	-	-	-	-
9					-	-	-	1	-	-	-	-	-
10						1	-	1	1	-	-	-	-
11							1	-	2	2	-	-	1
12								-	2	1	-	-	-
13									1	-	-	-	-
14										-	-	-	-
15											1	-	-
16												-	-
17													-

Table 1 Number of dyads per participant age. Each element of the table denotes the number of dyads for a given participant age pair (as given by the row and column). Dashes denote that there were no dyads for the given age pair.

B Performance across trials

Figure 4 shows how the tracking RMSE and SPARC smoothness evolved over the trials. The RMSE evolution indicates that there was some learning in the initial 10 (solo) training trials, whereas the performance was consistent across the last 14 trials (i.e. 7 trials of each condition), as indicated by a linear-regression slope not significantly different from 0 (statistics provided in the main text).

C RMSE modeling of age-dependent tracking performance

To evaluate the effect of connection and age on the test-phase RMSE, we fit a linear mixed-effects baseline model with fixed effects for centered age $age_c = age - 5$, condition solo/connected, and their interaction, and random intercepts for participants nested within dyads. Estimation used REML with Satterthwaite degrees of freedom. Fixed effects estimates and degrees of freedom are summarized in Table 2. Model fit indices were marginal $R^2 = 0.347$ and conditional $R^2 = 0.733$. Scaled residuals showed heavy tails (approximately -3.78 to 6.89), motivating subsequent evaluation of higher-order models.

Fixed effects	Estimate	SD	DF	t-value	p-value
Intercept	13.174	0.571	57.743	23.057	<0.0001
age_c	-0.759	0.080	49.941	-9.464	<0.0001
$condition_{connected}$	-2.387	0.260	722.067	-9.204	<0.0001
$age_c : condition_{connected}$	0.228	0.043	722.067	5.261	<0.0001

Table 2 Fixed-effects estimates for baseline mixed effect model of RMSE.

We then investigated whether adding quadratic age terms increased explained variance. Two quadratic models were fit: a shared-curvature model with age_c^2 (without interaction, see Table 3) and a condition-specific model with $age_c^2 * condition$ (Table 4), both with the same random effects and estimated by maximum likelihood for comparison. Adding a shared quadratic age (age_c^2, no interaction) yielded only marginal improvement over the linear model ($\chi^2(1) = 3.79$, $p = 0.052$; $\Delta AIC = 1.79$ (negligible); $\Delta BIC = +2.87$ (worse)). In contrast, allowing for condition-specific curvature improved the fit over a single shared curvature ($\chi^2(1) = 6.17$, $p = 0.013$; $\Delta AIC = 4.17$, meaningful; $\Delta BIC = +0.49$, slight penalty for complexity) and over the baseline model ($\chi^2(2) = 9.96$, $p = 0.007$; $\Delta AIC = 5.96$, meaningful; $\Delta BIC = +0.49$, slight increase).

Fixed effects	Estimate	SD	DF	t-value	p-value
Intercept	13.952	0.662	59.427	21.086	<0.0001
age_c	-1.175	0.221	36.294	-5.318	<0.0001
$condition_{connected}$	-2.387	0.259	724.071	-9.216	<0.0001
age_c^2	0.039	0.020	33.925	1.993	0.054
$age_c : condition_{connected}$	0.228	0.043	724.071	5.268	<0.0001

Table 3 Fixed-effects estimates for shared curvature mixed effect model of RMSE.

