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METHODOLOGICAL ARTICLE

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Capacity for social contingency detection continues to develop across adolescence

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Abstract

The capacity for dynamically coordinating behaviour is assumed to have largely matured in infancy. In adolescence—another sensitive period for social development—the primary focus on *individual* social cognition as the main driver of interaction has prevented the study of actual social interaction as behavioural coordination within dyads. From a dynamic perspective, however, capturing real-time social dynamics is essential for the assessment of social interactive processes. In order to improve the understanding of social development during adolescence, we investigated the potential developmental course of social contingency

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detection in dynamic interactions. Pairs of 205 Belgian adolescents (83 male, 122 female), aged 11–19, engaged in real-time social interaction via the Perceptual Crossing Experiment (PCE). Comparing early, middle and late adolescents, we found a generally higher performance of late adolescents on behavioural and cognitive measures of social contingency detection, while the reported awareness of the implicitly established social interaction was lower in this group overall. Additionally, late adolescents demonstrated faster improvement of behavioural social coordination throughout the experiment, compared with the other groups. Our results indicate that social interactive processes continue to develop throughout adolescence, which manifests as faster social coordination at the behavioural level. This finding underscores dynamic social interaction within dyads as a new opportunity for identifying altered social development during adolescence.

KEYWORDS
adolescence, development, dynamic social interaction, Perceptual Crossing Experiment, social capacity

1 | INTRODUCTION

Social interaction requires dynamic flexibility in the detection of and responsiveness to each other (Coey et al., 2012; Dale et al., 2013). This capacity for dynamically coordinating behaviour with each other—being social—can be assessed from infancy, when detection of and responsiveness to social contingencies start to develop (Trevarthen & Aitken, 2001). After infancy, adolescence has been posited as a second sensitive period of social development (Blakemore & Mills, 2014). During adolescence, peers become more important as adolescents achieve more independence from their caregivers, and social skills need to be developed to adapt and respond to varying new social environments and roles to prepare for adulthood (Crone & Dahl, 2012; Dahl et al., 2018). Social cognitive processes have been investigated extensively in developmental studies in adolescence (Blakemore & Mills, 2014; Crone & Dahl, 2012; Nelson et al., 2005). Social cognition reflects the cognitive capacity to process social stimuli (Green et al., 2015), and research has mainly focused on processes such as emotion recognition and Theory of Mind. In experimental designs to assess social development, including dynamic (online) coordination between individuals is important to capture the dynamic interplay of social interaction (Obhi & Sebanz, 2011). Given the specific needs for adolescent social development to adapt to changing social contexts throughout adolescence, it is plausible that this specific capacity to dynamically coordinate behaviour with each other in establishing social interactions follows a continued developmental course. Dynamically coordinating behaviour with each other requires the sensitivity to other people's responsiveness to one's presence and behaviour, referred to as the capacity for social contingency detection (Hermans et al., 2020). Testing this capacity's developmental course requires the assessment of social dynamics between at least two individuals, which has generally been very complex to grasp using assessments to test individual social cognition. In targeting underlying behavioural coordination, the study of the capacity for social contingency detection could, therefore, benefit from isolating basic interactive capacity, such that it can be studied at a level at which it could already be relevant to guide more complex behaviour (as suggested by De Jaegher et al., 2010). Recently, novel experimental techniques capturing dynamic social interaction at the level of milliseconds have emerged and can now be used in adolescence for the first time to investigate its developmental course (Hermans et al., 2020; Leong & Schilbach, 2019; Redcay & Schilbach, 2019).

The social coordination that takes place in establishing an interaction involves two individuals who continuously respond to each other (Gallotti et al., 2017). Recently, efforts have been made to integrate social coordination between two individuals in real time into neuroscience, resulting in research on hyper-scanning; inter-brain synchronisation during real-time social interaction between two individuals (Czeszumski et al., 2020; Kinreich et al., 2017). Although findings on brain synchronisation have been related to behavioural social coordination as well, this coordination mainly reflects motor synchronisation, which is not necessarily social. Moreover, these findings are based on very small sample sizes (fewer than 10 dyads) (Czeszumski et al., 2020). Therefore, to improve our understanding of the developmental course of dynamic social interactive processes, we argue that a study of behavioural coordination based on social contingencies in a large sample of dyads is warranted before it can be combined with measures of physiological and neurological synchronisation.

In order to capture dynamic social interaction at a behavioural level, the Perceptual Crossing Experiment (PCE) has been developed (Auvray et al., 2009; Lenay & Stewart, 2012). The PCE captures the capacity for social contingency detection and responsiveness within a minimalistic virtual environment and allows quantifying various aspects of dynamic interaction. Pairs of participants are instructed to detect and identify the other within this minimalistic virtual environment in which they cannot see or hear each other. They only receive haptic feedback (i.e., a vibration on their hand) whenever they cross another entity (Froese et al., 2014; Zapata-Fonseca et al., 2016; Zapata-Fonseca et al., 2018). This other entity could either be the 'avatar' of the other person, a non-responsive, moving entity or a non-responsive, non-moving entity. To detect and identify the other person, participants need to interact with the entity, moving back and forward, to establish an interaction and capture the responsiveness of the other, thus detecting social contingency in the interaction. By isolating and assessing this specific interactive capacity, using haptic feedback only, the PCE focuses on behavioural coordination via this single modality. Therefore, the PCE is a simplified version of real-life social interaction, which typically requires multiple modalities (e.g., visual, auditory input) to interact. However, similar to other research in social cognition which uses experimental designs to isolate and assess a specific aspect of social cognition (e.g., emotion recognition), we aim to specifically study social contingency at this haptic level. This is based on the idea that it may drive or may be fundamental to more complex social cognitive development (De Jaegher et al., 2010).

