Infants' visual sustained attention is higher during joint play than solo play: is this due to increased endogenous attention control or exogenous stimulus capture?

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Research highlights:

- Previous research has suggested that, when social partners attend to an object, this increases the attention infants pay to that object during spontaneous, naturalistic play.
- Are these changes because social context leads to increases in infants' *endogenous* (voluntary) attention control? Or because social context leads to increased *exogenous* attentional capture?
- To examine this we collected naturalistic play data from typical 12-month-olds in two contexts: Joint Play with a partner, and Solo Play alone.
- Overall, our results were more consistent with the second of the above-proposed hypotheses.

Abstract

Previous research has suggested that when a social partner, such as a parent, pays attention to an object, this increases the attention that infants pay to that object during spontaneous, naturalistic play. There are two contrasting reasons why this might be: first, social context may influence increases in infants' *endogenous* (voluntary) attention control; second, social settings may offer increased opportunities for *exogenous* attentional capture. To differentiate these possibilities, we compared 12-month-old infants' naturalistic attention patterns in two settings: Solo Play and Joint Play with a social partner (the parent). Consistent with previous research we found that infants' look durations toward play objects were longer during Joint Play, and that moments of inattentiveness were fewer, and shorter. Follow-up analyses, conducted to differentiate the two above-proposed hypotheses, were more consistent with the latter hypothesis. We found that infants' rate of change of attentiveness was faster during Joint Play than Solo Play, suggesting that internal attention factors, such as attentional inertia, may influence looking behaviour less during Joint Play. We also found that adults' attention forwards-predicted infants' subsequent attention more than *vice versa*, suggesting that adults' behaviour may drive infants' behaviour. Finally, we found that mutual gaze did not directly facilitate infant attentiveness. Overall, our results suggest that infants spend more time attending to objects during Joint Play than Solo Play, but that these differences are more likely attributable to increased exogenous attentional scaffolding from the parent during social play, rather than to increased endogenous attention control from the infant.

Keywords: naturalistic, social, joint attention

Introduction

Yu and Smith examined the naturalistic attention patterns of one-year-old infants during shared child-parent play. They found that, when the social partner (parent) visually attended to the object to which infant attention was directed, infants extended their duration of visual attention to that object (Yu & Smith, 2016). These results were interpreted as suggesting that visual sustained attention, which is generally considered at this age to be a marker of endogenous attention control (Colombo & Cheatham, 2006; Courage, Reynolds, & Richards, 2006 – although see Colombo & Mitchell, 2009; Hendry et al., 2018; Wass, 2014), is affected by social factors such as whether or not a parent was looking at the same object to which they were looking.

Infants are sensitive to some social signals, such as mutual gaze, even shortly after birth (Farroni, Csibra, Simion, & Johnson, 2002). But, over the first year of life, infants' spontaneous attentional allocation in social settings develops rapidly (Butterworth & Cochran, 1980; Carpenter, Nagell, & Tomasello, 1998; Corkum & Moore, 1998; Mundy & Newell, 2007). For example, Bakeman & Adamson studied attention during free play in 6 to 18-month-olds (Bakeman & Adamson, 1984). They studied triadic joint attention, the sharing of attention between an object and a play partner, and distinguished between passive joint attention, in which the infant followed the play partner's leads, and active joint attention, in which the infant took a more active role in guiding and initiating shared attention. Active joint attention was found to increase with age. At all ages, active joint attention was more likely to occur when infants played with their mothers than with peers (Bakeman & Adamson, 1984; see also Moore &

Dunham, 2014). Other research along similar lines has distinguished between Receptive Joint Attention, which is early-developing, primarily passive and mediated by posterior orienting and attention systems, and Initiating Joint Attention, which is later-developing and mediated by anterior orienting and attention systems (Mundy & Newell, 2007; Mundy, Sullivan, & Mastergeorge, 2009). Initiating Joint Attention is thought to develop starting from approximately 12 months (Mundy & Newell, 2007).

Thus, social attention becomes more active and internally (endogenously) controlled over developmental time. These changes are thought to take place as a result of multiple developmental and maturational factors (Johnson, 1990; Colombo & Cheatham, 2006), with progression particularly marked during the first 18 months of life (Mundy & Newell, 2007). In other work, Forssman and Wass used computerised paradigms to train non-social attention control in 10-month-old infants and found that non-social attention control training led to an increased likelihood of following gaze in semi-naturalistic social contexts (Forssman & Wass, 2017). Thus, increasing endogenous attention control leads to changes in infants' naturalistic social attention. Both of these ideas are, however, different to the notion proposed by Yu and Smith, which is that social context can lead to active, and immediate, increases in infants' endogenous attention control (Yu & Smith, 2016). Although arguably consistent with previous neuroimaging research (Farroni, Johnson, & Csibra, 2004; Leong et al., 2017; Striano, Reid, & Hoehl, 2006), this was, to our knowledge, the first direct claim of this kind.

There are, however, alternative possible explanations for the experimental findings of Yu and Smith. First, it is possible that, during the instances when parents were looking at the same object as the infant, they may also have moved the object more, or produced more or louder vocalisations. These 'low-level' sensorimotor cues may have increased the child's attention to the object by making it more exogenously salient (Johnson, 2002; Itti & Koch, 2001; Itti & Baldi, 2009; Luna, Velanova, & Geier, 2008). Movement, for example, is known to be exogenously salient, and to attract attention in an involuntary, or pre-conscious manner, using primarily low-level, subcortical neural mechanisms (Johnson, 1990; Luna, Velanova, & Geier, 2008; Mital, Smith, Hill, & Henderson, 2010;Tatler & Vincent, 2008). It is known that, in infants, the neural mechanisms that subserve 'bottom-up', stimulus driven attention are relatively mature at a time when the cortical neural mechanisms that subserve 'top-down', viewer-driven attention are relatively immature (Colombo & Cheatham, 2006; Johnson, 1990; Johnson, 2015; Luna, Velanova, & Geier, 2008). Behavioural research that examines how salience influences looking behaviour in children is consistent with this, suggesting that salience strongly influences looking behaviour in younger children (Frank, Vul, & Johnson, 2009; Courage et al., 2006; Shaddy & Colombo, 2004). If this explanation were true, then infant's increased looking behaviour in social settings would be best understood as a result of exogenous (externally-driven) attention mechanisms rather than endogenous (internally-driven) attention.

