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2 **Move together, bond together: Visuomotor synchrony and social bonding**
3 **in children and adults**

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Abstract

Interpersonal synchrony is a fundamental part of human social interaction, with known effects on facilitating social bonding. Moving in time with another person facilitates prosocial behaviour, however, it is unknown if the degree of synchronisation predicts the degree of social bonding. Similarly, while people readily fall in synchrony even without being instructed to do so, we do not know whether such spontaneous synchronisation elicits similar prosocial effects as instructed synchronisation.

Across two studies, we investigated how context (social vs non-social stimulus) and instruction (instructed vs uninstructed) influenced synchronisation accuracy and bonding with the interaction partner in adults (*Study 1*; 34 women, 6 men, $M_{age} = 20.38$, predominantly White undergraduates) and children (*Study 2*; 27 girls, 26 boys $M_{age} = 8.80$, from predominantly White middle-class families). The results revealed improved visuomotor synchrony within a social, compared to non-social, context in adults and children. Children, but not adults, synchronised more accurately when instructed to synchronise than when uninstructed. For both children and adults, synchronisation in a social context elicited stronger social bonding towards an interaction partner as compared to synchronisation in a non-social context. Finally, children's, but not adults', degree of synchrony with the partner was significantly associated with their feelings of social closeness. These findings illuminate the interaction of sensorimotor coupling and joint action in social contexts and how these mechanisms facilitate synchronisation ability and social bonding.

Keywords: interpersonal synchrony, social bonding, entrainment, visuomotor synchrony, mimicry

Move together, bond together: Visuomotor synchrony and social bonding in children and adults

Interpersonal synchrony, whereby two or more people move in temporal and spatial coordination with each other, is observed frequently and cross-culturally in group dance, marching bands, and children's clapping games (Ehrenreich, 2006; McNeill, 1995). Research investigating embodied cognition has shown that synchronous interpersonal movement plays a crucial role in social bonding starting from early in infancy (Trainor & Cirelli, 2015; Tunçgenç, et al., 2015; Tunçgenç & Cohen, 2016). Although the ability to synchronise movements with external stimuli develops in early childhood years (Kurgansky & Shupikova, 2011), relatively little is known about how a social versus non-social context impacts synchronisation accuracy and its subsequent social bonding outcomes in children and adults. Building upon bottom-up sensory and top-down joint action accounts of interpersonal synchrony, we examined the conditions that facilitate synchronisation and its social bonding outcomes in adults (*Study 1*) and in children (*Study 2*).

An individual can synchronise their movement with a non-social object (i.e., a metronome) or with another person (interpersonal synchrony). Research investigating interpersonal synchrony has found that individuals feel more bonded to others after performing a task with them that involves synchronous, as compared to asynchronous interpersonal movement. For instance, adults report increased feelings of cohesion, trust, empathy and pro-social behaviours following interpersonal synchrony (Anshel & Kippler, 1988; Hove & Risen, 2009; Launay et al., 2014; Valdesolo et al., 2010; Wiltermuth & Heath, 2009). Similarly, in children, interpersonal synchrony has been shown to facilitate pro-social sharing (Rabinowitch & Knafo-Noam, 2015; Rabinowitch & Meltzoff, 2017) and helping behaviour (Tunçgenç & Cohen, 2016). Therefore, moving in coordination with other people seems to incur social benefits. What, then, are the mechanisms that enable the positive social effects of movement synchrony? Two prominent accounts have been put forth in the literature to explain the synchrony – social bonding link: a bottom-up sensorimotor coupling account and a top-down joint action account.

Sensorimotor coupling defines the process whereby an external rhythm is identified (e.g., through visual observation) and integrated into one's own movements (Phillips-Silver et al., 2010). Previous research has shown that interpersonal synchrony is improved when information about an external rhythm is available through multiple modalities, for example

visual and auditory (Gipson et al., 2016). Further, some stimuli may be easier to couple with than others. For instance, viewing a biologically similar stimulus (i.e., hand), compared to a non-social, mechanical stimulus, can facilitate interpersonal synchronisation (Calvo-Merino et al., 2005; Iacoboni et al., 1999, Kirschner & Tomasello, 2009), arguably due to the ease of creating motor representations of the other person's actions (Brass & Heyes, 2005; Rizzolatti, 2005; Casile et al., 2011). In turn, perceptual representation of synchronised movement may result in a less effortful and more rewarding experience through minimising neural processing costs (Ramamoorthy & Konvalinka, 2017), thereby creating a cycle encouraging interpersonal synchrony. Indeed, an fMRI study has shown the brain's reward system to be activated following synchronous, as compared to asynchronous, interpersonal movement (Kokal et al., 2011). Thus, sensorimotor coupling plays a key role in interpersonal synchrony. Given that adults and children show greater social bonding to a partner following interpersonal synchrony, (e.g. Hove & Risen, 2009; Tunçgenç & Cohen, 2016) a social context that encourages sensorimotor coupling may facilitate synchronisation accuracy and social bonding.