The virtual environment simulates the dynamic process of interaction, and several slightly different set-ups have been used (reviewed by Deschamps et al., 2016). Within the current experiment, four aspects of the interaction have been quantified. First, adaptive interactive behaviour can be assessed in each round of the experiment, defined as the amount of time that the interacting partners spend in each other's proximity—capturing the behavioural component of the interaction. Second, awareness of the interaction is inquired about by asking participants after each round whether they felt that they were doing something together, whether the other avatar could sense their presence and whether they correctly identified the other. This variable purely captures awareness of the interaction, as individuals did not receive any feedback on whether they successfully established an interaction. Third, during the experiment, individuals are asked to make an explicit judgement on whether the other was detected. They push a button whenever they think they have detected and interacted with the other person, capturing a more cognitive component of the interaction. This variable is referred to as accuracy of social contingency detection. Fourth, to supplement quantitative findings and elucidate participants' strategy during the experiment, a qualitative item on the strategy used to successfully establish the interaction is added at the end of the experiment (similar to Froese et al., 2014).

Recently, it has been demonstrated that dynamic interaction can be assessed in a large sample of adolescents aged 12–19, using a shortened version of the adult-version PCE (Hermans et al., 2020). Findings from PCE studies in adults indicated that awareness was heightened in case of reciprocal interaction where both individuals in the dyad successfully identified the other, compared with one-way detection and no interaction at all (e.g., Froese et al., 2014; Froese et al., 2020). Compared to these studies, the results in the adolescent sample were similar but less marked (Hermans et al., 2020). These findings were interpreted as indicating a potential developmental course of social contingency detection, such that less marked results compared with adults reflect not fully matured dynamic interactive processes in adolescents (Hermans et al., 2020). Based on the dominant working hypothesis in the developmental literature that more implicit elements of social coordination have matured before adolescence (e.g., Crone & Dahl, 2012; Nelson et al., 2005), we hypothesise that, using the PCE, the awareness of the interaction and interactive behaviour (i.e., time spent together) in the PCE will not further improve during adolescence, while the accuracy of social contingency detection will follow a developmental course during adolescence. Similarly, we expect a more advanced (cognitive) strategy to detect social contingency (based on Auvray et al., 2009) to be associated with a higher age and with accuracy of social contingency detection. The first PCE study in adolescents (Hermans et al., 2020), which partially used the same dataset as the current study, was a methodological study focused on proof-of-principle of the PCE as a measure of social contingency detection. The current study adds to this work by directly examining age differences between three different adolescent age groups (in an extended sample with a more similar number of participants in each age group) on various task metrics (i.e., time spent together, awareness, accuracy, and strategy) to understand the developmental time course of PCE performance.

In the current study, we investigate the development of social contingency detection by comparing age groups reflecting early, middle, and late adolescence on overall PCE performance, captured by four separate variables—time spent together, accuracy, awareness, and strategy -, and the improvement on the first three variables throughout the experiment. We hypothesise that (H1) Older adolescents demonstrate a better average performance on accuracy, but not awareness and time spent together, (H2) Older adolescents will improve faster on accuracy throughout the experiment (interaction age group × round), and (H3) Older adolescents demonstrate a more advanced strategy to establish an interaction, which is associated with accuracy (association between strategy and accuracy).

2 | METHODS

2.1 | Sample

Two hundred and eight participants completed the PCE[1]. Participants from the general population were recruited in secondary schools, as part of a large longitudinal cohort study on adolescent well-being (Kirtley et al., 2021, April 2). Participants were recruited from the first, third, and fifth year of secondary school, reflecting an age range from 11 to 19 years. These age groups will hereafter be referred to as early, middle, and late adolescence, respectively, reflecting developmental stages (e.g., Blakemore & Mills, 2014). Ethical approval for this study was obtained from the local Medical Ethics Committee (Ref: S6 1395), including informed consent obtained for experimentation with human subjects. This study was post-registered on the Open Science Framework (a form of pre-registration that occurs following data collection, but before conducting the analyses; Benning et al., 2019), available via https://osf.io/ucqjn/?view_only=238f71d652774209abda936068795e8d.

2.2 | Perceptual crossing experiment

2.2.1 | Procedure

The PCE and procedure in adolescents have previously been described in detail elsewhere (Hermans et al., 2020). Briefly, participants performed the task in randomly assigned dyads. As a pair, participants sat back-to-back and

[1] Part of the current sample (N=148) has previously been described in a study on the proof-of-principle of the PCE (Hermans et al., 2020).

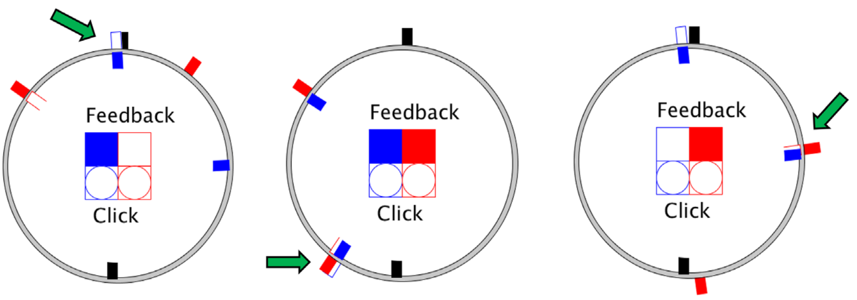

FIGURE 1 The virtual space included six entities: avatars of both participants (red and blue rectangles with white extension); free to explore the virtual space), shadows of red and blue avatars (red and blue rectangles without white extension; moving at a fixed distance of red and blue avatar), and two static objects, each perceivable by either the red or blue avatar (black rectangles; fixed in space at different locations for red and blue avatar). From left to right: blue avatar receives vibration from crossing with its static object; red and blue avatar receive vibration from crossing with each other; only red avatar receives vibration from crossing the blue avatar's shadow. Figure created by *L. Zapata-Fonseca* and *T. Froese*

listened to Brownian noise via a headphone, ensuring that they could not hear or see each other. Their goal was to find their partner and establish an interaction within a virtual environment, a one-dimensional loop, in which they were both embodied as avatars. The virtual environment and, therefore, the participants' position in virtual space during the experiment was invisible and inaccessible to both the participants and the researcher during the experiment. In order to move through the virtual space, they moved a trackball back and forth with their dominant hand. Each time they encountered an entity, they would feel a vibration via a pad attached to the hand moving the trackball. Moving and receiving haptic feedback (i.e., the vibration) was the only way in which participants could establish an interaction. In addition to the other participant's avatar, the virtual environment included two other entities that could be encountered; the shadow of the other participant's avatar and a static object (Figure 1). Each participant could perceive and interact with the other avatar, the shadow of the other avatar, and one static object. Tactile feedback was provided to the players during the time that their avatar overlapped with one of the entities, otherwise the vibration was off. Participants had 1 min (i.e., a round) to press a button (i.e., click) with their free hand once per round at the moment they were most confident of crossing with the other avatar. Both participants within a pair clicked independently, were not obliged to click, and were instructed to cooperate. This cooperation included helping the other by remaining responsive to the other after they clicked before the round ended. Participants were explicitly not explained how they should remain responsive to the other.

