

Proactive or reactive? Neural oscillatory insight into the leader-follower dynamics of early infant-caregiver interaction

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Abstract

We know that infants' ability to coordinate attention with others towards the end of the first year is fundamental to language acquisition and social cognition (Carpenter et al., 1998). Yet, we understand little about the neural and cognitive mechanisms driving infant attention in shared interaction: do infants play a proactive role in creating episodes of joint attention? Recording EEG from 12-month-old infants whilst they engaged in table-top play with their caregiver, we examined the ostensive signals and neural activity preceding and following infant- vs. adult-led joint attention. Contrary to traditional theories of socio-communicative development (Tomasello & Carpenter, 2007), infant-led joint attention episodes appeared largely reactive: they were not associated with increased theta power, a neural marker of endogenously driven attention, or ostensive signals before the initiation. Infants were, however, sensitive to whether their initiations were responded to. When caregivers joined their attentional focus, infants showed increased alpha suppression, a pattern of neural activity associated with predictive processing. Our results suggest that at 10-12 months, infants are not yet proactive in creating joint attention. They do, however, anticipate behavioural contingency, a potentially foundational mechanism for the emergence of intentional communication (Smith & Breazeal, 2007).

Significance Statement

Infants' ability to engage in joint attention predicts language development and socio-cognitive functioning. Despite its importance, we understand little about how joint attention is established. We use new techniques to investigate whether infants deliberately create joint attention during naturalistic interactions. Our results suggest they do not: infants showed no evidence of social signalling before leading their partner's attention, and their endogenous

oscillatory activity did not increase. Infants were, however, sensitive to their gaze being followed: when caregivers joined their attention, infants showed neural activity associated with anticipatory processing. Findings suggest infants do not actively control adults' attention – but perceive when adults respond to their initiations. Behavioural contingency may therefore be a key mechanism through which infants learn to communicate intentionally.

Introduction

Temporal and spatial coordination of one's gaze with another's, or joint attention, is fundamental to successful social interaction and shared cognition (1). Shared perception, afforded by joint attention, is thought to form the basis of shared intentions and human-specific forms of collective actions (2, 3). The ability to engage in reciprocally mediated joint attention, where both partners lead and follow each others' attention, develops towards the end of the first year, and is a key milestone in developmental trajectories of language learning and social cognition (4–6). A distinction is made between 'mutual' and 'shared' joint attention. The former involves two individuals mutually attending to the same environmental stimulus together, at the same time; to be considered *shared* attention, however, mutual attention must be intentional – i.e. the partner who leads the other's attention towards a stimulus checks that the other partner has perceived it (e.g. by checking the partner's gaze), and the follower communicates that attention is shared (7).

The onset of intentional, proactive communication is debated (5), but a popular view has been that, already by the end of the first year, infants achieve episodes of joint attention through the establishment of shared intentionality; using social signals deliberately, to direct and share the attention of a communicative partner (1, 5, 8). For example, 9-12-month-old infants are thought to use declarative gestures and vocalisations to direct the attention of an experimenter (4), and modify their behaviour depending on their success (9, 10). More recently, it has been suggested that infants initiate joint attention, not only to share attention, but to elicit information from a social partner about their environment (11). In this view, infants' initiations of shared attention are driven by curiosity (12, 13), and involve communicating intentionally and actively with their partner to regulate when and how they

learn (11). For example, infants aged 12-months point in an interrogative manner (14, 15), and, by 18-months, ask for help from their caregiver to complete a task where they are uncertain (16).

However, much previous work on joint attention development has been conducted using structured, experimental paradigms, where a researcher engages in behaviours aimed at eliciting either a response to their initiations for shared attention in the infant, or an initiation for shared attention *by* the infant; far from the fast-changing multi-layered complexity of naturalistic, free-flowing interactions (3, 17, 18). Micro-behavioural analysis of caregiver-infant table-top play has shown that, in fact, during naturalistic interactions, at the end of the first year, infants rarely engage in active attention-sharing behaviours; looking to their caregivers infrequently (19–21), and checking the focus of their partners' gaze before following their attention less than 10% of the time (19). Instead, infants most often look directly towards objects, and join their caregiver's gaze through attending towards the adults' hands, as they manipulate the attended object (19, 20). These findings challenge the view that joint attention is frequently initiated through proactive communication in early infancy (i.e. using ones' own gaze to signal communicative intention, and using partner gaze to infer intention), and suggest that shifts in infant attention might instead be mostly *reactive* to the sensorimotor behaviours of their partner.

Understanding how joint attention is established in caregiver-infant dyads, and addressing the mechanisms driving infant attention in shared interaction, is difficult using behavioural methods alone. This is because similar behaviours (e.g., looks towards objects or partners) can occur across different levels of attentional and intentional engagement (7, 21).

Electroencephalography (EEG) provides a method to explore sub-second changes in neural

activity at different oscillatory frequencies, which have previously been associated with broad mechanisms of cognitive engagement, in infancy and adulthood (17). Comparing EEG activity before, after and during specific inter-dyadic moments in a free-flowing interaction thus allows insight into the fast-changing cognitive processes that govern how each partner's attention is allocated. To examine whether shifts in infant attention are proactively driven in shared interaction, here, recording EEG from infants during naturalistic play with their caregiver, we investigated event-locked changes in oscillatory activity before adult- vs. infant-led mutual attention episodes.