Second, Yu and Smith only studied infants' gaze behaviour during joint play, without a control comparison in which the infant played with the same objects in the absence of the adult (i.e. a solo play condition). Within-participants, those of the infants' looks that were longer were found to be more likely to be accompanied by parent's concurrent gaze. However, some looks would naturally last longer than others, even without variability contingent on social context. A longer-lasting look naturally affords a longer period during which the parent has the opportunity to join the infants' look, which could, arguably, have explained the pattern of results observed (Wass & Leong, 2016).

Here we wished to examine, using a within-participants between-condition design, whether infants' endogenous (voluntary) sustained attention during naturalistic free play is higher in social as compared to non-social contexts. To assess this, we collected data from 12-month-old infants in two conditions. In both conditions, infants and their parents were seated opposite each other at a table. During Joint Play, each dyad was presented consecutively with toy objects and asked to play together silently (eliminating the potential confound of adult vocalisations). In the Solo Play condition a small, 40cm-high divider was placed between the infant and the parent, and two identical toys (the same used during the Joint Play condition) were presented concurrently to the child and the parent, who played separately with them, again silently (see Figure 1). The divider was high enough to ensure that both parent and child could see each other (to reduce the possibility of infant distress during this temporary social separation), but not the objects with which they were playing. In both conditions, the toy/toys were swapped for new ones at regular time intervals. The aim was to provide equivalent visual and auditory stimulation, except that play occurred in a non-social context.

Our initial planned analysis was to assess whether the original findings from Yu and Smith, that infants' visual attentiveness towards play objects is higher in social settings, could be replicated with a more stringent, non-social control condition. If we succeeded in replicating the original finding we planned further analyses to allow us to distinguish between two hypothetical underlying causes: first, that infants show superior endogenous (voluntary) attention control in social settings; second, that social settings offer increased opportunities for exogenous attentional capture.

Our first analysis examined attentional inertia (Anderson, Choi, & Lorch, 1987;Richards & Anderson, 2004). This is the finding that, as individuals become progressively more engaged with an object, their attention progressively increases. In other words, the longer a look lasts, the more its likelihood of ending during the next successive time interval diminishes. Convergent previous research has suggested that attentional inertia is a measure of endogenous (internally driven) attentional engagement (Richards, 2010; Richards & Anderson, 2004; see also Cohen, 1972). As attentional engagement increases, distractibility decreases (Anderson et al., 1987). Attentional inertia increases with increasing age (Richards & Anderson, 2004) and is lower in children with ADHD (Lorch et al., 2004). Attentional inertia has been documented in a variety of different naturalistic attention contexts, such as during free play (Choi & Anderson, 1991) and looking towards a screen (Richards & Anderson, 2004).

In order to assess whether attentional inertia influenced looking behaviour more strongly during Solo Play than Joint Play we calculated the Partial Autocorrelation Function (see Wass, Clackson, & de Barbaro, 2016; and Methods section, below) to quantify the rate of change of spontaneous attentional behaviours during naturalistic play. A slow-changing profile of attention would indicate that attentional inertia is high, and strongly influences looking behaviour. A faster-changing profile of attention would indicate lower attentional inertia. We hypothesised that, if social contexts lead to increased endogenous attention, then attentional inertia might be higher in social than non-social settings. However, if exogenous stimulus capture is stronger in social settings, then attentional inertia would be lower.

Our second analysis examined the directionality of attentional effects. By calculating the correlation of the epoch-by-epoch attention data from infant and parents, we examined whether episodes of attentiveness from one member of the dyad were likely to associate with attentiveness from the other member. And by recalculating the same correlation whilst introducing increasing time-lags in one member's data relative to the other, we examined whether changes in the infants' attention tended to take place before, or after, changes in the adults' attention (cf de Barbaro, Clackson, & Wass, 2016). We reasoned that, if infants' changes tended to precede (or be uncorrelated to) adults' changes in attention, this would support the view that infants' attention in social contexts is under endogenous control. If, however, changes in adults' attention tended to precede changes in infants' attention, this would be more consistent with the latter hypothesis, that infants' increased look durations in social contexts are due to exogenous capture by adults' behaviour.

The first two analyses examine overall changes in adults' and infants' object-oriented looking behaviour in social versus non-social (interactional) settings. However, one further, more specific, difference in the adult-infant pattern of social interaction that we wished to examine is that Joint Play afforded more opportunities for mutual (temporally co-incident) gaze to occur than Solo Play. Mutual gaze is a powerful ostensive signal that supports early communication and learning (Csibra & Gergely, 2009; Niedźwiecka, Ramotowska, & Tomalski, 2017). We were, therefore, interested in whether moments of mutual gaze within a Joint Play session would lead to immediate subsequent increases in infants' attentiveness. First we calculated the transitional probabilities between the three looking locations included in our coding scheme: Object, Partner and Inattention. We reasoned that, if mutual gaze directly facilitates object attention, then transitions between Partner and Object would be more likely during Joint Play than Solo Play. Next, we identified the ends of moments of parent-child mutual gaze. If mutual gaze leads to immediate increases in attentiveness, we reasoned that the proportion of gaze directed towards the Object relative to Inattention would be higher in the time periods directly after mutual gaze. Finally, to assess individual differences in socially-mediated gaze behaviour we examined whether infants who engaged in more mutual gaze showed a higher proportion of gaze behaviour to the Object relative to Inattention. We hypothesised that, if mutual gaze leads to increases in attentiveness, then infants who engage in more mutual gaze should show a higher proportion of looking to the Object relative to Inattention, across the whole trial.