Participants were instructed to find each other—detect the other's responsiveness (i.e., social contingency)—within each of six rounds of 1 min. Each new round, participants started at a random position within the virtual environment. They were instructed that they could encounter a 'chair' (i.e., static object) and another moving entity (i.e., the other's shadow), in addition to the other participant's avatar.

The total duration of the experiment was 20 min, including instructions and six 1-min rounds. Each round was followed by a three-item self-report questionnaire on a tablet computer, assessing awareness of the interaction. After the sixth round, participants received an additional open-ended question to disclose the strategy they used to detect the other during the experiment. For motivational purposes, participants were debriefed about a general strategy they could have used to find each other after the experiment ended. Both during and after the experiment, they did not receive any information on their own, or the other's performance, or the specific nature of the other's shadow. The experiment was either conducted or closely supervised by the first author in order to maintain high quality and consistency in the execution of the procedure. The experimental variables are described in Table 1.

TABLE 1 PCE variables: Description and details of computation

PCE variable	Description and details of computation
Behaviour defined as time spent together	Total time (in milliseconds) during which the distance between the entity and the participant's avatar was below the threshold value at 70 pixels (Froese et al., 2014; Hermans et al., 2020). Computed per round for each entity in the virtual space.
Accuracy	Proportion correct clicks from the total number of clicks. Computed independently of the other participant's click, rated as '1' if correct (i.e., assigned to the other avatar[a]) or '0' if incorrect (i.e., all other clicks).
Awareness	Average of 3-item self-report questionnaire across rounds with a click (or two items if no click). Three items included 'To what extent did you feel that the other could sense your presence?', 'To what extent did you feel you were doing something together?', and 'How confident were you that you clicked correctly?'[b], rated on a 7-point Likert scale (not at all – very much).

[a]Click assignment was based on the entity closest to the participant's avatar within a distance of 70 pixels. If not assigned to either the other avatar, the other's shadow, or the static object, the click was categorised as unclassified. .
[b]This item included 'I haven't clicked' as an answer option, which was coded as a missing value.

2.2.2 | Strategy

Data on the open-ended strategy question at the end of the experiment were missing for 20% of participants. This item was added to the procedure of the experiment following the first weeks of data collection to supplement our quantitative findings. Participants first indicated whether or not they used a strategy, and if they did, they entered this as free text. The qualitative answers were coded and categorised into three types with an increasing level of advancement. These have been formulated by the first author who set up and led the experiment, based on strategies described in the first study by Auvray et al. (2009) and open-text experiences described by Froese et al. (2014). Inspired by these studies and based on observations during the experiment (registered before analysis of the data), the three categories reflected the three stages participants went through to find each other: (1) moving, (2) detecting movement from the other entity, and (3) detecting responsiveness from the other entity. Following this, strategy type 1 included unspecific and vague strategies, for instance "just feeling". Strategy type 2 reflected strategies to distinguish entities mainly based on their movement, for example, giving meaning to perceived longer and shorter vibrations. Strategy type 3 included strategies to distinguish entities based on both movement and responsiveness, such as following the other avatar or going back and forth. Two independent raters performed the coding, and Cohen's kappa for the interrater agreement was $\kappa = .48$. Disagreements were discussed, after which the final coding was performed.

2.3 | Statistical analyses

2.3.1 | Testing of hypotheses

Statistical analyses were performed using STATA 14.2 (StataCorp., 2015). We used aggregated data using the mean score across six rounds for each participant for H1 and H3 to study the role of age group and strategy type on separate PCE variables, that is, time spent together, accuracy, and awareness. Age group was a three-level categorical factor variable, reflecting early, mid- and late adolescence. Strategy type was a three-level categorical factor variable. For H2, we used multilevel PCE data with six rounds for each participant.

In order to test the association between age group and specific PCE variables across rounds per individual (H1), we performed separate linear mixed-effect analyses with PCE variables as dependent variables and age group (with levels early, middle, and late adolescence) as the independent variable. As the coefficients provided differences compared to the reference group (early adolescence), differences regarding the mean level of outcomes between late and mid-adolescence were additionally tested using the "lincom" command. To study the moderating role of age group on the association between round and PCE variables (H2), we first performed separate mixed-effect multilevel analyses with PCE variables as dependent variables and round as the independent variable. To test if the association between round and PCE variables was different for different age groups, the interaction round × age group was added. Lastly, associations between strategy type and separate outcome variables were tested by performing separate linear mixed-effect analyses with strategy type (with levels 0, 1, 2, or 3) as independent variable and PCE variables as outcome variables (H3).

We performed the mixed-effect multilevel analyses with nested random effects for each level of measurement (participants nested in pairs and pairs nested in schools). For aggregated data, the random effect structure only included pairs nested in schools. The variable time spent together was square-root transformed for the analysis as the data were right-skewed and included zero values (Hermans et al., 2020). After the analysis, time spent together was back-transformed and reported in seconds per round. All statistical tests were two-tailed using $\alpha = .05$. In the Tables, we highlighted the significant, uncorrected results using the alpha of .05 in italics and the significant results corrected for multiple comparisons in bold, based on an alpha of .017 using the Bonferroni correction: .05 (α) / 3 (for the three separate PCE variables). Changes to the post-registered analysis plan are reported in a transparent changes document, available via https://osf.io/efhgs/?view_only=afa109b83f894bed99492da2526876a7.