Under the condition-specific quadratic fit, the tracking error decreased with age in both conditions ($F(1, 33.92) = 22.038$, $p < 0.0001$). Here, the decline was steeper for solo trials (slope at age 5: $\beta_{Age} = -1.36$ RMS/year; 95% $CI = [-1.87, -0.89]$)

Fixed effects	Estimate	SD	DF	t-value	p-value
Intercept	14.281	0.675	64.186	21.169	<0.0001
age_c	-1.357	0.233	44.631	-5.831	<0.0001
$condition_{connected}$	-3.044	0.369	724.070	-8.249	<0.0001
age_c^2	0.057	0.021	43.052	2.714	0.010
$age_c : condition_{connected}$	0.592	0.152	724.070	3.882	0.0001
$condition_{connected} : age_c^2$	-0.035	0.014	724.070	-2.490	0.013

Table 4 Fixed-effects estimates for condition-specific curvature mixed effect model of RMSE.

and milder for connected trials ($\Delta\beta_{condition,age} = +0.59$; 95% $CI = [0.29, 0.89]$). The curvature though indicated diminishing returns, especially in the solo condition ($\beta_{age^2} = +0.057$; 95%$CI = [0.015, 0.102]$) with smaller curvature in connected ($\Delta\beta_{condition,age^2} = -0.035$; 95% $CI = [-0.063, -0.007]$).

D RMSE modeling of tracking performance improvement with connection

To evaluate the effect of age, partner age, and performance difference on improvement, we fit a linear mixed-effects baseline model with relevant fixed effects and interactions, and random intercepts for participants nested within dyads (REML with Satterthwaite degrees of freedom). Fixed effects estimates and degrees of freedom are reported in Table 5. Random-effects standard deviations were 0.802 (dyad intercept), 0.653 (individual within dyad), and 1.890 (residual). Model fit indices were marginal $R^2 = 0.334$ and conditional $R^2 = 0.488$. Scaled residuals showed heavy tails (approximately -4.744 to 6.010), motivating evaluation of higher order.

Fixed effects	Estimate	SD	DF	t-value	p-value
Intercept	0.968	0.829	26.485	1.167	0.254
$age_p - age$	0.724	0.181	48.806	3.998	0.0002
age	-0.010	0.078	26.128	-0.128	0.900
$RMSE - RMSE_p$	0.203	0.118	633.395	1.716	0.087
$RMSE - RMSE_p : age_p - age$	-0.032	0.026	659.356	-1.245	0.214
$RMSE - RMSE_p : age$	0.011	0.012	646.105	0.888	0.375
$age_p - age : age$	-0.045	0.017	46.589	-2.689	0.010
$RMSE - RMSE_p : age_p - age : age$	0.006	0.003	626.360	2.367	0.018

Table 5 Fixed-effects estimates for baseline mixed effect model of improvement.

We then investigated whether adding a quadratic term in relative performance improved fit, retaining the same random-effects structure and using maximum likelihood for comparison (Table 6).

Including $((RMSE - RMSE_p)^2$ (no interaction) improved fit over the linear model ($\chi^2(1) = 12.33$, $p = 0.0004$; $\Delta AIC = 10.3$, large; $\Delta BIC = 5.7$, strong). We therefore retain the quadratic model for inference.

Fixed effects	Estimate	SD	DF	t-value	p-value
Intercept	0.749	0.879	24.846	0.851	0.403
$age_p - age$	0.776	0.185	46.357	4.186	0.0001
age	0.012	0.083	24.441	0.140	0.890
$RMSE - RMSE_p$	0.191	0.118	641.584	1.628	0.104
$(RMSE - RMSE_p)^2$	0.024	0.007	748.625	3.560	0.0004
$RMSE - RMSE_p : age_p - age$	-0.062	0.027	705.401	-2.306	0.021
$RMSE - RMSE_p : age$	0.011	0.012	653.365	0.855	0.393
$age_p - age : age$	-0.049	0.017	43.596	-2.880	0.006
$RMSE - RMSE_p : age_p - age : age$	0.004	0.003	618.016	1.692	0.091

Table 6 Fixed-effects estimates for quadratic mixed effect model of improvement.