Methods

Participants

76 participants (38 infants and 38 parents) participated in the study. The gender ratio was 21M/17F and mean (st. err.) of age on the day of visit was 348.5 (9.5) days. It should be noted that the recruitment area for this study, Cambridge, is a wealthy university town and the participants were predominantly Caucasian and from well-educated backgrounds, and so do not represent an accurate demographic sample (Henrich, Heine, & Norenzayan, 2010).

Experimental set-up.

Infants were seated in a high chair, and a table was positioned immediately in front so that toys on the table were within easy reach (see Figure 1). Parents (always mothers) were seated on the opposite side of the table, directly facing the infant. The width of the table was 65cm. In the Solo Play condition only, a 40cm high barrier was positioned across the mid-line of the table. The height of the barrier was chosen to ensure that, when it was in place, parent and child had direct line of sight to one another (in order to reduce the possibility of infant distress) but neither could see the others' objects on the table.

INSERT FIGURE 1 HERE

A within-subjects design was used in which each infant-parent dyad participated in both the Joint Play and Solo Play conditions (presented in a counterbalanced order). Parents were informed that the aim of the study was to compare behaviour while they were attending to objects separately from each other, and when they were attending to the same object. During the Solo Play condition parents were asked to play with the toys separately (from their infant), directing their attention to the objects as much as possible, and to make as little noise as possible. During the Joint Play condition they were asked to play silently with the toys whilst involving their baby in the play.

A research assistant was positioned on the floor, always to the right of the infant, but out of the infant's line of sight so as not to interfere with the social play context. The research assistant placed a series of toys onto the table, one at a time. In the Joint Play condition, one copy of each toy was presented to the infant and parent. In the Solo Play condition two identical toys were presented concurrently to the infant and parent, one on either side of the barrier. The toys were small (<15cm), engaging objects. The presentation order was randomised between conditions, and between participants. Approximately every two minutes, or more frequently if the child threw the object to the floor, the current toy object was replaced with a new object. The mean (st. err.) duration for which each object was presented was 140.1 (17.9) seconds for Joint Play and 110.3 seconds (7.9) for Solo Play.

Approximately 10 minutes of data was collected per condition from each dyad. The mean (st.err.) duration of play for each condition was 10.80 (0.46) minutes for Joint Play and 10.35 (0.33) minutes for Solo Play. On the occasions when the infant became fussy during testing, data collection was stopped earlier; however this occurred fairly rarely: the number of infants contributing sessions that lasted less than 8 minutes was 2/3 for the Joint/Solo Play conditions.

The presentation order of the Joint and Solo Play was randomised between participants, but the two conditions were always presented consecutively, with a short break in between. Of note, EEG data were also collected during this task; however these data are not reported in this paper.

Data recording

Play sessions were videoed using two camcorders positioned next to the child and parent respectively, in order to obtain a frontal head-and-shoulders view of each. Synchronisation of the two camcorders was achieved by placing radio-frequency (RF) receiver LED boxes behind the child's and parent's chairs, within view of the camcorders. These RF boxes simultaneously received trigger signals from a single source (a laptop running Matlab) at the start of the testing session, and concurrently emitted light pulses that were visible on parents' and infants' camcorders.

Accurate synchronisation could be not achieved for a proportion of the participants due to technical failure or human error. The number of dyads who gave accurate data for inclusion in the final analyses was 27 for the Joint Play Condition and 33 for the Solo Play Condition. The mean (st.err.) age of the included participants was 346 (11.3) days for Joint Play and 350 (10.2) days for Solo Play. The gender ratios were 18M/15F for Joint Play and 15M/12F for Solo Play.

The looking behaviour of parents and infants was manually coded by reviewing their respective video recordings on a frame-by-frame basis (30 frames per second, 33.3 ms temporal acuity) using video editing software (Windows Movie Maker). This coding identified the exact start and end times of periods during which the participant was looking at the toy object or at their social partner. Coding was performed at millisecond-level accuracy (to the nearest frame at 30fps) and rounded to the nearest second prior to conducting analyses. The start and end times of each of the individual looks to a) the Object and b) the Parent were recorded. Times when the infant was attending neither to the object nor the parent were coded as Inattention. The times at which new objects were placed on the table were also recorded. After coding, a second synchronization check was conducted by checking that the times when new toys were presented were identical between the infant and parent coding sheets.

Data analyses

Time-series analyses were used to examine two aspects of the looking time data: first, the rate of change of each time-series, relative to itself (auto-correlations). And, second, the inter-relationship (cross-correlations) between two time-series (child and parent). In each case the dependent variable was the presence or absence of attention to the target (either Object or Partner) within each epoch considered, treated as a dichotomous (1/0) variable (de Barbaro et al., 2016).

Auto-correlations.

To examine the rate of change of attention durations we calculated the Partial Auto-Correlation Function (PACF) (see Figure 2). The PACF is derived from the Auto-Correlation Function (ACF), which indexes the cross-correlation of a measure with itself at different lag-intervals in time (Chatfield, 2004). The ACF indexes the similarity between observations as a function of the time-lag between them in 1s steps. The PACF also indexes the cross-correlation of a measure with itself at different time lags, but at each time lag k it controls for the effect of auto-correlations at slower temporal scales from lag 1 to k-1 (Chatfield, 2004).

Figure 2 shows two data samples selected to illustrate this analysis. It can be seen that sample 1 (Fig 2a) shifts rapidly between long, and short looks (see e.g. 800 -1000 seconds). In sample 2 (Fig 2b), changes occur less rapidly. A series of continuously long looks (e.g. 500-700 seconds) is followed by a series of continuously short looks (e.g. 800-1100 seconds). For the ACF function (Figure 2c), the blue line (sample 1) falls off more sharply as the infant's rapid shifts in look duration produce lower overall self-similarity, particularly with increasing time-lags. For the PACF function (Figure 2d), at the first lag (1s offset) the same pattern is visible (sample 2>sample 1 in self-similarity) – again, indicating that sample 2 is the slower-changing measure. However, because the PACF controls at subsequent lags for previous autocorrelations, this difference disappears at longer lags.