2.3.2 | Sample size rationale

The PCE was part of a larger study (Kirtley et al., 2021, April 2), therefore we did not perform a separate power analysis for the PCE task. This decision was pre-registered. The first proof-of-principle study using the PCE in adolescents (Hermans et al., 2020) showed comparable results to adult studies and confirmed the feasibility of the shortened design. This initial sample of $N = 148$ exceeded previous adult studies that included 20–34 individuals (Froese et al., 2014; Froese et al., 2020; Zapata-Fonseca et al., 2016). Given the specific aim to study the developmental course of basic social capacity, we made every effort to balance recruitment according to age group (based on school year). To this end, we maximized the sample size within the scope of the project. The limited comparability with previous study samples based on their sample characteristics (adults with and without autism spectrum disorder) and potentially underpowered designs prevented us from drawing parameter estimates from other PCE datasets and conduct a sensitivity power analysis (Anderson et al., 2017).

3 | RESULTS

3.1 | Sample characteristics

For three out of the 208 participants, data on demographics and awareness of the interaction were missing. These participants were excluded, such that the analysed sample included 205 participants, of which 122 were female. The mean age was 14.4 years ($SD = 2.0$). Detailed sample characteristics for the age per age group are presented in Table 2, showing some overlap between age and age group as the latter was based on school year. The Flemish education system allows adolescents to redo a year, resulting in heterogeneous age groups that show some overlap. Due to this overlap, at the suggestion of an anonymous reviewer, we performed a post-hoc analysis (not pre-registered) with age as a continuous variable and reported the results in Table S1 in Supplementary Material C. The results as presented in Table S1 are comparable to the original results in which age groups are compared.

TABLE 2 Characteristics of the analysed sample ($N = 205$); age range and distribution, aggregated means of PCE variables

Age range per age group	Age distribution	Sample characteristics	Behaviour/time spent together[a]	Accuracy[b]	Awareness[c]
Early adolescence (year 1; 11–14 years)	11 ($n = 3$) 12 ($n = 58$) 13 ($n = 16$) 14 ($n = 2$)	Total $n = 79$/ 44 female $M = 12.2$ years ($SD = .55$)	20.54 ($SE = 1.18$)	.31 ($SE = .03$)	3.99 ($SE = .14$)
Mid-adolescence (year 3; 13–17 years)	13 ($n = 2$) 14 ($n = 20$) 15 ($n = 19$) 16 ($n = 4$) 17 ($n = 1$)	Total $n = 46$/ 34 female $M = 14.6$ years ($SD = .80$)	19.27 ($SE = 1.23$)	.35 ($SE = .05$)	3.67 ($SE = .23$)
Late adolescence (year 5; 16-19 years)	16 ($n = 46$) 17 ($n = 26$) 18 ($n = 7$) 19 ($n = 1$)	Total $n = 80$/ 44 female $M = 16.5$ years ($SD = 2.02$)	22.61 ($SE = 1.10$)	.49 ($SE = .05$)	3.37 ($SE = .20$)

[a]Time spent together in seconds of total round time (60 s).
[b]Proportion correct click as of total clicks .
[c]Awareness of the interaction as a mean of two or three items rated on a 7-point Likert scale.

3.2 | The relationship between age group and PCE variables

The outcome of a linear mixed-effect analysis including age group and PCE variables[2] demonstrated that late adolescents spent more time together compared to the mid-adolescents (time spent together; $B = .13$ (.01), 95% CI: .02 to .35, $p = .002$). Late adolescents also demonstrated a higher proportion correct clicks compared with both early (accuracy; $B = .18$ (.05), 95% CI: .09 to .26, $p < .001$) and mid-adolescents ($B = .14$ (.05), 95% CI: .04 to .24, $p = .008$). Late adolescents reported a lower awareness of the interaction compared with early adolescents (awareness; $B = -.62$ (.20), 95% CI: −1.02 to −.23, $p = .002$). The aggregated adjusted means of each PCE variable per age group are shown in Table 3 and Figure 2.

3.3 | The role of age on improvement of performance throughout the experiment

Results from mixed-effect multilevel analyses examining associations between round and PCE variables demonstrated whether PCE performance across age groups changed during the experiment. There was no effect of round on time spent together ($p = .216$), such that the average level of the entire sample on time spent together remained the same throughout the six rounds of the PCE. However, the interaction of round × age group was significant for late adolescents ($p = .001$), such that only this group increased their time together, while mid- and early adolescents decreased their time spent together with each progressing round (Figure 3).

With each progressing round, the average proportion correct clicks increased ($B = .09$ (.04), 95% CI: .01 to .17, $p = .027$). Late adolescents demonstrated a higher average proportion of correct clicks compared with the early adolescents ($B = .81$ (.21), 95% CI: .40 to 1.22, $p < .001$). However, the interaction of round × age group was not significant, such that the improvement did not differ between age groups (Figure 4).

There was an association between round and awareness of the interaction, such that if round increased, the entire sample's awareness of the interaction increased ($B = .11$ (.02), 95% CI: .08 to .14, $p < .001$). Late adolescents reported

[2] As the analyses have been done separately for each PCE outcome variable, we have added a Table (S2) with the (repeated measures) correlation (Bakdash & Marusich, 2017) computed between each variable to Supplementary material D.

TABLE 3 Differences PCE variables between age groups for overall performance (aggregated over six rounds) and performance per round

		PCE variables								
		Behaviour/time spent together[a]			Accuracy			Awareness		
		B (SE)	95% CI	*p*	B (SE)	95% CI	*p*	B (SD)	95% CI	*p*
Overall performance	Mid – early	−1.45 (1.26)	−3.93 to 1.02	.250	.04 (.05)	−.07 to .14	.475	−.32 (.23)	−.78 to .14	.174
	Late – early	2.18 (1.14)	−.05 to 4.41	.055	.18 (.05)	.09 to .26	**<.001**	−.62 (.20)	−1.02 to −.23	**.002**
	Late – mid	3.64 (1.15)	1.39 to 5.88	**.002**	.14 (.05)	.04 to .24	**.008**	−.30 (.23)	−.76 to .15	.193
Improvement across rounds[b]	Mid – early	−.11 (.37)	−.83 to .61	.766	−.03 (.11)	−.25 to .19	.798	.03 (.04)	−.05 to .11	.481
	Late – early	1.03 (.32)	.41 to 1.65	**.001**	.10 (.10)	−.09 to .29	.321	.03 (.04)	−.04 to .10	.389
	Late – mid	1.14 (.37)	.42 to 1.86	**.002**	.13 (.11)	−.08 to .33	.236	.00 (.04)	−.08 to .08	.975

[a]Square-root transformed.
[b]B's are unstandardised "lincom" coefficients for interaction effect age group × round.