In addition to perceptual and motor processes, top-down joint action processes are also thought to facilitate interpersonal synchrony. Joint action can be defined as the coordination or complementarity of two or more individuals' actions "to bring about a change in the environment" within a social interaction (Sebanz et al., 2006). According to this framework, the shared goal and mutual knowledge of the fact that this goal is shared unites the interaction partners' intentions, attention and representation of the task in hand (Tomasello et al., 2005). These shared representations enable easier prediction of the other's behaviour and movement coordination (Sebanz et al., 2006; Ramenozi et al., 2015). Prior research has indeed found that joint action contexts facilitate synchronisation, for instance when individuals shared the goal to synchronise with each other (van Ulzen et al., 2008). Even when individuals share a goal or intention that is not related to synchronisation, enhanced interpersonal synchrony can be observed. For example, individuals who shared a mutual goal to empty a box of 100 plastic balls coordinated movements more than those without a shared goal (Allsop et al., 2016). These works indicate that when individuals share a common goal, they are more likely to coordinate their movements with each other and thus joint action contexts can facilitate interpersonal synchrony. Developmentally, it was found that children as young as 2.5 years old synchronised better when performing a drumming activity with another person as opposed to with a robot (Kirschner & Tomasello, 2009). Notably, the richness of visual information was comparable in the person and robot drummer conditions. Thus, the synchronisation boost observed in the

person condition can be attributed to the ease of sensorimotor coupling with a biological stimulus and/or sharing a representation of the “jointness” of the action. Although this study shows that synchronisation improves in a condition in which both sensorimotor coupling and joint action are facilitated simultaneously, it does not show whether social bonding outcomes would follow. These highlighted works demonstrate how top-down processes, such as social engagement in joint action contexts, can improve interpersonal synchrony. Thus, joint action context may also serve to boost synchronisation accuracy *and* social bonding.

In laboratory settings, interpersonal synchrony has often been studied in two conditions: by explicitly instructing the participants to move in synchrony with the target stimuli (“instructed synchrony”) or by leaving the participants to move as they wish (“uninstructed synchrony”). Research has found that adults are better at walking in time to a non-social stimulus, such as an auditory beat, when they are explicitly instructed to do so (Leow et al., 2018). Furthermore, adults are more likely to tap in time to an auditory beat when they are instructed to do so (Repp & Keller, 2004). These works suggest that intention to synchronise is highly influential for synchronisation with non-social objects. Considering interpersonal synchrony, studies have repeatedly shown that people tend to spontaneously entrain to others’ movements when walking (Nessler et al., 2011), swinging their legs (Schmidt et al., 1990), clapping (Nèda et al., 2000) and rocking in chairs (Richardson et al., 2007). These findings suggest humans have a natural propensity to synchronise with others however, interpersonal synchrony can also be enhanced when an explicit instruction to synchronise is given (van Ulzen et al., 2008). Based on this research, we might expect that instructing participants to synchronise in either a social or non-social context would facilitate synchrony. Yet, no study has directly compared the effects of instruction within social and non-social contexts for synchronisation and its social bonding outcomes.

Given that our knowledge of social bonding effects is largely, if not entirely, based on research using instructed interpersonal synchrony (Anshel & Kippler, 1988; Hove & Risen, 2009; Launay et al., 2014; Valdesolo et al., 2010; Wiltermuth & Heath, 2009), it is unclear whether uninstructed synchrony can elicit similar feelings of social bonding. Empirical findings show that people have a tendency to fall into interpersonal synchrony with each other (Nèda et al., 2000; Nessler et al., 2011; Richardson et al., 2007; Schmidt et al., 1990) yet we do not know whether spontaneous interpersonal synchrony serves a social bonding function. It is worth noting that when investigating interpersonal synchrony, the instructed and

uninstructed conditions do not necessarily differ in terms of the degree of sensorimotor coupling or joint action context. When an individual is instructed to move in synchrony with another person, this goal is not necessarily shared between the two partners, and thus, a joint action context is not necessarily created. Whilst there is evidence that humans do have a natural propensity to synchronise with others, it is unknown whether similar social bonding effects are seen following uninstructed versus instructed synchrony.

Across two studies, we investigated how adults (*Study 1*) and children (*Study 2*) synchronise their movements and subsequently bond with their interaction partner. Synchronisation was assessed with a finger-tapping task, with participants being randomly assigned to either the instructed or uninstructed condition. Combining the bottom-up and top-down accounts of interpersonal synchrony, we created a social context that included joint action (i.e., participant tapping together with the partner) and better opportunities for sensorimotor coupling (i.e., participant viewing the partner's hand). This social context was contrasted to a non-social context that included neither joint action (i.e., participant tapping on their own while the partner is doing another task) nor enhanced sensorimotor coupling (i.e., participant viewing a moving ball).

We made four predictions: (1) participants will synchronise with the stimulus better in the social than in the non-social context, (2) participants will feel more bonded to their partner after completing the finger tapping task in a social as compared to a non-social context, (3) synchrony and social bonding will be greater in the instructed compared to uninstructed condition, and (4) the degree of interpersonal synchrony in the social context will positively predict social bonding. The latter hypothesis would reveal the relative contributions of the top-down versus bottom-up processes – beyond performing a task in a joint action context, the precise degree of sensorimotor coupling would be associated with the social effects observed after interpersonal synchrony.