Individual Partial-Auto-correlation functions showed that all looking data analysed showed the same sharp fall-off between the lag 1 term and subsequent terms as observed in the single data sample illustrated in Figure 2d (see Supplementary Materials Figure S1). This indicates that looking data show a strong first-order auto-regressive tendency (Chatfield, 2004), such that the looking time at time t is influenced by time t-1, but that there are no independent relationships to higher-order time lags (as would be seen, for example, if looking time showed periodic increases at regularly spaced time intervals). Therefore only the lag 1 PACF terms were used in subsequent analyses.

INSERT FIGURE 2 HERE

Cross-correlations. The lagged cross-correlation analysis is based on similar principles to the auto-correlation analysis described above (see Figure 3). First, the correlation was calculated across all pairs of time-locked (i.e. simultaneously occurring) looking data from the infant and parent in each dyad, using a Spearman's nonparametric order correlation. This allowed us to examine whether episodes of attention in one partner are were likely to associate with episodes of attention from the other partner. The value obtained is plotted as time "0" (t=0) in the cross-correlation. To examine lagged cross-correlations, such as, for example, lag-time t=-1, the epochs created from the infant looking data were shuffled one second backwards relative to the adult looking data, and the correlation between all lagged pairs of data was calculated. In this way, we can estimate how the association between two variables changes when we increase the time-lag between them. Further details of how this was calculated are given elsewhere (de Barbaro et al., 2016; Wass et al., 2016). Of particular interest in the present case is to examine whether the adult's looking behaviour predicts the infant's looking behaviour several seconds *after* that moment more strongly than it predicts the infant's looking behaviour several seconds *before* that moment. In other words, do changes in the adult's looking behaviour tend to occur before, or after, changes in the infant's looking behaviour?

INSERT FIGURE 3 HERE

Transitional probabilities. Our data from the Joint Play condition were coded continuously into one of three gaze categories: Object, Partner and Inattention. We identified the end of each attention episode (the moment at which attention transitioned from one location to another) and recorded the direction of the transition: whether gaze had transitioned from the Object to the Partner, or to Inattention. Averaging across the whole trial we then calculated the proportion likelihood of all six possible transitions between the three possible gaze locations.

We compared the observed transitional probabilities with the probabilities that would have been observed by chance. To estimate chance we used three different procedures. Each of these procedures has its own strengths and weaknesses, as we discuss in the Discussion. The first procedure assumed that all transitions were equiprobable (i.e. that, at the end of an attention episode to the Object, there was a 50% likelihood of transitioning to attending to the Partner, and a 50% likelihood of transitioning to Inattention). The second procedure directly compared the transitional probabilities observed in the Joint Play and Solo Play conditions. The transitions between, for example, Partner and Object were calculated separately for each dyad and for each condition, and the results were compared between conditions. The third procedure counted the total number of discrete attention episodes observed per condition and per participant, and used this to calculate the 'chance' transitional probabilities. Thus, say for example, that, across a single trial, 100 attention episodes were observed to the Object, 50 to the Partner and 200 to Inattention, then the chance probability of transitioning from the Object to the Partner would be 50/(50+200)=0.2. The chance probabilities were calculated on a participant-by-participant basis, and compared with the observed probabilities. Since results were not all parametrically distributed, these comparisons were performed using Wilcoxon Signed Rank test. Results from Procedures 1 and 2 are given in the Supplementary Materials; from Procedure 3 in the main text.

In addition, we also conducted two separate analyses to further examine moments of mutual gaze:

Mutual gaze moments: Analysis 1. We identified moments of mutual gaze (when infant was looking at parent at the same time as the parent was looking at the infant). We then excerpted the 60 seconds before, and after, the end of this mutual gaze moment. Second by second, for each of the 60 seconds before and after that moment, we calculated the relative likelihood that the infant would be looking at the Object relative to Inattention. We reasoned that, if mutual gaze leads to immediate increases in attentiveness, we would see an increase in the relative likelihood of looking to the Object, relative to Inattention, during the time period after the end of mutual gaze.

Mutual gaze moments: Analysis 2. This analysis was similar to that described in Analysis 1. However, instead of examining transient changes within a Joint Play session it examined between-dyad differences averaged across an entire session. The total number of mutual gaze moments observed across the entire Joint Play session was recorded, along with the total proportion of looking time to the Object relative to Inattention during that session. We reasoned that, if mutual gaze leads to immediate increases in attentiveness, then infants who engaged in more mutual gaze would spend more time attending to the Object than Inattentive.

Results

The Results section is in four parts. First, we present descriptive statistics and comparisons of the mean attention (looking) durations between the Joint Play and Solo Play conditions. Second, we present auto-correlation analyses to examine whether attentional inertia influences looking behaviour more strongly during Solo Play or Joint Play. Third, we present cross-correlation analyses to examine whether changes in adults' attention occur before, or after, changes in infants' attention. Fourth, we present analyses to examine whether moments of mutual gaze within a Joint Play session lead to increases in infants' attentiveness.

i) Descriptive statistics and comparison of mean attention durations

Figure 4 shows the raw descriptive results obtained for the infants' looking behaviour, compared between Joint Play and Solo Play conditions. Results show that all look durations are heavily positively skewed (see Figures 4c-4e), as is universally observed in look duration data (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016), and so a log transform was applied. Our first planned comparison was to examine whether the attention durations to Object, Partner and Inattention differed significantly between the Solo Play and Joint Play conditions. The Shapiro-Wilk test suggested that, even following the log transform, not all variables were normally distributed and so the less powerful non-parametric Related-Samples Wilcoxon Signed Rank test was applied throughout. As predicted, we observed that attention durations to Object were significantly higher during Joint Play than Solo Play ($Z=3.8$, $p<.001$), see Figure 4a. The duration of episodes of Inattention was also found to be higher during Solo Play ($Z=3.8$, $p<.001$). Infants' look durations towards the Partner showed a marginally significant difference between conditions ($Z=1.9$, $p=.052$). Next, the number of discrete attention episodes in each of the three categories was calculated (Figure 4b). Shapiro-Wilk tests again suggested that not all variables were normally distributed and so non-parametric statistics were used. No significant difference was observed between the number of discrete attention episodes towards the object between the Solo Play and Joint Play conditions (Z=1.3, p=.20). Significantly fewer looks towards the Partner were observed during Solo Play relative to Joint Play (Z=2.8, p=.005) (as described above looks towards Partner were still possible in the Solo Play condition (see Figure 1), but only over the top edge of the screen). The difference in number of episodes of Inattention was marginally non-significant (Z=1.9, p=.064).