Theta activity (3-6Hz) is an oscillatory rhythm thought to be associated with endogenous cognitive processing in infancy (22), that increases over fronto-central electrodes during anticipatory and sustained attention (23–25). We hypothesised that, if controlled top-down processes drive infant attention when they lead their partner's attention towards an object, theta activity would increase in the time-window preceding infant-initiated looks to mutual attention, compared to adult-led looks. To explore whether communicative signalling necessary for *shared* joint attention (7) also preceded moments of infant-led mutual attention, we compared the probability of infants looking to their partner or vocalising in the time before look onset. Based on findings from experimental paradigms, an increase in ostensive signalling before infant-led attention was expected (9, 10). As a secondary research question, we also examined whether proactive engagement with their partner in the time before an infant-led look affected whether the look was followed by the caregiver. It was hypothesised that infant theta activity and their use of ostensive signals would increase in the time before infant-led looks to mutual attention, compared to nonmutual attention.

A key process involved in the deliberate and intentional re-orientation of a social-partners' attention in shared interaction, is the anticipation of the partner's response in the time after the initiation (7, 26–28). We therefore also compared infant neural oscillatory activity and ostensive signalling occurring immediately after the onset of infant- and adult-led looks to mutual attention. Naturalistic, observational studies have shown that infants are sensitive to the contingency of an adult partner. For example, responding contingently to an infant's gestures immediately improves the quality and quantity of the attention that they pay to objects (29, 30); and when caregivers behave redirectively (i.e. non-contingently), infants' visual attention durations immediately decrease (31, 32). To our knowledge, however, no previous work has investigated whether infants proactively anticipate, or predict, a response by the partner to their behaviour, i.e. do they check whether their partner has perceived their new attentional focus, and communicate about it, once attention is shared (7).

As well as examining infants' behavioural cues signalling the anticipation of joint attention *after* leading their partner's attention, here, we also investigate whether we can identify neural markers of predictive processing in the time following gaze onset. In adults, alpha desynchronisation is thought to represent release from inhibition during sensory information processing (33). Reduced alpha activity has been identified at the onset of a predicted stimulus (34) and, in social paradigms, predicting the outcome of another persons' action is associated with alpha desynchronisation over pre-central motor cortices (35–37). In infancy, similar patterns of alpha suppression (6-9Hz) have been shown over motor areas when observing the predicted outcome of another individuals' manual behaviour (38–40), and one recent study also showed alpha desynchronisation over central-parietal areas when infants viewed the behavioural response of a video-recorded experimenter to their own behaviour, who followed the infant's gaze towards an object (41) (see also ref. 42). If infants anticipate

the behavioural response of their partner where they lead a look towards an object, alpha desynchronisation would be expected to occur in the time after infant-led looks to mutual attention; with infants encoding the predicted outcome of their initiation towards an object, on their partner's behaviour (i.e. following their attention).

Based on the traditional theoretical view that infants deliberately and proactively initiate shared attention with their partner during social interaction (1, 8), we hypothesised that infant looks to their partner's face would increase in the time after infant-led looks to mutual attention (i.e. that they would check whether their partner had followed their attention towards a new object of interest). It was further hypothesised that infant vocalisations would show some increase in the time after infant- and adult-led looks to mutual attention, with the infant communicating, intentionally, to their partner about the shared focus of attention (7, 8). Consistent with previous neurophysiological findings (38–41), we hypothesised that, if infants anticipate the behavioural contingency of their adult partner where they lead attention towards an object, decreased oscillatory activity in the alpha range (6-9Hz) would occur in the time after infant-initiated looks to mutual attention, compared to adult-initiated looks, and infant-initiated looks to nonmutual attention.

Results

The results section is in three parts. Section 1 presents descriptive statistics on infant and adult gaze and vocal behaviour. Section 2 compares the attentional, behavioural and neural dynamics preceding a) infant-led vs adult-led looks to mutual attention, and b) infant-led looks to mutual vs nonmutual attention. Section 3 repeats this analysis in the time-period following look onset. As behavioural cues are slower-changing in comparison to EEG activity, a 5000ms time-window was used to compare infant behaviour in the time before and after a look onset (customary for this type of research; see ref. 19), whilst a 2000ms time-window examined infant EEG activity.

Section 1 – descriptive statistics

Prior to testing our main hypotheses, we conducted three descriptive analyses. Before interpolating through looks to partner, we investigated the proportion of time that caregivers and infants spent vocalising, looking to their partner, attending to objects, and inattentive during the interaction (Fig. 1a,b). Second, after interpolating through looks to partner, we tested how many times per minute infants and adults engaged in episodes of mutual attention (infant or adult-led), and nonmutual attention. Finally, we examined the length of infant attention episodes, and of caregiver-infant mutual attention episodes (Fig. 1c,d).

Infants spent the majority of the time looking towards objects, whereas caregivers divided their attention between their infant and the objects (consistent with ref. 21; Fig. 1a). Infant vocalisations were infrequent, whereas adult vocalisations were more frequent (Fig. 2b). Comparisons between caregivers and infants were significant using two-tailed independent t-

tests: looks to objects [$t(72)=10.81, p<0.001, d=0.84$], looks to partner [$t(72)=-14.01, p<0.001, d=-1.02$] and vocalisations [$t(36)=-5.61, p<0.001, d=-0.60$]. The proportion of time spent in states of inattention did not differ [$t(72)=1.32, p=0.198, d=0.08$].