STUDY 1: Adults

Methods

Participants

Forty-three adults (37 women, 6 men, $M_{\text{age}} = 20.44$), predominantly White, undergraduate students, participated in the current study. Students volunteered to participate in return for course credit. Data from three participants were removed due to experimenter error. Therefore, the final sample consisted of forty adults (34 women, 6 men, $M_{\text{age}} = 20.38$) evenly split into the instructed and uninstructed conditions. Post-hoc power analysis and the reported effect sizes (see Results section below) show that despite some variability, our sample size allowed for sufficient power to detect the main effects found in both studies, when the type I error rate set was to .05 ($1 - \beta \geq .9$). Ethical approval for both *Study 1* and *Study 2* were granted by the [masked for blind peer-review]. The experiment was conducted in accordance with the ethical standards of the Declaration of Helsinki and GDPR.

Design

A 2 (context: social vs non-social) x 2 (instruction type: instructed vs uninstructed) x 2 (stimulus tempo: 750ms vs 1000ms tempo) mixed design was used. All participants were presented with two social and two non-social trials, with the visual stimulus being presented at 750ms and 1000ms tempo within each condition. The two speeds (750ms and 1000ms) were used in order to maintain engagement with this repetitive task; no specific hypotheses were made about the effects of the speed conditions. The between-group factor was type of instruction, in which half of the participants were explicitly instructed to synchronise with the visual stimulus whilst the remaining half were told to tap as they wish, without any emphasis on synchronising with the stimulus. Participants were randomly assigned to the instructed or the uninstructed condition. Order of the social and non-social trials as well as the stimulus tempi was fully counterbalanced. The dependent variables were synchronisation accuracy (i.e., difference from the stimulus in ms) and social bonding as measured by subjective assessment of proximity with the partner.

Materials and Measures

Synchronisation accuracy. The tapping tasks were conducted using a mediated reality device called MIRAGE (see Figure 1A; Newport et al., 2010), which presents live video images of the participant's hand in real time. When participants put their hand into the MIRAGE device, they can no longer see their actual hand; instead, they see a live footage of their hand

in the same spatial location, depth plane and from the same visual perspective as their ‘real’ hand. Each participant had their arm covered with a black curtain to prevent them from viewing their ‘real’ hand within the MIRAGE device. This device has been successfully used with adults and children in previous research (e.g. Greenfield et al., 2017; Newport & Gilpin, 2011; Newport et al., 2015; Ropar et al., 2018).

In our study, the social (hand) and non-social (moving circle) stimuli were presented in the MIRAGE window opposite the live image of the participant’s hand, as can be seen in Figure 1A. Finger taps were registered using a button placed under the participant’s index finger. The MIRAGE device was connected to a computer that controlled the tempo of the visual stimulus and recorded the timestamps of the participants’ taps at millisecond precision. Each participant completed four trials in total: two trials in the social context (at 750ms and 1000ms tempo) and two trials in the non-social context (at 750ms and 1000ms tempo). Each trial consisted of 70 cycles of visual stimulus. Therefore, for each participant, approximately 140 responses were recorded for the social context and 140 for the non-social context.

Synchronisation error was calculated as the Root Mean Square (RMS) of the difference between the participant’s and the stimulus’ inter-tap intervals. The stimulus inter-tap intervals were constant over time within a trial (i.e., either 750 or 1000, depending on the stimulus tempo). To calculate the participants’ inter-tap intervals, we subtracted the timestamp of one tap from the timestamp of the subsequent tap in a sliding window fashion (window size = 2). Next, the difference between the participants’ inter-tap intervals and that of the stimulus was taken. Finally, the RMS of this difference was calculated, yielding one synchronisation error score per participant per trial. To obtain single synchronisation accuracy scores for the social and non-social conditions each, we took the mean of the two trials comprising these conditions, respectively. Synchronisation error scores closer to zero indicate less difference between the participant and the stimulus, and thus better synchronisation accuracy.

Social closeness. Social closeness was measured using the 7-point Inclusion of Other in Self scale (Aron et al., 1992). In this scale, two circles labelled “you” and “[partner’s name]” were shown in differing proximities to each other across the 7 points, starting with very distant at 1 and gradually getting closer, with a near-merging image at 7. To calculate the change in feelings of closeness, a baseline measure was taken once at the start of the study and four more times at the end of each tapping trial. Change in social closeness was calculated separately for each experimental trial by deducting the participants’ baseline score from their score following

that trial. Then, the mean of the two difference scores obtained from the social and the non-social trials were taken to construct one social and one non-social score per participant, respectively. The more positive the social bonding difference values are, the closer the participant felt towards the experimenter after the tapping task as compared to baseline.

Procedure

All participants were tested in a quiet room at [masked for blind peer-review], where they were sat across from the experimenter and the partner in both social and non-social context conditions (see Figure 1B for a schematic of the set-up). The experimental procedure took a total of 30 minutes.

Firstly, participants completed a baseline measure of the Inclusion of Other in Self scale. Then, participants placed their dominant hand into the MIRAGE to start the finger tapping task. The participants were instructed to place the tip of their index finger on a button that was used to register taps. The button made a dull click when tapped. The participants were instructed to keep their hand in this location throughout all trials. All participants completed a practice trial to ensure they were comfortable with MIRAGE and that they understood the task. Once five consecutive taps had been successfully registered, the practice trial was terminated, and the participant proceeded to the experimental trials.