INSERT FIGURE 4 HERE

Next we examined whether attention durations towards the object are a stable feature of individual differences across conditions, and across parent-child dyads (Figure 5a, 5b). First we examined the bivariate relationship between infants' look durations towards the Object in the Solo and Joint Play conditions (Figure 5a). The Shapiro-Wilk test suggested that both variables were normally distributed (p values >.8) and so a Pearson correlation was used. A significant bivariate relationship was observed r(23)=.59, p=.003 (see Figure 5b), suggesting that infants who showed longer look durations in the Joint Play condition also showed longer look durations in the Solo Play condition. This is consistent with previous research (Wass, 2014). Next we examined the bivariate relationship for the Joint Play condition between infants' attention durations towards the object and parents' attention durations towards the object. Shapiro-Wilk tests again demonstrated that both variables were not normally distributed and so a Spearman rank order correlation was used. A significant bivariate relationship was observed ρ (28)=.55, p=.002. This suggests that, between dyads, where the parent is more attentive, the infant is likely to be, too.

INSERT FIGURE 5

ii) Partial Auto-Correlation function – does attentional inertia influence looking behaviour more strongly during Joint Play or Solo Play?

Our next planned analysis was to examine whether attentional inertia influences attentional behaviours more strongly during Joint Play or Solo Play. In order to examine this the Partial Auto-Correlation function was calculated for infants' and adults' looking time series in order to examine whether the Solo or Joint Play conditions showed a faster rate of change of attention (see Figure 2). As described in the Methods, and as illustrated in the Supplementary Materials (Figure S1), all looking data showed a strong fall-off between the lag 1 PACF term and subsequent terms, and so only the lag 1 terms were analysed.

First, as a preliminary analysis, we examined the bivariate relationship between the lag 1 PACF term and average attention durations towards the Object (Figure 5c). A significant positive bivariate relationship was observed between PACF and attention duration $r^2(60)=.32$, p=.013. This suggests that, overall, longer attention durations are associated with a slower-changing profile of attention durations. This may be an artifactual relationship, such that longer attention durations, which transition less frequently, create the appearance of a slower-changing profile. Next the PACF values for attention durations towards the Object in the Joint Play and Solo Play conditions were examined (Figure 5d). Lower PACF values were observed during Joint Play relative to Solo Play, showing that a faster-changing profile of attention durations is observed during Joint Play relative to Solo Play. Of note this is the opposite relationship to that expected based the fact that average attention durations during Joint Play were longer: longer attention durations were observed in Joint Play relative to Solo Play, a positive association was observed between attention duration and PACF term, and higher PACF values were observed in Solo Play relative to Joint Play. This suggests that the difference in PACF is not attributable to differences in mean attention duration. An ANCOVA with PACF as the dependent variable and Condition (Joint vs Solo Play) as the within-subjects factor, controlling for attention duration, indicated a significant difference between the two conditions $F(1,59)=10.03$, $p=.002$. This suggests that a faster rate of change of attention duration (lower attentional inertia) was observed during Joint Play relative to Solo Play. This finding is not attributable to differences in average attention duration between the two conditions.

iii) Cross-correlation functions – do changes in adult's attention occur before, or after, changes in the infant's attention?

Our planned analysis was to examine whether changes in infants' attention tended to take place before, or after, changes in adults' attention. Figure 6 shows the lagged cross-correlation plots obtained. (Figure 3 includes an explanation of how these were calculated.) Two points are of interest. First, at Time=0 (indicating zero lag), both categories of looking (to Object and Partner) show positive infant-adult correlations in looking behaviour. This suggests that, during Joint Play, moments of longer looking from the infant are more likely to be accompanied by moments of longer looking from the adult.

The second point of interest is that Figures 6a and 6c appear asymmetric around Time=0, such that the cross-correlation between Adult at time x and Infant at time x+t was significantly greater than between Adult at time x and Infant at time x-t. (In other words, that changes in adults' attention preceded changes in infants' attention.) Figure 6b is a scatterplot showing the participant-by-participant correlations that were averaged to create Figure 6a. The Y-axis shows the cross-correlation observed between the parent's attention at time t and the infant's attention from time t-5 to t-0; X-axis shows the cross-correlation observed between the parent's attention at time t and the infant's attention from time t+0 to t+5. In order to assess whether these variables differed significantly a paired sample t-test was conducted. This indicated that 'parent pre infant' was significantly higher than 'parent post infant' $t(27)=2.80$, $p=.01$. This suggests that changes in adults' attention towards the objects precede changes in infants' attention.

Next, an identical cross-correlation plot was calculated for attention to Partner (Figure 6c). The same asymmetry was observed. Figure 6d suggests, again, that the same pattern was observed relatively consistently across all dyads. In order to assess whether this difference reached significance a paired sample t-test was conducted. This suggested that 'parent pre infant' was significantly higher than 'parent post infant' $t(27)=3.33$, $p=.003$. These findings suggest that changes in adults' attention towards the partner precede changes in infants' attention.

INSERT FIGURE 6 HERE

iv) Do moments of mutual gaze within a Joint Play session lead to increases in infants' attentiveness?

INSERT FIGURE 7 HERE

First we examined the transitional probabilities between different attention locations. In the Methods section we describe three procedures we conducted for comparing the observed possibilities with chance. Procedures 1 and 2 are shown in the Supplementary Materials in Figure S2; Results from Procedure 3 are shown in Figures 7a and 7b.