Infant object look durations were positively skewed before log transform (consistent with ref. 21), as were episodes of caregiver-infant mutual attention (Fig. 1c). The number of times each type of attention episode occurred per minute was similar for caregivers and infants, with leader looks to mutual attention the most infrequently occurring category (Fig. 1d). Two-tailed independent t-tests showed that infants followed their partner's attention significantly more often per minute compared to their caregivers [$t(72)=2.94, p=0.004, d=0.77$]; all other comparisons were not significant (leader to nonmutual looks [$t(72)=1.49, p=0.139, d=0.35$]; leader to mutual looks [$t(72)=-0.73, p=0.467, d=-0.14$]).

Section 2 – Before look onset: are infants proactively initiating joint attention episodes?

This section is in two parts. Section 2.1 compares infants' use of ostensive signals and their neural oscillatory activity occurring before infant-led looks to mutual attention, and adult-led looks to mutual attention, in order to test for differences between infant- and adult-initiated mutual attention episodes. Section 2.2 subsequently compares infant-led object looks resulting in mutual and nonmutual attention, in order to test for differences between infant-led looks that were followed, or not followed, by their adult partner.

2.1 Infant-led vs adult-led mutual attention

2.1.1 Ostensive signals and infant attention

First, we tested whether infants were more likely to use ostensive signals before an infant-led mutual attention episode, compared to where they followed their caregiver's look into mutual attention. If true, this would support the hypothesis that infants proactively lead their caregiver's attention to objects during naturalistic table-top play. To investigate this, we conducted a probability analysis examining ostensive signals in the time-window $\pm 5000\text{ms}$ relative to each look type.

For each look type (infant-led to mutual and adult-led to mutual), the frame at which an object look onset occurred was identified in the vocalisation and partner look time-series separately, and the 5000ms preceding look onset extracted. The probability of the behaviour occurring at each 20ms frame was then calculated as the proportion of looks where each ostensive signal (looks to the partner's face and vocalisations) was present in that frame. Results of the probability analysis are presented in Fig. 2a-d. Cluster-based permutation analysis (see methods) indicated that infants were significantly more likely to look towards their caregiver in the time-period immediately preceding an episode of infant-led mutual attention, compared to an adult-led mutual attention episode (Fig. 2a). There were no other significant differences between look types (Fig. 2a,b).

Any significant difference between adult-led and infant-led attention could, however, be driven either by an increase relative to baseline in looking prior to infant-led attention episodes, or by a decrease relative to baseline prior to adult-led attention episodes. To

differentiate between these hypotheses, we generated a random probability time-series of partner looks and vocalisations in the time immediately before and after each type of infant object look by inserting a random event into each ostensive cue time series, and extracting the 5000ms preceding the event. A cluster-based permutation analysis was again conducted using paired t-tests to investigate where the behavioural time-series differed from chance (Fig. 2a-d). Results indicated that the probability of infants looking to their partner was below levels expected by chance in the 1s time-period before the onset of adult-led attention. Overall, then, these results suggest that infants are less likely to look to their partner during the time-window preceding adult-led looks to mutual attention.

In addition, to investigate whether infant attentiveness differed in the time before look onset between each look type, using the uninterpolated gaze time series, we also examined how frequently infant attention changed in the 5000ms time-period leading up to each attention episode, and the length of infant gaze towards the previous object for each type of look (Fig. 2e,f). Two-tailed paired t-tests showed no difference in the number of object looks occurring 5s before the onset of an infant-led look to mutual attention [mean=1.85, SEM=0.08], compared to an adult-led look to mutual attention [mean=1.17, SEM=0.06; $t(36)=-0.27$, $p=0.792$, $d=-0.24$]; nor was there a difference in the length of infant attention to the previous object [$t(36)=-0.61$, $p=0.544$, $d=-0.10$].

2.1.2 Neural oscillatory activity

We compared how the neural oscillatory activity differed in the time before infant-led and adult-led mutual attention episodes. Results of the time-frequency analysis are presented in Fig. 3. Two-dimensional cluster-based permutation analysis revealed no significant clusters

of time*frequency points, comparing between infant-led looks to mutual attention, and adult-led looks to mutual attention. Three-dimensional cluster-based permutation analysis, including all electrode by time by frequency points, also revealed no significant clusters. Contrary to what would be expected if infants were deliberately orienting their partners towards objects when shifting their gaze to an unattended object, this primary analysis suggests that there were no significant differences in infants' neural activity in the time-windows before they led their partner's attention towards an object.

In our naturalistic data, some of the epochs included in each look category will also have contained additional object and partner looks during the 2000ms before the onset of the look to which the data were event-locked. Even though eye movement-related artifacts were removed through ICA decomposition during pre-processing (see methods), we also conducted an additional analysis to examine the possibility that this may have contributed to the null result. The results suggested that it did not: the average proportion of looks with object and partner looks occurring in the time before look onset did not differ between attention episodes (Fig. S2,S3,S4). Conducting analyses including looks with no shifts in infant attention before look onset *only* was not possible due to low trial numbers (Fig. S2). For comparison with the behavioral analysis presented in section 2.1, Fig. S5 shows EEG activity over the same time-windows (-5000ms). Two-dimensional cluster-based permutation analysis again revealed no significant clusters of time*frequency points, comparing between infant-led looks and adult-led looks to mutual attention.