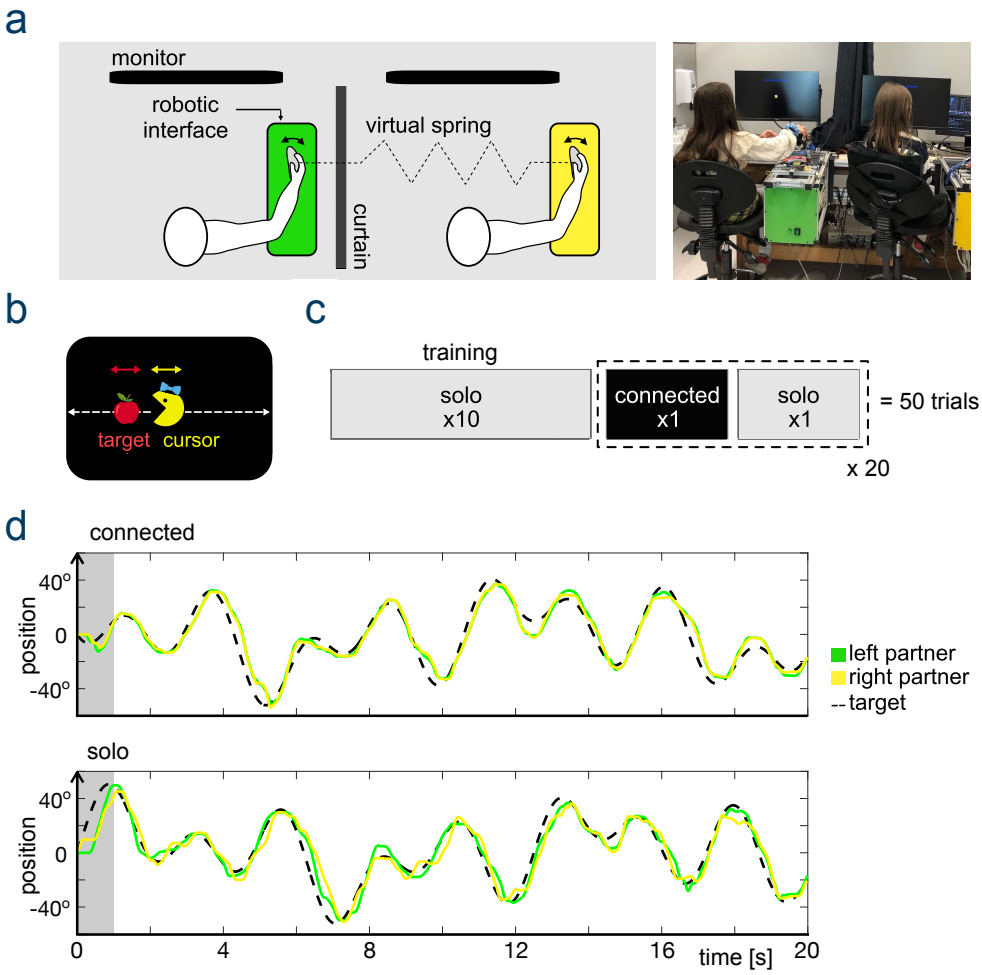


Fig. 1 Experiment to investigate haptic communication in children. (a) Pairs (or *dyads*) of participants sat in front of a monitor and held one handle of a dual robotic interface with their dominant hand. (b) Each participant controlled the motion of a cursor on their monitor, shaped as a Pac-Man-like character and tracked a target shaped as a fruit. (c) After completing ten solo training trials, participants performed 20 connected trials and 20 solo trials, alternating between the two conditions. (d) Example trajectory, showing the wrist angle of two partners along the reference trajectory during their last connected and solo trial. Participants tracked the target for 20 seconds in each trial, where the first second (shaded grey area) was discarded for analysis.