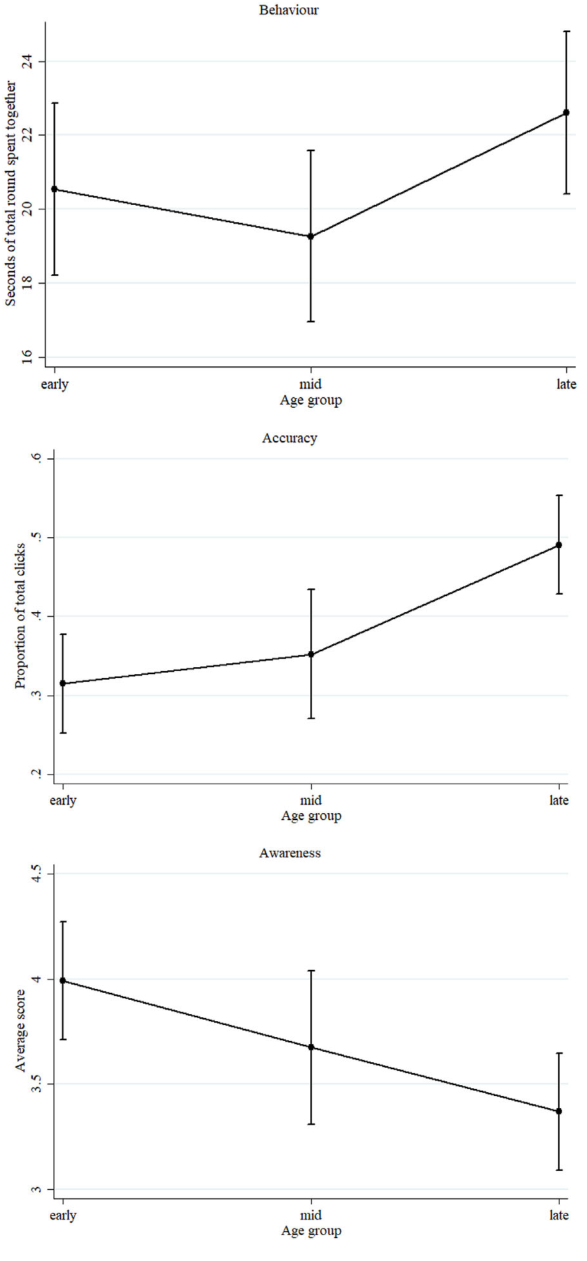

FIGURE 2 Adjusted aggregated mean scores of PCE variables with 95% confidence intervals per age group: early, mid, and late adolescents. Upper panel: behaviour measured as time spent together (back-transformed and reported as seconds from total round). Middle panel: accuracy measured as proportion correct clicks (of total number of clicks). Lower panel: average score of awareness (average rating of two or three items rated on a 7-point Likert scale)

a lower average awareness of the interaction compared with early adolescents ($B = -.62$ (.20), 95% CI: −1.01 to −.22, $p = .002$). Again, the interaction of round × age group was not significant, such that the increase of awareness did not differ between age groups (Figure 5).

3.4 | The relationship between strategy type and PCE variables

The subsample for the analyses on strategy included 166 participants. In 17.5%, no strategy was used. In the 82.5% that a strategy was used, it was coded '1 – unspecific and vague' in 16.3%, '2 – distinguished between static and

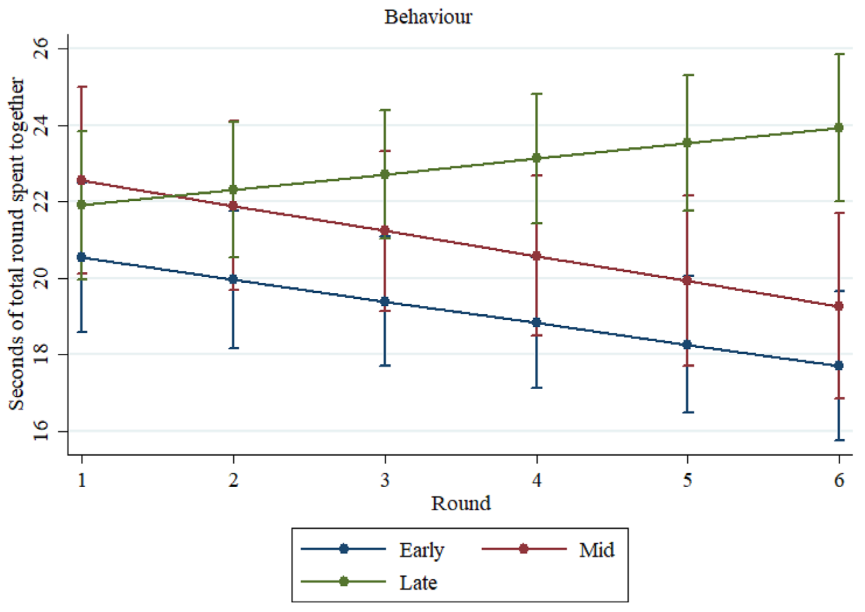

FIGURE 3 Behaviour measured as average time spent together in seconds of total round with 95% confidence intervals per round, per age group: early, mid, and late adolescents.