2.2 Followed vs not followed infant-led looks

2.2.1 Ostensive signals and infant attention

Here, we also tested whether infants were more likely to use ostensive signals before an infant-led mutual attention episode, compared to an infant-led nonmutual attention episode, in order to examine differences between infant-led looks that were followed, or not, by their adult partner. No significant differences were observed either in the likelihood of the infant looking to their caregiver in the time-period preceding a look (Fig. 2c), or in the likelihood of the infant vocalising (Fig. 2d). In addition, no significant differences were observed in the duration [$t(36)=1.01$, $p=0.321$, $d=0.12$; Fig. 2f], or number [$t(36)=1.45$, $p=0.157$, $d=0.24$] of infant objects looks in the time-period preceding infant-led looks to mutual attention [mean=1.85, SEM=0.08], and nonmutual attention [mean=1.06, SEM=0.07; Fig. 2e].

2.2.2 Neural oscillatory activity

We also compared how neural oscillatory activity differed in the time before infant-led mutual attention episodes and infant-led nonmutual attention episodes (Fig. 3). No significant differences were observed using either the 2-dimensional (Fig. 3) or the 3-dimensional cluster-based permutation analyses. Again, the number of looks including object and partner looks before each attention episode did not differ (Fig. S2,S3,S4). EEG activity occurring 5000ms before look onset for each type of look is presented in Fig. S5. Two-dimensional cluster-based permutation analysis revealed no significant clusters of time*frequency points of the difference between attention episodes.

2.3 Summary

In summary, these results suggest that there is little change in infants' behaviourally ostensive signalling before infant-led mutual attention episodes, compared with adult-led mutual attention (section 2.1.1). The main finding was a decrease in infant looks to their caregiver in the time before adult-initiated mutual attention. There were no differences in infants' ostensive signalling between infant-led looks that were followed vs not followed by their adult partner (section 2.2.1).

The neural analyses suggested that there were no differences in neural oscillatory activity before infant-initiated and adult-initiated mutual attention (section 2.1.2). There were also no differences in neural oscillatory activity between followed vs not followed infant-led attention episodes (section 2.2.2). There was thus very little evidence that 12-month-old infants proactively initiate joint attention with their partner during shared play.

Section 3 – After look onset: do infants anticipate their gaze being followed?

In this section, we present a similar analysis to section 2, investigating change in infant behaviour and neural oscillatory activity in the time-period *after* look onset. Again, the section is organised in two parts: first we examine mutual attention, comparing infant-led and adult-led mutual attention episodes (section 3.1). Second, we compare infant-led attention that was followed vs. not followed by their adult partner (section 3.2).

3.1 Infant-led vs adult-led mutual attention

3.1.1 Ostensive signals and infant attention

First, we tested whether infants were more likely to use ostensive signals during the time-period after the start of infant-led, compared to adult-led mutual attention. To investigate this, we conducted the same probability analysis described in section 2.1.1, extracting the 5000ms following look-onset from the vocalisation and partner-look time-series. No significant difference in the likelihood of partner looks was observed, but a significant increase in the likelihood of infant vocalisations following adult-led mutual attention was shown (Fig. 4b). Baseline comparisons suggested that infant vocalisations significantly decreased from baseline in the time after infant-led looks to mutual attention, potentially driving this difference (Fig. 4b).

We also examined whether infant-led mutual attention episodes tended to be longer lasting than adult-led mutual attention (Fig. 4e). No significant difference was observed [$t(36)=-1.17$, $p=0.248$, $d=-0.19$]. Finally, we examined the time interval it took caregivers to follow their infant's attention during infant-led looks to mutual attention (Fig. 4f). This analysis suggested that most looks were followed within 1-2s after look onset [mean=1.49s, SEM=6.91].

3.1.2 Neural oscillatory activity

In this section, we compare differences in infant EEG activity occurring over fronto-central electrodes after look onset for infant-led and adult-led looks to mutual attention (Fig. 5).

Consistent with our hypothesis, infant-led mutual attention episodes led to a decrease in EEG power, particularly in the theta/alpha range towards the end of the 2000ms time-period, as compared to adult-led looks (Fig. 5a,b). The 2-dimensional cluster-based permutation analysis identified a significant positive cluster with an average frequency of 7Hz (ranging 5-9Hz), 92-2000ms post look onset ($p=0.003$; Fig. 5c). Three-dimensional cluster-based permutation analysis also revealed one trend-level positive cluster, with a wide topographical distribution, in the 5-9Hz range ($p=0.099$; see Fig. S6).

Again, due to the naturalistic nature of our data, some of the epochs included in these analyses contain additional object and partner looks. Similar to the pre-look analysis, there were too few trials per participant to compare EEG activity occurring during looks without any gaze shifts (see Fig. S7). A higher proportion of adult-led looks involved looks to other objects and the partner in the 2000ms time-window, an effect that was driven by a greater number of object looks after the onset of adult-led attention (Fig. S7). When the post-look time-period was broken down into 1000ms intervals, however, the difference between infant-led and adult-led looks was only seen in the first 1000ms after look onset (Fig. S8,S9), and a high proportion ($>70\%$) of infant- and adult-led looks to mutual attention did not contain any object or partner looks (Fig. S7). For comparison with the behavioral analysis presented in section 3.1, Fig. S10 shows EEG activity over the same time-windows (+5000ms). Two-dimensional cluster-based permutation analysis revealed no significant clusters of time*frequency points, comparing between infant-led looks and adult-led looks to mutual attention.