Of primary interest were the transitional probabilities observed around looking times to the Partner in the Joint Play condition (Figure 7a). We hypothesized that, if mutual gaze facilitates attentiveness, looks to the Partner during Joint Play would be more likely to be followed by looks to the Object than would be expected by chance. Overall, .54 of looks to the Partner were followed by a look to the Object during Joint Play, compared with .46 of looks to the Partner that were followed by Inattention. Procedure 2 suggested that this figure *was* significantly higher during Joint Play than Solo Play. However, procedures 1 and 3, which used alternative methods for calculating the chance probabilities, suggested that the proportion of attention transitions from Object to Partner during Joint Play was not higher than expected by chance (Figure S2a; Figure 7a). In the Discussion we discuss the relative strengths of these three approaches.

Next we identified periods around the end of mutual gaze episodes (Figure 7c). We hypothesized that, if mutual gaze facilitates attentiveness, then the time period following the end of a period of mutual gaze would lead to an increase in attentiveness (indexed as the proportion time looking to Object relative to Inattentive). In fact, no such pattern was observed. The highest attentiveness (proportion attention to Object relative to Inattention) is observed at a time interval of 60 seconds *prior* to the start of a period of mutual gaze.

Finally we examined, on a dyad-by-dyad basis, the relationship between the total number of mutual gaze periods observed across the Joint Play session and infant attentiveness (measured as the proportion of the time spent attending to the Object vs in Inattention). We hypothesized that, if mutual gaze facilitates attentiveness, then in dyads who spend more time in mutual gaze, infants should be more attentive (measured as a higher proportion of time spent attending to the Object relative to Inattention). In fact, no such relationship was observed. A weak, non-significant relationship in the opposite to predicted direction was observed ($r(28)=-.26$, $p=.18$. This suggests that, in dyads with fewer mutual gaze moments, the infants tend towards being more attentive to the Object.

Discussion

In order to study how social context influences infants' attention to objects we examined infants' naturalistic gaze behaviour in two settings: during Solo Play, and during Joint Play with a parent. In the Joint Play condition, infants and parents played across a table with a succession of toys that were placed onto the table by a researcher (see Figure 1). In the Solo Play condition the set-up was identical, except that a 40cm high divider was placed down the centre of the table and infants and parents played in parallel with two identical sets of toys. The divider was high enough to ensure that both parent and child could see one other (to reduce the possibility of infant distress), but not the objects with which the other was playing. Both play sessions were conducted in silence.

First, when comparing between infants, we found individual infants who showed longer attention durations towards the Object during Joint Play also showed longer attention durations during Solo Play (Figure 5a). This suggests that attention duration is stable as an index of individual differences across the two conditions. In addition, though, we found that infants showed significantly longer attention durations during Joint Play than during Solo Play (Figure 4). This finding replicates, using a different method, previous findings suggesting that infants' visual sustained attention towards toys is higher in social contexts (Yu & Smith, 2016). Comparing between dyads we also found associations between the parent's attention duration to the Object during Joint Play and the infant's (Figure 5b).

Analyses 2, 3 and 4 were intended to distinguish between two hypothesized mechanisms underlying the findings described above. The first is that increased attention durations are due to the infant showing increased endogenous (voluntary) attention control during Joint Play relative to Solo Play. The second is that increased attention durations are due to increased exogenous (external) stimulus capture.

Analysis 2 examined attentional inertia. Attentional inertia is the finding that our naturalistic attention patterns show slow-varying fluctuations over time, such that, the longer a look lasts, the less likely it is to end in the next successive time interval (Anderson et al., 1987;Richards & Anderson, 2004). These slow-varying fluctuations in attentional engagement are thought to be due to internal changes in the child, in attentional engagement (Cohen, 1972) and/or autonomic arousal (de Barbaro et al., 2016; Richards & Casey, 1991). We hypothesised that, if social contexts lead to increased endogenous attention, then attentional inertia might be higher in social than non-social settings. However, if exogenous stimulus capture is stronger in social settings, then attentional inertia would be lower.

We found faster-changing patterns of attention to the object during Joint Play relative to Solo Play, suggesting that attentional inertia influences looking behaviour less strongly in social contexts (Figure 5c, 5d). This finding was independent of the fact that attention durations to the Object were, overall, higher during Joint Play. This may be because, during Joint Play, more moving objects (such as a face of the Parent) are present within the visual field of the child. This increases the likelihood that a look that otherwise would have lasted for longer is unexpectedly interrupted, leading to a faster-changing profile of attention. In this regard, it is instructive to consider both that an increased number of possible distractors were present in the field of view of the child during Joint Play (the Parent's face), and that, overall, look durations toward the Object were higher (cf Smith, Yu, & Pereira, 2011).

The next analysis used lagged cross-correlations to examine whether changes in infant attention during Joint Play tended to take place before, or after, changes in adult attention. We reasoned that, if infants' changes tended to precede adults' changes, this would support the view that infants' attention in social contexts is under endogenous control. If, however, adults' changes tended to precede infants' changes, this would be more consistent with the latter hypothesis, that infants' increased attention durations in social contexts may be due to exogenous capture.

We found, for attention episodes both to the Object (Figure 6a) and to the Partner (Figure 6c), that changes in adult attention tended to temporally precede changes in infant attention. These observations were found with a remarkable degree of consistency across dyads (Figure 6b, 6d). The lagged cross-correlation analysis that we used can be compared to other approaches, such as Autoregressive Integrated Moving Average (ARIMA) analyses that have been used to examine temporal co-fluctuation of affect during social play (Cohn & Tronick, 1988; R. Feldman, 2006). ARIMA analyses can identify shared bidirectional influences (such that both infants, and parents, influence one another), whereas lagged cross-correlation approaches merely indicate that, overall, changes in adult attention tended to precede changes in infant attention. Furthermore, our findings do not allow us to evaluate whether the relationship was driven by currently overlapping, or by discrete, previous looks. However, our present findings do appear to suggest that changes in infant attention follow, temporally at least, from changes in adult attention. As such, they appear to challenge an approach which assumes that the longer infant attention durations observed during Joint Play are primarily due to endogenous factors on behalf of the child.