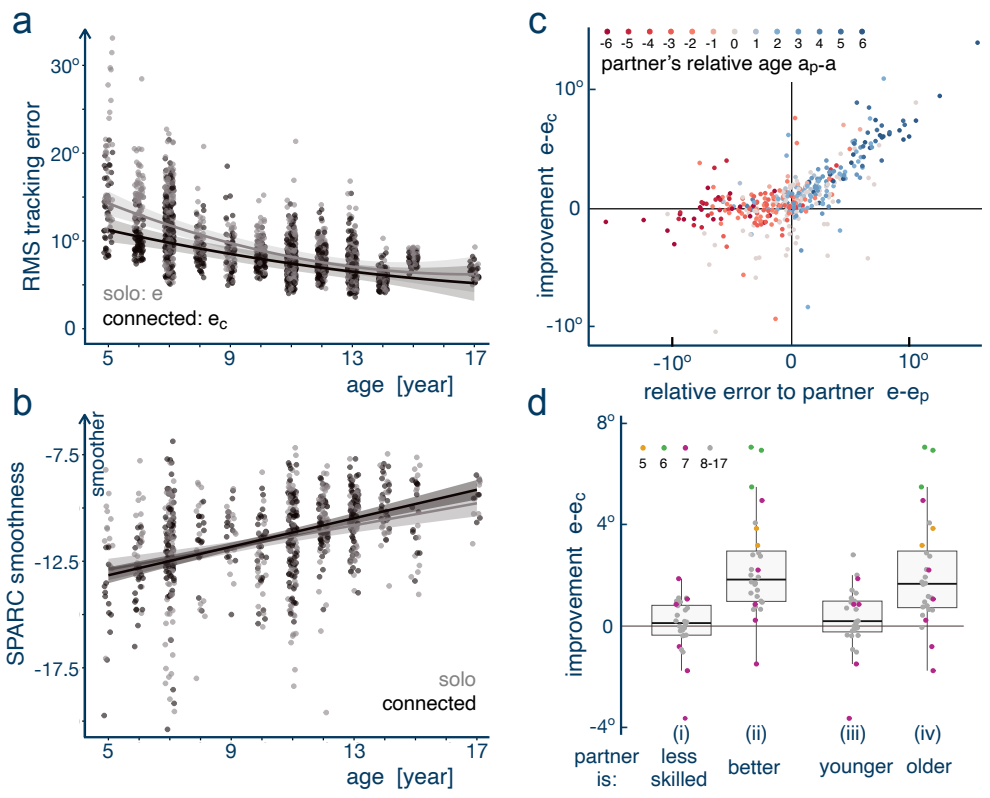


Fig. 2 Tracking performance of school-age children in solo and connected (dyad) conditions (during trials 37-50). a) Tracking error decreases with age and is further reduced when connected. b) Movement smoothness increases with age independent of the connection. c) Performance improvement, defined as the total tracking error in a solo trial minus the error in the preceding connected trial, plotted against the difference in the solo-trial tracking error relative to the partner (relative performance). The resulting non-negative, nonlinear increasing trend is similar to that observed in adults [27], suggesting that school-aged children also use haptic communication. Each point corresponds to one participant in one of the last 14 trials; the color gradient encodes the partners' age difference (partner age minus own age). d) Haptic communication is corroborated, as (i) connection with an older (or better) partner improves tracking while a younger partner does not impair it; and similarly (ii) a less skilled partner does not degrade performance while a more skilled partner improves it. Each point corresponds to one participant using the average of their last 14 trials; the colored dots highlight children aged 5, 6 and 7, compared to those aged 8-17 (in grey).