3.2. Followed vs not followed infant-led attention

3.2.1. Ostensive signals and infant attention

We examined whether ostensive signals differed between infant-led looks that were followed vs. not followed by their adult partner, in the time after look onset. No significant difference in the likelihood of partner looks was observed, but there was a significant increase in the likelihood of infant vocalisations following infant-led nonmutual attention, 3s after look onset (Fig. 4d). Again, this effect is likely driven by the significant reduction in infant vocalisations from baseline following infant-led looks to mutual attention (Fig. 4d). Infant-led looks to nonmutual attention lasted a significantly shorter amount of time, compared to infant-led looks to mutual attention, and this difference was marked [$t(36)=6.84, p<0.001, d=1.13$; Fig. 4e]. Indeed, mutual attention extended infant attention, irrespective of whether the attention episode was adult- or infant-led, with adult-led mutual attention episodes also lasting significantly longer compared to infant-led nonmutual attention [$t(36)=8.25, p<0.001, d=1.36$; Fig. 4e].

3.2.2. Neural oscillatory activity

Corresponding to the significantly shorter object looks during episodes of nonmutual attention, infant-led looks to nonmutual attention included significantly fewer looks that lasted the whole 2000ms after look onset, compared to infant-led looks to mutual attention, resulting in more looks containing object looks and looks to partner combined, both 0-1000ms, and 1000-2000ms after look onset (Fig. S7, S8, S9). Due to there being so few infant-led looks resulting in nonmutual attention that lasted the whole 2000ms time-period

(<50%; Fig. S7), cluster-based permutation comparing infant-led looks to mutual and nonmutual attention was excluded from analysis.

3.3 Summary

Consistent with our hypothesis, infant-led mutual attention episodes were accompanied by significantly greater alpha desynchronisation after look onset, compared with adult-led mutual attention (section 3.1.2). Against our predictions, infants also showed some decrease in their vocalisations after infant-led looks to mutual attention, compared to adult-led looks, and infant-led looks to nonmutual attention, corresponding to a marked decrease from baseline after infant-led looks to mutual attention (section 3.1.1). No differences in partner looks were observed (section 3.1.1).

Discussion

This study investigated whether infants play a proactive role in creating episodes of joint attention during naturalistic tabletop play. In contrast to the results observed using structured, experimental paradigms (4, 9, 10), our results suggested that, in free-flowing interaction, 12-month-old infants do not readily use their gaze or vocalise before an infant-initiated mutual attention episode; the occurrence of these behaviours throughout the interaction was generally low (Fig. 1a,b). Though a significant difference in the probability of partner looks 1s before look onset was identified, baseline comparisons indicated that this was driven by a reduction in infant looks to their partner before adult-initiated looks, rather than an increase before infant-initiated looks (Fig. 2a). Against hypotheses, EEG activity at theta frequencies (3-6Hz), did not increase in the 2s before infant-led looks to mutual attention, compared to adult-led looks: cluster-based permutation analysis revealed no significant clusters at any frequency band investigated (Fig. 3c).

Contrary to our prediction that infants' proactive engagement with their partner would affect whether a look was followed by the adult, no differences were identified between infant-led looks in ostensive signals (Fig. 2c,d), or EEG activity (Fig. 3), before look onset. Taken together, our results are inconsistent with the idea that infants routinely exert active and intentional control over the allocation of their attention where they lead their partners' attention, and could suggest that similar processes drive infant attention, when leading a mutual attention episode, and joining the attentional focus of their partner (i.e. adult-led attention).

The null findings reported here are unlikely to be driven by eye-movement related artifact, introduced by temporally variable shifts in infant looking in the time before each look onset. Eye-movement artifacts were removed using ICA decomposition, and, though this does not remove all artifact introduced to the EEG signal (43), we also showed that each look type was equally affected by object and partner looks occurring in the 2000ms preceding look onset (Fig. S2). The large sample size included here, particularly for infant EEG research (44), will have also increased signal-to-noise ratio in our data. It is also unlikely that this effect is driven by removal of neural activity during ICA decomposition: the algorithm used to reject ICA components during pre-processing (see methods), has been shown to be successful in retaining neural signal, especially in comparison to traditional manual rejection techniques (43).

Though infant-led episodes of mutual attention did not appear proactively driven, infants were nevertheless sensitive to whether their look was followed by the adult. In line with hypotheses, in the time-period after look onset, a significant *decrease* in EEG activity was observed over fronto-central electrodes in the alpha band (7Hz), after infant-led looks to mutual attention, compared to adult-led looks (Fig. 5c). This finding reflects the pattern of neural activity observed in infants whilst observing the predicted outcome of another persons' goal-directed behaviour (38, 39, 40), and is consistent with previous experimental work showing reduced alpha activity where infant gaze was contingently responded to by a video-recorded experimenter (41). Thus, the reduction in EEG activity after infant-led looks to mutual attention may be interpreted as a neural marker of predictive processing during online social interaction, with infants predicting and encoding the behavioural contingency of their partner where they lead a look towards an object, and their partner follows. Against hypotheses, however, infants did not show an increase in looking to their partner in the time

after look onset; suggesting that the anticipated contingency of their caregiver was not realised by the infant through observing partner behaviours signalling intention to share attention (7).