Figure 1. Schematic of the study procedure.

(A) Participant view of the MIRAGE window, with their hand on the bottom right of the window and the social stimulus (partner's hand) and non-social stimulus (red ball) opposite. The cartoon house and animal were used in the child-friendly dummy task.

(B) Study set-up. The partner sat in the same position in both the social and the non-social context conditions.

(C) Procedure of Study 1 and Study 2 (order of context and stimulus tempo counterbalanced across participants).

In the experimental trials, participants completed two social and two non-social context trials, each followed by the social closeness measure (see Figure 1C). Regardless of the instruction condition, all participants were first given the following instructions: “If you look through the MIRAGE window, you will see a ball (non-social context) moving elliptically up and down or [the partner’s name]’s finger (social context) tapping. Please start tapping as soon as you see the ball/finger start and keep tapping until it stops”. At this point, the instructions diverged depending on the instruction condition. While participants in the instructed condition were told “to try to tap in time with the ball/finger as best as you can”, participants in the

264 uninstructed condition were told “to keep looking at the ball/finger while tapping as slowly or
265 as fast as you wish”.

266 In the non-social context, a red ball moved up and down in an elliptical movement for
267 the duration of the trial. In the social context, participants viewed a pre-recorded video of a
268 hand tapping although they were told that the partner was tapping in real time. The size of the
269 area in which the visual stimulus moved was kept constant across the social and non-social
270 stimuli to ensure that the amount of visual information was similar between conditions. In both
271 social and non-social context, the partner sat opposite the participant, without explicitly
272 interacting with the participant (e.g., by making eye contact or smiling). The only differences
273 between contexts were that in the social context: (a) the participants were told that the partner
274 was also finger-tapping, and (b) the participants viewed a hand, rather than a ball, as they
275 tapped.

276 To ensure that all participants attended to the stimuli similarly in all conditions, we also
277 introduced a dummy task. A child friendly dummy task was used so it could also be introduced
278 in *Study 2*. Participants were told the visual stimulus was knocking on the door of the house
279 (see Figure 1A) and waking up the animals inside. Pictures of animals would then appear next
280 to the visual stimulus 2-3 times per trial. Since the animal pictures appeared next to the target
281 stimulus, participants were required to look towards the stimulus at all times and then tell the
282 names of the animals whose pictures popped up.

Results

Analysis

For both *Study 1* and *Study 2*, the timestamp data was processed using a custom-written script on MATLAB R2018b and the statistical analyses (including the power analysis using package “pwr”; Champely et al., 2020) were conducted using R (R Core Team, 2014). To examine Hypotheses 1 – 3, mixed 2 (context: social vs non-social – within variable) x 2 (instruction: instructed vs uninstructed – between groups variable) x 2 (stimulus tempo: 750ms vs 1000ms – within variable) separate ANOVA tests were conducted with synchronisation accuracy and social bonding measures as the dependent variables. Stimulus tempo was included in the analyses as an independent variable despite not being part of a specific hypothesis to control for its potential effects on our outcome measures. To examine Hypothesis 4, linear regression was conducted within the social context, with synchronisation accuracy as the predictor and social bonding measure(s) as the outcome variable(s).

Synchronisation accuracy

A mixed 2x2x2 analysis of variance (ANOVA) was used to investigate the effects of context (social vs non-social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on synchronisation accuracy (i.e., RMS of inter-tap intervals). The results revealed main effects of context ($F(1,37) = 31.71, p < .0001$, partial $\eta^2=.46$), and tempo ($F(1,37) = 85.83, p < .0001$, partial $\eta^2=.70$) on synchronisation accuracy. There was no significant main effect of instruction or any significant interactions (all $ps > .05$). Participants synchronised better (i.e., lower error) in the social context ($M = 343.66, SD = 103.04$) than in the non-social context ($M = 408.67, SD = 97.38$; see Figure 2A) and better when the visual stimuli moved at 750ms tempo ($M = 319.81, SD = 93.52$) as compared to at 1000ms tempo ($M = 431.70, SD = 84.68$). These findings show that irrespective of whether explicitly instructed to do so, participants were better able to synchronise with the partner’s hand in the social context compared to the moving ball stimulus in the non-social context. To account for the possibility of more errors in cases when inter-tap intervals are larger (i.e., stimulus tempo at 1000ms vs 750ms), we also calculated a normalised synchronisation accuracy metric by dividing the RMS inter-tap intervals by the stimulus tempo. Analyses using this normalised metric similarly showed significantly better synchrony performance in the social than in the non-social context (see Appendix A).

Figure 2. Synchronisation accuracy and social closeness by context and instruction conditions in adults. (A) Synchronisation accuracy per context and instruction condition. The y-axis shows mean RMS of the difference in inter-tap intervals between the participant and the stimulus, with higher scores indicating more errors and worse synchrony accuracy. (B) Social closeness per context and instruction condition. Mean change in closeness score (test – baseline), with higher scores indicating an increase in closeness as compared to baseline. Coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.