TABLE 4 Examples of strategy types

Strategy type	Strategy example
0	Participant indicated that no strategy was used
1	"If it really keeps vibrating"
1	"Keep moving forward"
2	"Keep still if I found something and see whether it moved"
2	"If it moves it's a person and if it keeps still, it's the chair"
3	"Every time I caused a vibration, I went back and forth to cause multiple diverse vibrations. If I got that back, I knew it was him"
3	"Every time I felt a vibration, I went back and forth for a few times and afterwards when I kept still, the other person did the same I think"

Note. Translated from Dutch to English.

moving entity' in 41.6%, and '3 – distinguished between responsive and non-responsive moving entity' in 24.7% of the cases. Table 4 lists some examples of each strategy type. Given that interrater reliability was weak (McHugh, 2012) to moderate (Landis & Koch, 1977), the results of the analyses are only reported in Supplementary Material A.

4 | DISCUSSION

4.1 | Main findings

Our PCE findings showed that, on average, late adolescents performed better on time spent together and accuracy compared to early and mid-adolescents, while at the same time, they reported an average lower awareness of the

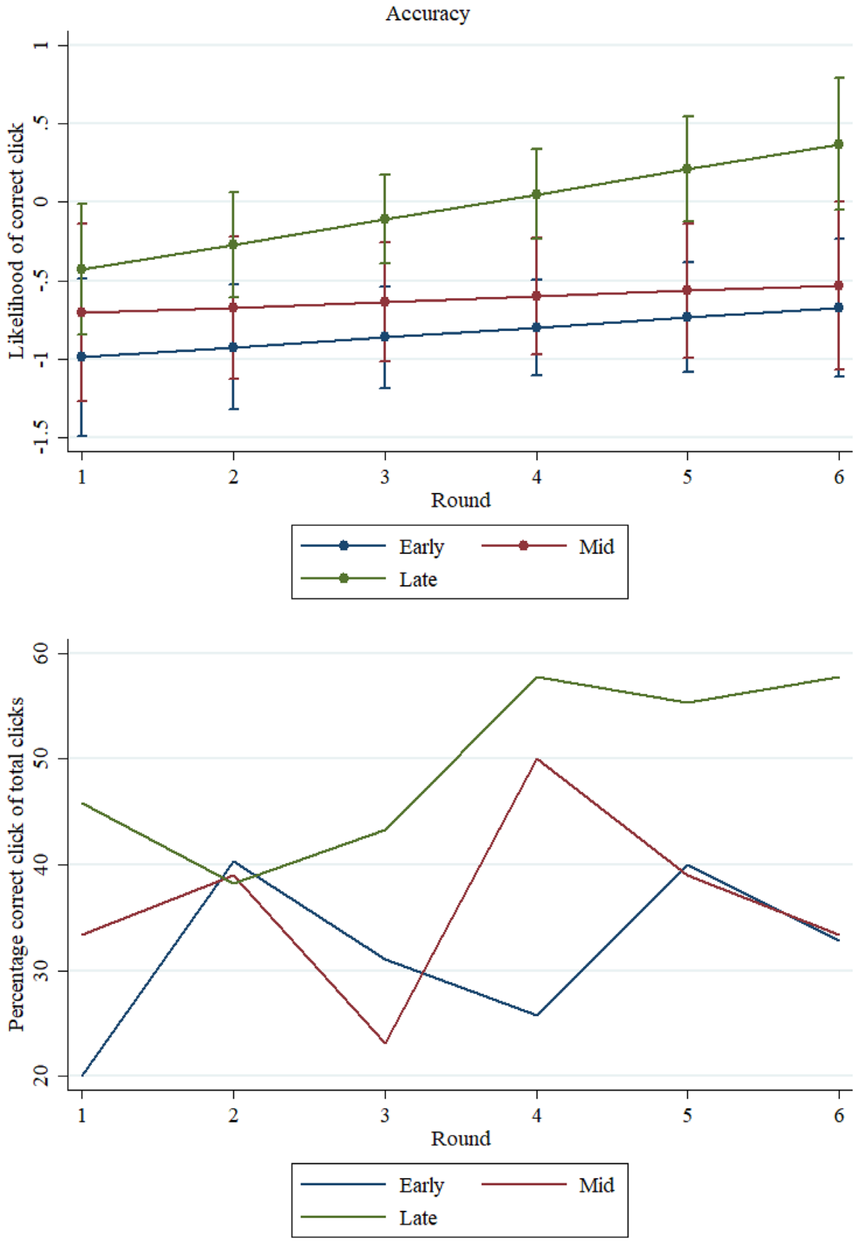

FIGURE 4 Average accuracy reflected by correct clicks. Upper panel: Average likelihood of a correct click per round with 95% confidence intervals. Lower panel: Average percentage of correct clicks of total clicks per round. Both graphs per age group: early, mid, and late adolescents.

interaction. Throughout the experiment, late adolescents demonstrated faster improvement of coordinated behaviour compared with younger adolescents, who showed a decline with each progressing round. The increase of accuracy and awareness of the interaction per round was similar for each age group.

The overall better performance we expected to find for older adolescents regarding accuracy was supported by our findings, but in addition, the overall performance of time spent together was better in late adolescents as well. Further, we did not find the expected faster improvement in older adolescents regarding accuracy, while we did find faster

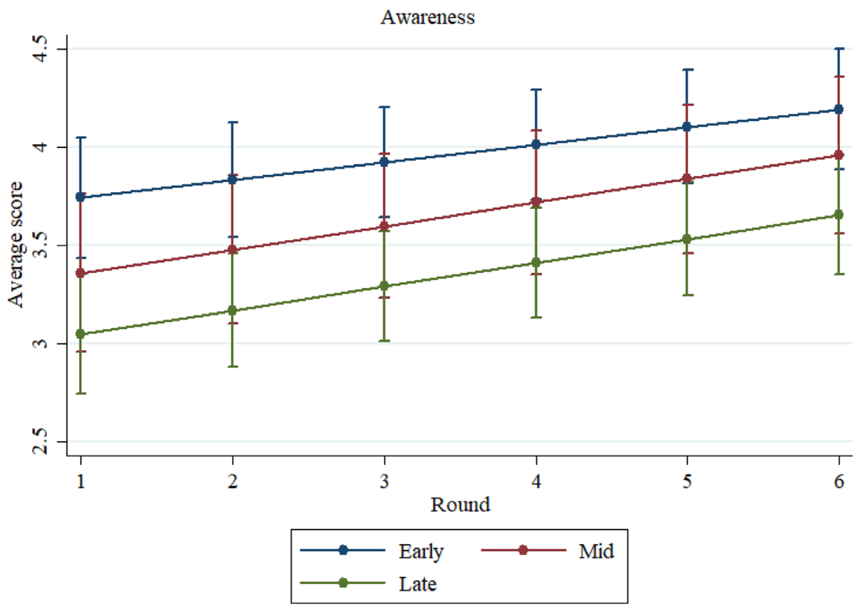

FIGURE 5 Average score on three items assessing awareness of the interaction with 95% confidence intervals per round, per age group: early, mid, and late adolescents. The average score included two items if there was no click in that round (excluding confidence of correct click)