Previous research has suggested that, when adults look first to the face of an infant before looking at an object relative to when they look just at the object, the neural responsiveness of the infant to that object is enhanced (Striano et al., 2006; see also Hoehl, Michel, Reid, Parise, & Striano, 2014; Kylliainen et al., 2012). These research findings appear to indicate a special role for mutual gaze in enhancing infant responsiveness, and engagement (see also Moore & Dunham, 2014; Frischen, Bayliss, & Tipper, 2007). Therefore we explored the possible role of mutual gaze in causing changes in infant attentional engagement during the joint play session. We hypothesized that mutual gaze may lead to increases in endogenous attention control on behalf of the infant. If so, this would manifest as an increase in attentiveness, defined as the proportion of attentional allocation towards the Object, relative to Inattention, in the time after the end of the mutual gaze period.

Across three analyses (Figure 7a-7d, S2) we investigated whether mutual gaze directly facilitates attentiveness. First, we examined the probability of attention transitioning between Partner and Object during Joint Play (see Figure 7a, 7b and S1). We compared whether the *observed* probabilities differed from the *expected* probabilities using three procedures (described in the Methods). Procedure 2, which directly compared the transitions between Partner and Object during Joint Play and Solo Play, (Figure S2) suggested that these transitions *were* more common during Joint Play than Solo Play. However, this is probably because of differences in the physical set-up between the conditions: in the Joint Play condition, the face of the partner was close to the object, whereas in the Solo Play condition it was not (Figure 1). Procedure 3 (Figure 7) directly attempted to control for this difference. It, along with Procedure 1 (which used an alternative method), both suggested that the observed likelihood of transitioning from Partner to Object was *not* higher than predicted by chance.

In Analysis 2 we also found that infants did not show immediate increases in attentiveness in the time periods after mutual gaze (Figure 7c). In Analysis 3 we found that infants who engaged in more mutual gaze were not more attentive overall (Figure 7d). Overall, then, our results suggest that mutual gaze does not directly facilitate attentiveness.

In sum, our findings appear most consistent with a model in which infants do show increased attention to the Object during Joint Play, but that this increased attention is most likely due to increased exogenous (externally-driven) attentional capture during Joint Play. During Joint Play a parent is more likely to move, or manipulate an object, making it more salient to the infant and therefore making it easier for them to sustain their attention on it.

To say that exogenous, externally-driven attentional capture may be more prevalent during Joint Play than Solo Play, and that this may explain why infant sustained attention is greater during Joint Play, is not to say that endogenous, internally-driven attention is completely absent in either condition. Indeed, the fact that we observed consistent inter-individual differences in attention across the Joint Play and Solo Play conditions (Figure 5a) is evidence of this. One telling comparison may be to liken the present findings, that compare infant attention during Joint Play and Solo Play, with previous findings that compare infant attention towards static and dynamic screen stimuli (Courage et al., 2006; Shaddy & Colombo, 2004; Richards, 2010). Here, similarly, consistent inter-individual differences in attention durations towards static and dynamic screen stimuli are observed (Wass, 2014), which probably suggests that endogenous factors influence attention for both types of stimuli. At the same time, the exogenous influences on gaze behaviour during the viewing of dynamic stimuli are thought stronger (S.V. Wass & T.J. Smith, 2014; S.V. Wass & T.J. Smith, 2014; Courage et al., 2006), and, most likely because of this, infants' attention durations towards dynamic stimuli are markedly higher than towards static stimuli (Shaddy & Colombo, 2004).

If our findings *do* indicate that the longer attention durations observed during joint play are most likely attributable to increased exogenous attentional capture, then how are we to reconcile these findings with previous research? Specifically, how can we reconcile them with research that suggests that infants who spend more time in joint engagement with parents during play show better subsequent long-term gestural and linguistic communication (Carpenter et al., 1998), along with superior visual attention control (Niedźwiecka et al., 2017)? One answer may be to do with scaffolding. During joint play, parents, who naturally show longer attention durations than infants, scaffold their infants' attention patterns, using exogenous cues, so that the infants' patterns of attentional shifts become more like the adult's (Bibok, Carpendale, & Müller, 2009; Dilworth-Bart, Poehlmann, Hilgendorf, Miller, & Lambert, 2010). Through time, by doing this, infants' who receive more attentional scaffolding may spontaneously begin, over longer time-frames, to show natural patterns of attentional allocation that are more like an adult's (Yu & Smith, 2016).

At the same time, though, it is instructive to consider that, during TV watching, for example, long attentional episodes are similarly evoked primarily using exogenous attention capture. The attention patterns of a typical six-year-old viewing static stimuli are comparable to those of a six-year-old with ADHD viewing dynamic stimuli (Lorch et al., 2004; Richards & Anderson, 2004). At the same time, however, these longer patterns of attention during TV viewing are not thought to confer long-term attentional benefits in the same way as joint engagement during social play (Courage & Howe, 2010); indeed, the opposite is more often thought the case (Lillard & Peterson, 2011; Christakis, Zimmerman, DiGiuseppe, & McCarty, 2004).

Two reasons present themselves for why this might be. The first is that, in addition to scaffolding their infants' attention using exogenous attention cues, parents are also sensitively *responding* to their infants. ('Building a scaffold that fits.') Consistent with this, previous research has uncovered *bi-directional* co-regulation of affect during joint play between infants and parents: infants influence their parents during joint play, just as parents influence their infants (Cohn & Tronick, 1988; R. Feldman, 2006; R. Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011; Harrist & Waugh, 2002; Leclère et al., 2014). Greater infant->parent directional influences in affect during social interaction at 3 months associate with better infant self-control at 2 years, controlling for temperament, IQ and maternal style (Ruth Feldman, Greenbaum, & Yirmiya, 1999). Parental sensitivity and exogenous attention scaffolding may both act as contributors to emergent endogenous attention control (Kopp & Vaughn, 1982).