Social closeness

To assess the impact of context (social vs non-social), stimulus tempo (750ms vs 1000ms), and instruction condition (instructed vs uninstructed) on change in social closeness from baseline, a mixed 2x2x2 ANOVA was employed. This analysis revealed a significant main effect of context ($F(1,38) = 32.49, p < .0001$, partial $\eta^2 = .46$), on social closeness. No other main effects or interactions were statistically significant ($p > .05$). While participants' social closeness towards the partner increased in the social context ($M = 0.40, SD = 1.09$), a decrease was observed after doing the tapping activity in the non-social context ($M = -0.71, SD = 0.9$), as can be seen in Figure 2B. This suggests that social context, but not explicit instructions to synchronise, affected the participants' feelings of social closeness.

Finally, using linear regression analysis, we explored whether synchrony accuracy is associated with change in social closeness within the social context condition. The results were not significant ($F(1,38) = 0.92, p = .34, \beta = .003, SE = .003, p = .34$), indicating that the degree of synchronisation with the partner was not related to the observed increase in feelings of social closeness.

Discussion

As predicted, we found that a social context facilitated synchronisation accuracy and social bonding with an interaction partner in adults. This novel finding in adults corresponds to previous work that has demonstrated social facilitation of synchronisation accuracy in children (Kirschner & Tomasello, 2009). Contrary to our predictions, synchronisation accuracy was not enhanced when the participants were explicitly instructed to tap in time with the stimulus, and the degree of interpersonal synchrony within the social context did not predict subsequent social bonding.

Despite the partner being present in both the social and non-social contexts, only the social context enhanced synchronisation accuracy and social bonding. This finding suggests that both synchronisation accuracy and social bonding can be facilitated (a) in a context in which the partner is perceived to be engaging in the task, and (b) when the participant views a biologically more similar stimulus that facilitates sensorimotor coupling. Given that our social context combined these two elements, we cannot identify specifically which aspect of the social context led to the observed effects. Nevertheless, these findings extend previous work that has found increased social bonding following instructed interpersonal synchrony (e.g., Hove & Risen, 2009; Marsh et al., 2009; Launay et al., 2014) by showing that the same effects are observed following uninstructed synchrony as well.

The hypothesised effect of instruction on synchronisation accuracy was not observed; participants were similarly accurate at synchronising with the visual stimulus in the instructed and uninstructed conditions. Yet, visual inspection of the data shows that participant responses were less variable in the instructed condition than in the uninstructed condition, with the responses in the instructed condition displaying a bipolar distribution, suggesting a clustering of the errors based on the stimulus tempo. The absence of an effect of instruction seems to contradict previous work demonstrating that intentionality facilitates synchronisation (van Ulzen et al., 2008; Leow et al., 2018). However, in the current study, the intention was not explicitly shared between the participant and the partner, whilst in previous work the intention was shared between individuals (van Ulzen et al., 2008). This may suggest that shared intentionality between individuals, rather than individual intention, is key to facilitating coordination, rather than merely the instruction to synchronise.

Additionally, we found no relationship between the degree of synchronisation accuracy and the strength of feelings of social closeness. This may suggest that sensorimotor coupling of visual information did not drive the bonding effects; instead, joint action factors within the social context may have been sufficient to boost social closeness.

363 Finally, despite not having any specific hypothesis based on stimulus tempo, we also
364 found that visuomotor synchronisation accuracy was higher with stimuli moving at a faster
365 tempo. This effect is most likely attributable to the Spontaneous Motor Tempo of individuals
366 being faster than the tempo at which the stimuli was presented. Previously work has found that
367 adults aged 18-38 years-old have a mean spontaneous motor tempo of 630ms (McAuley et al.,
368 2006). It is therefore likely that participants were more comfortable tapping at the faster rate of
369 750ms than they were at 1000ms, therefore synchronisation accuracy was greater when the
370 tempo of the stimuli was faster.

STUDY 2: Children

Methods

Participants

Sixty-one children (30 girls, 31 boys) aged 4.53 to 14.32 years old ($M_{age} = 8.79$, $SD = 2.18$) from predominantly White, middle class families took part in the present study. The participants were recruited through a public event held at [masked for blind peer-review] in July 2019, in which children participate in short research studies over the course of a week. Three participants with a confirmed clinical diagnosis of Autism Spectrum Disorder were removed from analysis as previous work has found this population to exhibit atypical synchrony behaviour (Marsh et al., 2013; Fitzpatrick et al., 2016; Kaur et al., 2018). Four participants were removed from analysis for being extreme outliers (± 2 SDs from the mean). Therefore, the final sample consisted of fifty-four neurotypical children (27 girls, 26 boys) aged 4.53 to 14.32 years old ($M_{age} = 8.80$, $SD = 2.16$). There were 26 participants in the instructed condition and 28 participants in the uninstructed condition. All children were screened for developmental difficulties via a parental background questionnaire. Verbal mental age was assessed using the British Picture Vocabulary Scale III (BPVS III; Dunn & Dunn, 2009) to ensure participants did not have a delay in their cognitive development. The parents of all children gave written consent for their child to participate and the children provided verbal assent at time of the study.