A possible interpretation of our findings is that, rather than the establishment of shared intentionality, inter-dyadic coordination is largely achieved and perceived by the infant through attending towards their partner's sensorimotor behaviours. In line with previous findings in naturalistic studies, infants did not use their partner's gaze to follow their attention (19). In fact, infants looked to objects more (rather than to their partner) in the 1s time-period before adult-initiated looks. This is consistent with Yu and Smith's observation that moments infants join their partner's attention are driven by the partner's manual activity on objects (19, 20). The neural analyses of the current study, that show no increase in endogenous oscillatory activity before infant-led looks, relative to adult-led looks, suggest that similar, external inputs might also drive infant attention where they lead a look towards an object. As well as overt behaviours such as object manipulations and gestural communication, other sensory inputs could also influence shifts in infant gaze. For example, in very early face-to-face interactions, salient events such as pauses in adult vocalisations, and changes in the fundamental frequency of their voice modulate infant attention towards and away from the partners' face (45, 46). In the current study, analysis of caregivers' ostensive signalling revealed that partner looks increased and vocalisations decreased in the time before infant-led looks to concurrent attention, compared to adult-led looks, and infant-led looks to nonconcurrent attention (Fig. S11).

Entrainment to the low-level sensorimotor dynamics of shared interaction (3) could also be the mechanism through which infants *perceive* the behavioural contingency of their

communicative partner, suggested by the alpha suppression observed after infant-led looks to mutual attention. Research into action-oriented predictive processing suggests that motor intentions actively elicit active predictions about the ongoing consequences of our own actions (47, 48). Perhaps similar processes operate across the dyad during early behavioural coordination, with the infant anticipating the effect of their own action on the behaviour of their partner (26, 28). Again, as well as overt manual behaviours (19), other fast-changing cues such as temporal and spectral modulations in the partner's vocalisations could also signal behavioural contingency to the infant (45, 46).

Thus, the expectancy of a response from their partner when 12-month-old infants shift their attention towards a new object could predominantly be driven by repeated experiences of sensorimotor contingency between their own behaviour, and the behaviour of their partner (49). According to neurocomputational, associative learning accounts, attunement to these contingencies might form the basis for later developments in intentional communication (50, 51). These accounts postulate that infants learn about their environment, and how to act on it through repeated reinforcement, where the value given to an action is based on previous experience of how that action affected the environment (13, 49–51). In the context of social interaction, then, infant behaviour is assigned meaning by the adult through consistent and contingent behavioural feedback. Over time, these statistical regularities form the basis for infant representations about the intentions of others, and how their own intentionally-motivated behaviours affect those of their partner (51). Consistent with this, the current EEG findings suggest that infants predict and encode the behavioural contingency of their partner to their own actions before they show signs of intentionally initiating joint attention episodes.

In future research, it will be important to investigate how adult behaviours change around moments that their gaze follows infant attention. Equally important is to explore infants' overt and covert behaviour that affect change in the caregiver. Previous work has, for example, shown that caregivers are more likely to respond contingently to speech-like vocalisations produced by the infant (52, 53). At the macro-level, identifying mechanisms operating across the dyad that give rise to these contingencies, through modelling the dynamics of inter-dyadic multi-modal behaviours, and how they co-fluctuate together, in time, will be key (54) (see ref. 55 for a granger-causal model of gaze and manual activity during caregiver-infant joint play). Another important avenue will be to use the methods developed here to explore neural and cognitive mechanisms associated with early language acquisition during naturalistic, free-flowing interaction (18).

Whilst this study is the first to show how infant neural activity changes around moments of infant- vs. adult-led episodes of mutual attention during naturalistic interactions, predictive encoding models, investigating the dynamic relationship between infant attention, inter-dyadic behaviour and infant neural activity should be a next step (56). Neural tracking of auditory information to controlled experimental stimuli has been shown in both adults (57) and more recently, infants (58, 59). Whether and how infants' neural activity dynamically responds to modulations in their partners' behaviours, including features and the timing of caregiver vocalisations, manual activity, and bodily movement, and how this associates with the timing of infant- and adult-led episodes of joint action is yet to be investigated.

Examining these questions developmentally will be integral to understanding the development of intentional communication in infancy, and in identifying atypical trajectories (60).

Our use of naturalistic data is a limitation, as well as a strength, as we were unable to control for how much infants moved their attention between objects in the time before and after look onsets. This not only introduces artifact to the EEG signal, but also means that the extent to which oscillatory activity is influenced by object processing, differs between looks. However, we showed that the number of object and partner looks did not differ in the 2000ms before look onset for either comparison, and differed only in the first 1000ms after look onset, comparing infant- and adult-led looks to mutual attention (Fig. S2, S8, S9). Increased gaze shifts after infant-led looks to nonmutual attention did, however, mean that we were unable to compare infant-initiated looks to mutual and nonmutual attention in the time after look onset. Employing continuous methods of analysis to naturalistic data would overcome this issue (56).

The ability to engage in reciprocally mediated joint attention towards the end of the first year is catalytic to developments in language and social cognition (4, 18). The findings reported here suggest that at 10-12-months, infants are not yet predominantly proactive in creating and maintaining episodes of joint attention with their adult partner. They are, however, sensitive to whether their behaviour is contingently responded to, potentially forming the basis for the emergence of intentionally-mediated communication.