improvement of time spent together throughout the experiment in older adolescents. Therefore, we found support for hypothesis H1, although we did not find support for H2, as we demonstrated a developmental course of basic social capacity throughout adolescence that was more profound for time spent together than for accuracy. We could not use the qualitative data to test H3.

4.2 | Continued development of basic social capacity into late adolescence

The overall better performance of late adolescents compared to mid- and early adolescents regarding time spent together and accuracy provides support for the developmental course of social contingency detection. It underscores the enduring development of dynamically coordinating behaviour over the course of adolescence. While neuroscientific research generally supports this as well, stating that these more basic processes of adapting behaviour to the social environment need fine-tuning during adolescence (e.g., Nelson et al., 2016), most neuroscientific research during adolescence has focused on social cognitive processes, often investigated (statically) within individuals (Osborne-Crowley, 2020). The current study assessed behavioural social dynamics directly by capturing social interaction in real time in interacting dyads. The current evidence for continued social development across adolescence in this relatively new paradigm points to a second or prolonged critical period for the maturation of dynamical social contingency detection, in which adolescents use relevant experiences to develop this capacity (Larsen & Luna, 2018).

In addition to accuracy, time spent together also improved with older age, reflected by more time spent together in interaction during the experiment. This finding supports the idea that time spent together and accuracy are dependent or coupled, which is what would be expected from a dynamic perspective (e.g., Thelen & Smith, 2007), as both individuals continuously affect each other while establishing a coordinated interaction. We might interpret our additional finding that, during the experiment, time spent together improved more quickly than accuracy in late adolescents as evidence for the social interaction first hypothesis (De Jaegher et al., 2010; Schneider et al., 2019). This hypothesis states that social interaction is a prerequisite for social cognition, such that social interaction itself is the basis for developing social cognition. In showing that dynamic coordination, implicit to the participants, improved during the experiment while accuracy stayed behind, this finding might point to the primacy of social coordination over cognition (in the PCE reflected by accuracy) and thus function as a basic stepping stone before social cognition (Happé et al., 2017). However, this should be further investigated by combining neuroscientific and dynamic measures, which has indeed be posited as necessary to progress the field of social interaction and learning (Olsson et al., 2020; Redcay & Schilbach, 2019), for instance using interaction-based sociometrics (e.g., Leong & Schilbach, 2019). Apart from this speculation, our findings on coordinated behaviour (i.e., time spent together) at least indicate that the assessment of social dynamics within a dyad captures a unique element that cannot be captured by information provided by individual measures (in the PCE reflected by accuracy and awareness) alone. This underscores the added value of the PCE in the assessment of dynamic interactive processes relative to isolated measures of social cognition or awareness, which is in line with recent calls in neuropsychiatry (Leong & Schilbach, 2019; Zampella et al., 2020). Within the PCE, this finding could be strengthened by studying the probability to click as a function of time spent together, as time spent together and accuracy measures are closely related.

In addition to improved time spent together and accuracy within the PCE, we also found an overall lower awareness of the interaction reported by the late adolescent group. We may explain this in terms of experiential learning of social contingencies. That is, social coordination based on detection and responsiveness to each other (i.e., social contingencies) is rewarding (Jones et al., 2011; Jones et al., 2014), and as such could reinforce and maintain this behaviour. Learned behaviour requires less conscious awareness as it becomes more natural and integrated (Barch et al., 2017), which is also referred to as habits. More experience with social interaction could then—based on experience-dependent learning (Blakemore & Choudhury, 2006)—contribute to the development of social contingency detection. Behaviour that is based on habits is typically linked to lower awareness, as long as the environment remains stable. For instance, new social skills may need to be learned after moving to another country (Bohl & Van den Bos, 2012). Relevant social experiences that are required for the maturation of social contingency detection during adolescence are facilitated by the quickly changing social environments and new social roles that adolescents need to adapt to (Dahl et al., 2018). Our findings in older adolescents may, therefore, reflect more experience with changing situations and adapting to others compared to their younger counterparts, who just entered secondary school. Given that late adolescents also showed improvement in behaviour and accuracy in the PCE may imply that this development is rather implicit than explicit. As this knowledge could advance our understanding of trajectories of social development in adolescence (see Blakemore & Mills, 2014 on introspective awareness), this is an interesting avenue for future work.

4.3 | Faster improvement of social behaviour throughout the experiment

The faster improvement of social coordinating behaviour (i.e., time spent together) during the experiment, as demonstrated by the late adolescent group compared with the younger groups, further emphasised the developmental course of behavioural coordination. In a previous study, in which learning per age group was not distinguished, an increase in time spent together with each progressing round was not found (Hermans et al., 2020). In this previous sample, late adolescents represented half of the entire sample (51%). Given that in the current sample with more balanced age groups, early and mid-adolescents showed a decrease in time spent together, while the late adolescents showed an increase, the currently found overall increase of time spent together per round could have been cancelled out in the previous study.

In contrast to time spent together, the increases in accuracy and awareness per round were similar for each age group. One could argue that the increase of awareness per round in the late adolescent group is unexpected given our previous interpretation of reinforcement learning, possibly reflecting an internalization of implicit social behaviour with age. A plot of the number of clicks per progressing round for the late adolescent group sheds light on this

(Supplementary Material B). This group demonstrates a decrease in the number of clicks per progressing round (i.e., fewer clicks), compared with the other two age groups demonstrating an increase in the number of clicks. In other words, while late adolescents spent an increasing amount of time together and their accuracy of reports increased at the same rate as the other age groups, their absolute number of reports decreased. This combination of findings indicates that the cognitive judgements (i.e., clicks) they did make were more accurate compared with the judgements made by the other age groups, as these groups had to increase their number of judgements to show the same improvement throughout the task.