Design

The design of *Study 2* differed slightly from *Study 1* due to adjustments made for a child sample. Participants completed two, rather than four, tapping trials in total: one in the social context and one in the non-social context. This meant that stimulus tempo and the order of context conditions were counterbalanced across, not within, participants, such that half of the participants were presented with the social stimulus at 750ms and the non-social at 1000ms, while the remaining half were presented with the social stimulus at 1000ms and the non-social at 750ms. The independent variables of this study were identical to *Study 2*: context (social vs non-social), instruction type (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms). The dependent variables were synchronisation accuracy (i.e., difference from the stimulus in ms) and social bonding. Social bonding was measured in two ways: change in social closeness, measured by subjective assessment of proximity with the partner and change in spontaneous behavioural mimicry, measured by frequency of mimicked behaviours. The

mimicry task was added as a child-friendly way of assessing social bonding in addition to the proximity measure that mimicked the scale measure used in the adult study. The nature of the testing event in which *Study 2* was conducted allowed for the addition of the spontaneous behavioural mimicry.

Materials and Measures

Synchronisation accuracy. To measure synchronisation accuracy, the same MIRAGE virtual reality device and the same measure of RMS of inter-tap intervals was used as in *Study 1*.

Social closeness. A child-friendly version of the social closeness task was used here as compared to *Study 1* to ensure participants could understand and relate to the task. To assess social closeness, the participants were asked to imagine a hypothetical scenario (e.g., waiting for a train at the station) and indicate first where they would like to sit, and then where they would like the partner to sit in this scenario by placing stickers that represented the child and the partner. The scenarios were accompanied by matching pictures that had 7 seats on them. Building upon similar measures that used physical closeness as a proxy for social closeness (Ijzerman & Semin, 2010; Over & Carpenter, 2015; Tuncgenç & Cohen, 2016b), participants placing themselves closer to the partner was considered indicative of higher social closeness. Since the children were first asked to place themselves and then the partner, the distance between the two people was calculated as a proportion of the number of available seats once the children had placed themselves. To examine change in social closeness, the baseline distance score was subtracted from the distance scores following the tapping trials. Therefore, positive values indicated increased closeness from baseline, while negative values indicated decreased closeness.

Mimicry. Based on research showing positive affiliative effects of mimicking and being mimicked (for reviews, see: Lakin et al., 2003; Stel & Vonk, 2010), spontaneous behavioural mimicry was assessed as a proxy for social bonding. Mimicry was assessed three times with a two-minute-long, semi-structured picture-guessing game played between the participant and the partner: first at baseline, and twice more thereafter each tapping trial. In the game, the partner viewed three pictures in sequence and described each to the participant. The participant, who had not seen the pictures, then guessed which picture (out of three options per picture) they thought the partner had been describing. Whilst describing the pictures, the

partner made upper body touches on three areas (i.e., rubbing or scratching her head, shoulder or upper arm), amounting to a total of nine touches per block. The same picture descriptions were used across participants with the touches occurring at the same timepoints.

The frequency of spontaneous behavioural mimicry was post-hoc coded from the video recordings of the mimicry sessions using the open-source E-LAN software (version 5.8). An action was considered an instance of mimicry if the children touched, rubbed or scratched their head, shoulders or upper arms following the partner performing one of these actions within the same block. Two raters, one blind to the hypotheses and both blind to the actions of the partner, coded the videos. Inter-rater reliability on 40% of the videos was excellent ($r(25) = .89, p < .0001$). To examine change in mimicry, difference scores were obtained by deducting the frequency of mimicry at baseline from the frequency of mimicry following each tapping trial.

Procedure

The procedure was identical to *Study 1* with the addition of the spontaneous behavioural mimicry measure completed at baseline and following each tapping trial.

Results

Synchronisation accuracy

A mixed 2x2x2 ANOVA was used to investigate the effects of context (social vs non-social – within variable), instruction (instructed vs uninstructed – between groups variable) and stimulus tempo (750ms vs 1000ms - within variable) on synchronisation accuracy (i.e., RMS of inter-tap intervals). The results revealed significant main effects of context ($F(1,48) = 9.56, p = .003$, partial $\eta^2 = .17$), instruction ($F(1,49) = 84.11, p < .000$, partial $\eta^2 = .63$) and tempo ($F(1,48) = 9.89, p = .003$, partial $\eta^2 = .17$). As can be seen in Figure 3A, participants' synchronisation accuracy was higher (i.e., lower error) in the social context ($M = 295.16, SD = 205.9$) than in the non-social context ($M = 343.53, SD = 227.75$). Participants also synchronised better in the instructed condition ($M = 154.22, SD = 87.27$) than in the uninstructed condition ($M = 452.06, SD = 188.07$) and when the stimulus moved at 750ms ($M = 290.16, SD = 195.57$) than at 1000ms ($M = 352.92, SD = 237.63$). There was a significant interaction between context and tempo $F(1,48) = 35.19, p < .0001$ (see Figure 3B), such that within the 1000ms tempo, synchronisation accuracy was better in the social ($M = 268.59, SD = 188.41$) than in the non-social ($M = 443.99, SD = 254.76$) context ($F(1,22) = 34.07, p < .0001$), while no such difference was observed within the 750ms tempo ($p = .56$).

Similar to the approach followed in *Study 1*, we also assessed the normalised synchronisation accuracy metric, which was calculated by dividing the RMS of inter-tap intervals by the stimulus tempo for that trial. These results confirmed that even when accounting for the possibility of increased errors in larger inter-tap intervals, the effect of context remained significant such that children synchronised with the stimulus better in the social than in the non-social context (see Appendix B).