Materials and Methods

Participants

Fifty-eight caregiver-infant dyads took part in the study; 37 participants contributed useable data (13 excluded due to recording error, 2 excluded due to infant fussiness, 6 excluded due to poor quality infant EEG (see artifact rejection and pre-processing section for more information on EEG exclusion criteria)). The final sample included 18 females and 19 males; mean age, 11.12 months (SD=1.33). All caregivers were female. Participants were recruited through baby groups and Children's' Centers in the Boroughs of Newham and Tower Hamlets, as well as through online platforms such as Facebook, Twitter and Instagram. Written informed consent was obtained from all participants before taking part in the study, and consent to publish was obtained for all identifiable images used. All experimental procedures were reviewed and approved by the University of East London Ethics Committee.

Experimental set-up

Caregivers and infants were seated facing each other on opposite sides of a 65cm wide table. Infants were seated in a high-chair, within easy reach of the toys (see Fig. 6c). The shared toy play comprised two sections, with a different set of toys in each section, each lasting ~5 minutes each. Two different sets of three small, age-appropriate toys were used in each section; this number was chosen to encourage caregiver and infant attention to move between

the objects, whilst leaving the table uncluttered enough for caregiver and infant gaze behaviour to be accurately recorded (cf. 19).

At the beginning of the play session, a researcher placed the toys on the table, in the same order for each participant, and asked the caregiver to play with their infant just as they would at home. Both researchers stayed behind a screen out of view of caregiver and infant, except for the short break between play sessions. The mean length of joint toy play recorded, combining the first and second play sections was 9.92 minutes ($SD=2.31$).

Equipment

EEG signals were recorded using a 32-channel BioSemi gel-based ActiveTwo system with a sampling rate of 512Hz with no online filtering using ActiView Software. The interaction was filmed using three Canon LEGRIA HF R806 camcorders recording at 50 fps. Caregiver and infant vocalisations were also recorded throughout the play session, using a ZOOM H4n Pro Handy Recorder and Sennheiser EW 112P G4-R receiver.

Two cameras faced the infant: one placed on the left of the caregiver, and one on the right (see Fig. 6c). Cameras were placed so that the infant's gaze and the three objects placed on the table were clearly visible, as well as a side-view of the caregiver's torso and head. One camera faced the caregiver, positioned just behind the left or right side of the infant's high-chair (counter-balanced across participants). One microphone was attached to the caregiver's clothing and the other to the infant's high-chair.

Caregiver and infant cameras were synchronised to the EEG via radio frequency (RF) receiver LED boxes attached to each camera. The RF boxes simultaneously received trigger signals from a single source (computer running MATLAB) at the beginning of each play section, and concurrently emitted light impulses, visible in each camera. Microphone data was synchronised with the infants' video stream via a xylophone ding recorded in the infant camera and both microphones, which was hand identified in the recordings by trained coders. All systems were extensively tested and found to be free of latency and drift between EEG, camera and microphone to an accuracy of ± 20 ms.

Video coding

The visual attention of caregiver and infant was manually coded using custom-built MATLAB scripts that provided a zoomed-in image of caregiver and infant faces (see Fig. 6c). Coders indicated the start frame (i.e. to the closest 20ms, at 50fps) that caregiver or infant looked to one of the three objects, to their partner, or looked away from the objects or their partner (i.e. became inattentive). Partner looks included all looks to the partner's face; looks to any other parts of the body or the cap were coded as inattentive. Periods where the researcher was within camera frame were marked as uncodable, as well as instances where the caregiver or infant gaze was blocked or obscured by an object, or their eyes were outside the camera frame. Video coding was completed by two coders, who were trained by the first author. Inter-rater reliability analysis on 10% of coded interactions (conducted on either play section 1 or play section 2), dividing data into 20ms bins, indicated strong reliability between coders ($\kappa=0.9$ for caregiver coding and $\kappa=0.8$ for infant coding).

Vocalisation coding

The onset and offset times of caregiver and infant vocalisations were coded using custom-built MATLAB scripts that allowed coders to identify the onset and offset of a vocalisation based on the spectrogram, as well as auditory sound. A vocalisation was defined as a continuous sound produced by the caregiver or infant, with a pause less than 500ms. Due to the labour-intensive nature of the vocalisation coding, vocal coding was completed for a subsample of the caregiver-infant dyads ($n=19$). Inter-rater reliability on 10% of coded interactions (conducted on either play section 1 or play section 2), dividing data into 1ms bins, again indicated strong reliability between coders ($\kappa=0.8$).

Behavioural look extraction and analysis

Data pre-processing

The aim of our analysis was to identify moments where the infant's attention transitioned from one play object to another, and to examine whether the infant or the caregiver initiated the transition. Before doing this, however, we first interpolated through infant and caregiver looks to their partner. This is because, as shown in Fig. 6a,b, during periods of concurrent looking towards an object, caregivers, and, to a lesser extent, infants, alternated their attention frequently between the object and their partner. Without interpolation, each subsequent look back to the object would be classified as a separate follower look to the object. This procedure thus allowed us to accurately identify moments in the interaction where the infant was leading and following their partner's attention, while considering the dynamic nature of joint attention documented in previous studies (19).