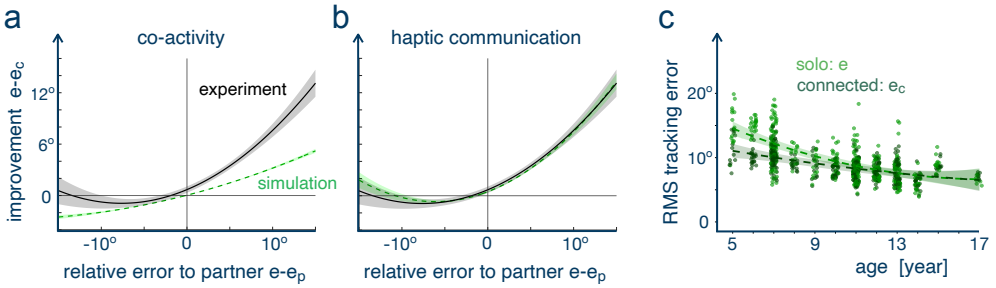


Fig. 3 Simulation of joint tracking in children. Experimental (black) and simulation (green) improvement with co-activity using only the mechanical connection (a) and with haptic communication (b). The central lines indicate the mean, and the shaded region the 95% confidence interval of the linear mixed effect model that best fits the data. c) Similar to the experimental results, simulated haptic communication yields tracking error that decrease with age and are further reduced when partners are connected.

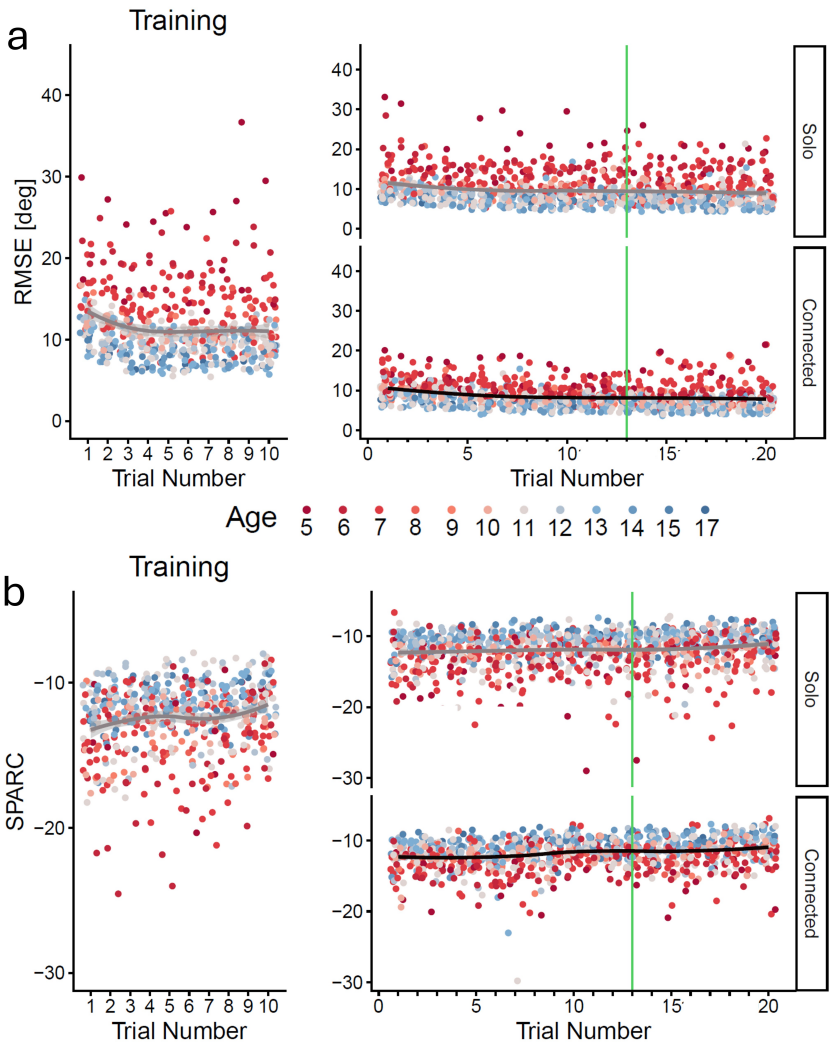


Fig. 4 Evolution of performance across trials. a) Tracking RMSE. b) SPARC smoothness. Each data point represents one participant on a given trial in either the connected or solo condition; all training-phase trials are solo. Dot color encodes participant age. Solid curves show a locally weighted polynomial (LOESS) fit with shaded confidence bands. The vertical green line marks the time of the last break.