Figure 3. Synchrony accuracy by context, stimulus tempo and instruction conditions in children. Lower scores on the y axis indicate less synchrony errors and better accuracy. Coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.
(A) Synchronisation accuracy per context and instruction condition.
(B) Synchronisation accuracy per context and stimulus tempo conditions.

Social closeness

A mixed 2x2x2 ANOVA was used to examine the effects of context (social vs non-social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on change in social closeness (i.e., difference from baseline). This analysis revealed a significant main effect of context on social closeness ($F(1,44) = 9.38, p = .004, \text{partial } \eta^2 = .18$). There was no significant main effect of instruction or stimulus tempo and no interaction effects (all p 's $> .05$). As can be seen in Figure 4A, while social closeness towards the partner increased following tapping in the social context ($M = 2.13, SD = 37.41$), a decrease was observed in feelings of closeness following tapping in the non-social context ($M = -14.85, SD = 37.69$).

Figure 4. Social bonding by context, instruction and synchronisation accuracy in children.

In (A) and (B), coloured dots indicate individual data points, black diamonds indicate group mean and whiskers indicate standard error of the mean.

(A) Change in social closeness (test – baseline) per context and instruction condition, with positive scores indicating an increase and negative scores indicating a decrease in closeness as compared to baseline.

(B) Change in mimicry frequency (test – baseline) per social context and instruction condition, with positive scores indicating an increase and negative scores indicating a decrease in mimicry as compared to baseline.

(C) Relationship between synchrony error and change in social closeness within the social context.

492 Mimicry

493 A mixed 2x2x2 ANOVA was used to investigate the effects of context (social vs non-
 494 social), instruction (instructed vs uninstructed) and stimulus tempo (750ms vs 1000ms) on
 495 change in mimicry frequency (i.e., difference from baseline). The results revealed a main effect
 496 of context on mimicry frequency ($F(1,44) = 19.93, p < .0001$, partial $\eta^2 = .31$). There was no
 497 significant main effect of instruction, stimulus tempo or any interaction effects (all p 's $> .05$).
 498 As can be seen in Figure 4B, while mimicry frequency showed an increase from baseline in
 499 both social and non-social context conditions, this increase was significantly greater in the
 500 social context ($M = 1.72, SD = 2.69$) as compared to the non-social context ($M = 0.34, SD$
 501 $= 1.47$).

Additionally, we conducted two separate linear regression tests to investigate whether synchronisation accuracy within the social context condition predicted change in spontaneous behavioural mimicry and social closeness. While synchronisation accuracy did not predict change in mimicry frequency ($F(1,45) = 0.29, p = .59, \beta = .001, SE = .002, p = .59$), it significantly predicted change in social closeness ($F(1,48) = 20.47, p < .0001, \beta = .08, SE = .02, p < .0001$). Pearson correlation test similarly showed a significant negative relationship between synchrony errors and social closeness ($r(48) = -.34, p = .01$; see Figure 4C). Therefore, as synchrony between the children and the partner increased, so did the children's subsequent feelings of social closeness.

Discussion

As predicted, and in line with previous works (Kirschner & Tomasello, 2009; Tunçgenç et al., 2015), we found that both visuomotor synchrony and social bonding were facilitated in a social as compared to a non-social context. Extending previously used measures of social bonding, we showed that children spontaneously mimicked their partner more following interpersonal synchrony compared to synchronisation in the non-social context.

In line with Hypothesis 3, children synchronised with significantly greater accuracy when explicitly instructed to synchronise with the stimulus compared to when they were left free to tap as they wished. Unlike the adults in *Study 1*, children may have had a heightened sense of commitment when instructed, and hence increased effort to synchronise (Michael & Szekely, 2018). In addition, prior work has demonstrated children are less consistent in how they tap as compared to adults (Geuze & Kalverboer, 1994; Greene & Williams, 1993), so it is possible that an explicit instruction therefore increased effort and improved synchronisation accuracy in the instructed condition.

Additionally, despite lower synchronisation in the uninstructed condition, social bonding for both measures remained similar across uninstructed and instructed conditions. This may suggest that merely completing the task together with the partner allowed for social bonding to occur. Yet, in line with Hypothesis 4, the degree of interpersonal synchrony still mattered: the more synchronous the children were with the partner, the greater was their feelings of social closeness. In comparison to adults, this may suggest that children are more likely to base social bonding on unconscious precise sensorimotor coupling between themselves and a partner.

Similar to the adult data, we found an unexpected effect of stimulus tempo on synchronisation accuracy. It is likely that a faster spontaneous motor tempo of children led to greater accuracy in the 750ms tempo compared to the 1000ms tempo (McAuley et al., 2006).

General Discussion

As predicted, we found that a social context, as compared to a non-social context, facilitated interpersonal synchrony and social bonding in both adults (*Study 1*) and children (*Study 2*). Uniquely in children, we found that magnitude of social closeness was related to the degree of synchronisation accuracy.