We interpreted the lower performance on accuracy and behaviour of the early and mid-adolescent groups compared with the late adolescent group as a less developed capacity for social contingency detection. Notably, however, an alternative interpretation is that these younger age groups did not understand or correctly perform the task. It may be that the younger groups clicked mainly when in the proximity of the static object, as part of the 42% of participants who reported distinguishing between static and moving entities as their strategy. Future research could address this alternative interpretation by studying the erroneous patterns of clicks per age group and potentially including a more elaborate interview on the strategy used to obtain more information on what participants aimed to do to complete the task.

4.4 | Implications of dynamic assessment of interactive processes

As the developmental course of dynamically coordinated interactive processes was most robust for time spent together, so social *behaviour* instead of the initially hypothesised *cognition* only, we expect altered social development of social contingency detection as captured within the PCE to mainly express itself in altered or delayed social coordination. Given that successful social exchanges are generally perceived as social rewards (Jones et al., 2014), we argue that people with lower social contingency detection capacities may benefit less from rewarding social interaction, therefore engaging less in social interaction, which would, in turn, further limit the development of a mature basic social interactive capacity. Initial evidence for this idea comes from studies with participants with autism spectrum disorder, which have shown links with altered or decreased capacity for social contingency detection (Klin et al., 2009; Northrup, 2017; Northrup et al., 2017; Zapata-Fonseca et al., 2018). Moreover, Zapata-Fonseca et al. (2019) specifically found PCE accuracy to be similar in participants with autism and controls, while the latter group's behavioural exploration patterns differed. Their results indicated that, as the experiment progressed, participants with autism continued exploring the virtual environment, while controls spent less time exploring and more time in interaction with the other. This difference in exploration patterns can be interpreted as a difference in response to the rewarding nature of the interaction between participants with autism and controls.

Importantly, by being the first to demonstrate that dynamic interactive processes are still flexible, and, therefore, subject to both positive and negative change, we open up new avenues of research to inform broader prevention and early intervention efforts focused on social development in adolescence. Altered social interaction or social impairments are increasingly viewed as overarching characteristics of prevalent mental disorders with their onset in late adolescence, also coined disorders of social interaction (Leong & Schilbach, 2019; Schilbach, 2016). We argue that the social contingency detection we captured with the PCE is universal and independent of social context, as evidenced by similar findings across previous PCE studies conducted in diverse sociocultural contexts, such as Japan (Froese et al., 2014), Mexico (Froese et al., 2020) and Belgium (current study). We made an effort to representatively reflect the general population of Belgian adolescents, based on geographical location and level of education (Kirtley et al., 2021, April 2). Nevertheless, as one of the first studies in adolescence, our current findings can strictly only be generalized to Belgian adolescents as long as these are not replicated. If our findings can be replicated in future and different samples in this age group, the study of implicit, interactive properties might become of diagnostic value. For instance, the semi-controlled modelling of social dynamics with the PCE could, potentially in adapted form, be promising as a tool to investigate social alterations that may become social impairments later in adolescence. This adapted form may take a multimodal approach to increase realism of the experiment.

4.5 | Methodological considerations

First, in order to strengthen the interpretation that the lower performance of the early and mid-adolescent group compared with the late adolescent group is attributed to a less developed capacity for social contingency detection, alternative interpretations of our findings should be ruled out in future research. Addressing the erroneous response patterns per age group and ensuring that participants understood the task are, therefore, considered a vital part of replication studies. Nevertheless, based on the idea that behavioural coordination does not primarily require social cognition, our finding that younger groups lagged behind the late adolescent group on the behavioural component of social contingency detection still adds to our main message to include social dynamics in social interaction research in developmental adolescent research.

Second, due to weak to moderate interrater reliability for strategy coding, analyses to test H3 were not included. Nevertheless, we categorised most strategies as distinguishing between static and moving entities, which indicates that participants were not aware that they were specifically detecting responsiveness. Although these qualitative data seem to support our findings, no firm conclusions could be drawn from this outcome. Based on the previous limitation, we still encourage future research to supplement quantitative results with qualitative findings and undertake measures to increase interrater reliability, such as ensuring that both raters were equally familiar with the experiment.

Third, the assessment of the developmental course of social contingency detection would be optimised by analysing data from the same participants over time. This requires a longitudinal study design, in which participants complete the PCE at regular times throughout adolescence. Our study, using a cross-sectional design with age groups to represent developmental stages (e.g., Steinberg, 2005), generated hypotheses to test in a longitudinal set-up, in which we expect our current findings to be amplified.

5 | CONCLUSION

This is the first experimental study assessing social contingency detection in adolescence based on real-time social dynamics. We have demonstrated that, relative to younger adolescents, late adolescents spent more time interacting with others in the task, and learned to do so faster. In addition to this behaviour, overall, late adolescents made more accurate cognitive judgements about the interaction, while at the same time being less aware of it. These findings provide some first evidence for the continued development of social contingency detection throughout adolescence, specifically captured by coordinating behaviour, although maturation of this capacity started well before adolescence. We strongly encourage the use of experiments capturing the dynamics of social interaction, such as the PCE, for the assessment of social capacity throughout adolescence. The developmental course of social interactive processes at the behavioural level, including the dynamic interplay of behaviour, cognition, and awareness, opens up new potential avenues for assessment and interventions of social alterations in adolescence, targeted at this broader mechanism.

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CONFLICT OF INTEREST

The authors declare no competing interests.

ETHICS STATEMENT

Ethical approval for this study was obtained from the local Medical Ethics Committee (Ref: S6 1395), including informed consent obtained for experimentation with human subjects.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions. The research material – The Perceptual Crossing Experiment – has been developed by Creative Robotics Ltd. Hardware and software of version 2.0 are available via a GitHub repository: https://github.com/CreativeRobotics/PCE2.

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