Recent research has also begun to investigate the neural mechanisms that subserve these reciprocal, bidirectional influences. Neural phase-locking – the alignment of temporal patterns of firing in Theta and Alpha bands between the adult and child during live interaction - has been demonstrated (Leong et al., 2017). During videoed interactions (comparing infant's live EEG with adult's pre-recorded EEG) uni-directional influences (adult->infant but not infant->adult) were observed; during live interactions, bi-directional influences (adult->infant *and* infant->adult) were documented (Leong et al., 2017).

In current, ongoing work we are investigating how the relationship between brain activity and attention differs between Solo Play and Joint Play. Based on present findings we predict that infants' own, endogenous brain activity will show a weaker forwards-predictive relation with infant attention during Joint Play than Solo Play. We are also investigating whether direct inter-personal Granger-causal influences of adult brain activity on infant attention can be shown. If proven, such a finding might open the possibility of more direct mechanisms of inter-personal influence than the attention scaffolding via exogenous attention cues that we have postulated here.

The second, and related, possibility is that this exogenous parental attention scaffolding may be specific to the age range being studied. The age of the infants in this study, 12 months, was selected as representing the age at which endogenous attention control is just beginning to emerge (Colombo & Cheatham, 2006; Courage et al., 2006). It may be that, if the experiment were repeated with older infants, different patterns of results would be noted. If observed, such a finding would be consistent with previous research that has suggested that infants' naturalistic attention behaviours become progressively more voluntary (endogenously controlled) over developmental time (Carpenter et al., 1998). Future research with younger and older age groups is necessary in order to investigate this.

Figure Legends

Figure 1: Left: sample plot of the concurrent gaze data collected from infant-parent dyads. Gaze behaviour is summarised in one-second windows based on whether infants and parents were looking at Object, Parent or Neither. Right, top: illustration of the set-up in the Joint Play condition. Right, middle: illustration of the set-up in the Solo Play condition. Right, bottom, illustration of the Parent's perspective during the Solo Play condition. The infant was visible to the parent, but the object that the infant was playing with was not.

Figure 2: Demonstration of auto-correlation analyses. a) and b) show look duration data from two different infants. Different individual looks to the toys are shown. For clarity, the duration of each look is shown both by its height on the Y axis and its length on the X axis. c) shows the preliminary analysis conducted, the auto-correlation function (ACF). The dashed red line shows the 95% confidence intervals for both time series. d) shows the partial auto-correlation functions (PACF) for the same two samples. This is derived from the ACF, but at each time lag k it controls for the effect of auto-correlations at lower temporal scales from lag 1 to k-1. The dashed red line shows the 95% confidence intervals. Only the first-order PACF term is significant, suggesting that the data show a strong first-order auto-regressive tendency. The same pattern was observed in all look duration data analysed (see Supplementary Materials Figure S1).

Figure 3: Demonstration of the cross-correlation analyses. The top two plots show the looking data recorded from an individual infant (top) and parent (middle) during a Joint Play episode. In each case, the duration of different individual looks towards the

object are shown. The bottom plot shows the time-lagged cross-correlation between the two sets of looking data. Two features are visible. The first is the peak of r=0.4 at a time lag of 0. This indicates that, during periods when the infant is showing longer look durations, the parent is, at that same moment in time, also showing longer look durations. The second is that the cross-correlation plot is asymmetric around Time=0, with higher correlation values at positive lags (infant after adult) than positive lags (infant before adult). This indicates that, over shorter time-scales (0-10 seconds), the parent's attention tends to predict subsequent attention in the infant more than vice versa.

Figure 4: a) Average duration of attention to Object, Partner and Inattention for the infant during the Joint Play (JP) and Solo Play (SP) conditions. b) Average number of attention episodes to Object, Partner and Inattention for the infant during the Joint Play and Solo Play conditions. c)-e) histograms showing the distribution of individual attention episodes towards the (c) Object, (d) Partner and (e) Inattention, comparing the Solo and Joint Play conditions.

Figure 5: a) bivariate relationship between infant attention durations to Object during Solo Play and Joint Play; b) bivariate relationship between parent and infant attention durations to object during Joint Play. c) bivariate relationship between PACF and look durations during Solo Play and Joint Play; d) PACF – comparison of the PACF values for look durations towards the object in the Joint Play and Solo Play conditions for the infant alone.

Figure 6: a) lagged cross-correlation plot showing the relationship between infants'

and adults' attention to Object during Joint Play. b) scatterplot showing the participant-by-participant correlations that were averaged to create Figure 6a. Y-axis shows the cross-correlation observed between the parent's attention at time t and the infant's attention at time t-5 to t-0; X-axis shows the cross-correlation observed between the parent's attention at time t and the infant's attention at time t+0 to t+5. The line is the 1:1 correspondence line; a position above this line indicates that 'parent pre infant' is higher than 'parent post infant'. c) cross-correlation plot showing the relationship between infants' and adults' attention to Partner during Joint Play. d) scatterplot showing the (+/- 0 to 5 seconds window) from the lagged cross-correlation plot in Figure 6c.

Figure 7: a) and b) probabilities of transitioning between each of the three looking categories – looking to Object, to Partner, or Inattentive for a) Joint Play and b) Solo Play. The numbers above the arrows indicate the probability of transitioning from one category to another: thus, Figure 7a shows that the probability of transitioning from Inattentive to Object was 0.81, and from Inattentive to Partner was 0.19. Colours indicate the significance values compared with the chance calculations (see Methods). Red indicates that the transitional probability was higher than predicted by chance; blue indicates lower; grey indicates no difference. The key comparison is whether transitions from Partner to Object during Joint Play were more likely than predicted by chance. c) identifies, for the joint play condition, the end of a period of mutual gaze (time 0) and examines infants' attentiveness (indexed as the proportion looking to Object relative to Inattention) in the time periods before and after that moment. It can be seen that, in the time intervals immediately after the end of a period of mutual gaze, infants do not show an increase in attentiveness, as would be indicated by an increase

in the proportion looking to Object relative to Inattention. d) scatterplot showing, dyad by dyad, the number of mutual gaze moments against the proportion of time that the infant spent looking at the Object vs Inattentive. A weak, non-significant, negative correlation is observed, such that, in dyads with fewer mutual gaze moments, the infant is more attentive.

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