We found evidence of social context facilitating interpersonal synchrony in adults and children. Previous paradigms have been criticised for their use of social and non-social contexts as often the social condition holds more sensory information, therefore allowing for more accurate synchronisation (see Kirschner & Tomasello, 2009). For instance, the available sensory information is much richer viewing the movement of a whole body as compared to a flashing dot or metronome. However, in the current study only the image of a hand was used as the social context, therefore the area covered by the moving visual stimuli was the same between conditions. Subsequently, this social facilitation effect is unlikely to be attributable to the amount of visual information. Instead, viewing a finger tapping may have enhanced neural representation of the external stimulus (i.e., hand movement), therefore increasing predictability and coordination with the stimulus, (Brass & Heyes, 2005; Calvo-Merin et al., 2005; Iacoboni et al., 1999) making it easier to synchronise with. According to predictive coding principles, synchronisation with the social stimulus may have been less cognitively demanding and effortful, therefore producing fewer errors (Koban et al., 2019). Furthermore, this current finding corresponds to previous works that have suggested the presence of a social agent can induce perceptions of a joint action (Kirschner & Tomasello, 2009; Tunçgenç et al., 2015). Such joint action formation is argued to allow for better anticipation of movement of the external stimulus (Sebanz et al., 2006) and therefore give rise to a coupling of self and other movement (Hove, 2008).

Our social context differed from the non-social context both in terms of providing better opportunities for participants to couple with the visual stimulus (i.e., with a hand as opposed to a ball), and in terms of the partner engaging in joint action with the participants. Both of these factors may facilitate social bonding through promoting participants' perception of the partner as *moving* like them and *being* like them (Meltzoff, 2007). We found that in adults, the degree of synchronisation accuracy did not predict subsequent feelings of social closeness,

while in children it did. This may suggest that sensorimotor coupling was not fundamental for adults to feel social closeness; instead, the joint action context of the social condition may have been sufficient to enhance social bonding. Alternatively, as the accuracy of synchronisation was not consequential to task success, it may have reduced the extent that accuracy impacted upon feelings of social closeness. Future research can create experimental conditions that disentangle the relative roles of bottom-up and top-down factors in facilitating social bonding following synchrony.

In addition, children mimicked the partner more following interpersonal synchronisation. Whilst this corresponds to previous research that has shown mimicry can facilitate social bonding (Lakin et al., 2003; Stel & Vonk, 2010), the present finding shows for the first time that synchronisation in a joint action context can elicit increased mimicry. This expands possible measures of social bonding to include mimicry. Although interpersonal synchrony enhanced both social closeness and mimicry, the two aspects are distinguishable as synchronisation accuracy did not predict a change in mimicry. One reason for this may be the relatively reduced variability in the mimicry frequencies compared to the social closeness scores, yielding a correlational approach less powerful. Still, the absence of a link between mimicry and interpersonal synchrony suggests that while social closeness may be more selectively boosted by interpersonal synchrony compared, merely completing the tapping task with the partner appears to be sufficient for increased mimicry to occur.

This study has emphasised the importance of interpersonal synchrony for social bonding, which opens up further questions as to whether an impaired ability to synchronise, especially in social contexts, may be related with social-communicative impairments. For instance Autism Spectrum Conditions are characterised by both socio-communication (Wing & Gould, 1979) and sensorimotor differences (Greenfield et al., 2017; Ropar et al., 2018). Future work could therefore explore visuomotor synchrony in autistic children and adults.

Whilst the present study provides key insights into the roles of instruction, context, and tempo on visuomotor synchronisation and social bonding, certain limitations should be noted. Firstly, in *Study 2* not all participants experienced both contexts at both tempi due to time constraints of the event at which the experiment was conducted. While it is unlikely that groups of children would be distinguished by their ability to synchronise better at social-fast vs social-slow stimuli, thereby affecting the results in a systematic way, future research can implement full counterbalancing to eliminate this possibility. Finally, the social vs non-social contrast in the current study was created by combining insights from the bottom-up sensorimotor accounts

with the top-down joint action accounts. Future research can tease apart how either factor affects synchrony accuracy and its subsequent bonding effects.

The current research adds to a growing body of literature by revealing the importance of social context for interpersonal synchronisation and social bonding in children and adults. For the first time, we show how social bonding can be elicited following spontaneous (uninstructed) interpersonal synchronisation. These findings provide an evidence-base that social contexts with increased opportunities for sensorimotor coupling and joint action improve synchronisation and bonding between partners.

Author Contributions

Conceived and designed the experiment: [masked for blind peer-review]. Performed the experiments: [masked for blind peer-review]. Analysed the data: [masked for blind peer-review]. Wrote the paper: [masked for blind peer-review]. Edited the paper: [masked for blind peer-review]

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Appendix A

Regression table examining how synchrony accuracy predicts social bonding in adults. (outcome variable: Inclusion of Other in Self scale scores).

Predictor	β	SE	t value	p value
Synchrony accuracy (RMS of ITI)	.003	.003	.96	.34

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Appendix B

Regression table examining how synchrony accuracy predicts social bonding in children (A) with social closeness scale scores as the outcome variable, and (B) with mimicry frequency as the outcome variable.

Predictor	β	SE	t value	p value
(A) Synchrony accuracy (RMS of ITI)	.08	.02	4.53	< .0001
(B) Synchrony accuracy (RMS of ITI)	.001	.002	.54	.59

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