Interpolation involved identifying moments where the caregiver or infant looked up to their partner and then interpolating through that look, so that the partner look became an extension of the preceding object look. No threshold was set for interpolation: a new look was considered to have started at the beginning of each new object look (see Fig. 6b). After interpolation, the first and last frame of all attention episodes were extracted. Infant object looks were categorised into adult-led and infant-led looks. Infant-led looks were subdivided into two further categories: infant-led looks to mutual and nonmutual attention (see Table 1 for description of each look category). Looks that followed or preceded uncodable gaze behaviour were excluded from analysis, as well as leader looks where the partner's gaze in the time after look onset preceded an uncodable period.

Cluster-based permutation analysis

To test for significant differences in the likelihood of ostensive signals during the time-periods before and after infant-led and adult-led looks, a permutation-based temporal clustering analysis was conducted (61). This approach controls for family-wise error rate using a non-parametric Monte Carlo method. For each comparison, a t-statistic was independently calculated at each frame, using a paired t-test, and significant effects were thresholded at an alpha level of 0.05 (two-tailed). Clusters constituted consecutive frames with significant effects. One thousand permutations were then conducted whereby one data stream was shuffled randomly in time, and the largest cluster of contiguous significant effects identified. The Monte Carlo estimate of the permutation p-value was calculated as the proportion of random clusters longer than the clusters found in the observed data. Contiguous clusters >95th centile were considered significant, corresponding to a critical alpha level of 0.05 (two-sided test).

Infant EEG analysis

Artifact rejection and pre-processing

A fully automatic artifact rejection procedure including ICA was adopted, following procedures from commonly used toolboxes for EEG pre-processing in adults (62, 63) and infants (64, 65), and optimised and tested for use with our naturalistic infant EEG data (43, 66, 67). This was composed of the following steps: first, EEG data were high-pass filtered at 1Hz (FIR filter with a Hamming window applied: order 3381 and 0.25/ 25% transition slope, passband edge of 1Hz and a cut-off frequency at -6dB of 0.75Hz). Although there is debate over the appropriateness of high pass filters when measuring ERPs (see ref. 68), previous work suggests that this approach obtains the best possible ICA decomposition with our data (43). Second, line noise was eliminated using the EEGLAB (70) function *clean_line.m* (62).

Third, the data were referenced to a robust average reference (63). The robust reference was obtained by rejecting channels using the EEGLAB *clean_channels.m* function with the default settings and averaging the remaining channels. Fourth, noisy channels were rejected, using the EEGLAB function *clean_channels.m*. The function input parameters ‘correlation threshold’ and ‘noise threshold’ (inputs one and two) were set at 0.7 and 3 respectively; all other input parameters were set at their default values. Fifth, the channels identified in the previous stage were interpolated back, using the EEGLAB function *eeg_interp.m*. Interpolation is commonly carried out either before or after ICA cleaning but, in general, has been shown to make

little difference to the overall decomposition (70). Infants with over 21% electrodes interpolated were excluded from analysis. After exclusion, the mean number of electrodes interpolated for infants was 0.19 (SD=0.67) for play section 1, and 2.36 (SD=1.87) for play section 2.

Sixth, the data were low-pass filtered at 20Hz, again using an FIR filter with a Hamming window applied identically to the high-pass filter. Seventh, continuous data were automatically rejected in a sliding 1s epoch based on the percentage of channels (set here at 70% of channels) that exceed 5 standard deviations of the mean channel EEG power. For example, if more than 70% of channels in each 1-sec epoch exceed 5 times the standard deviation of the mean power for all channels then this epoch is marked for rejection. This step was applied very coarsely to remove only the very worst sections of data (where almost all channels were affected), which can arise during times when infants fuss or pull the caps. This step was applied at this point in the pipeline so that these sections of data were not inputted into the ICA. The mean percentage of data removed in play section 1 was 7.96 (SD=7.44), and 3.16 (SD=4.32) for play section 2.

Data collected from the entire course of the play session (including play section 1 and play section two, as well as two further five minute interactions) were then concatenated and ICAs were computed on the continuous data using the EEGLAB function `runica.m`. The mean percentage of ICA components rejected was 52.03% (SD=19.18). After ICA rejection, data from each play section were re-split.

Time-frequency analysis

Each infant look onset was identified in the EEG signal, and activity occurring 2500ms before to 2500ms after look onset extracted, across all channels. An additional 200ms was

also extracted immediately prior to this segment to serve as the pre-look baseline. Only look epochs with 25% or fewer data points excluded during artifact rejection were included in analysis, and missing data points were set to NaN.

Time-frequency decomposition was conducted on each look epoch via continuous Morlet wavelet convolution, whereby the EEG signal at each channel was convolved with Gaussian-windowed complex sine-waves, ranging from 1-16Hz, in linearly spaced intervals. This frequency range was selected as the frequency range least sensitive to movement artifacts inherent in naturalistic infant EEG, which affects both low ($<2\text{Hz}$) and high ($>16\text{Hz}$) frequency activity (66). The width of the Gaussian was set to 7 cycles. Before wavelet convolution, the epoched data was reshaped into continuous data, and afterwards transformed back to individual epochs. To remove distortion introduced by wavelet convolution, the first and last 500ms of each epoch was chopped off, so that the epochs were 4200ms in length. After convolution, power was extracted as the absolute value squared, resulting from the complex signal, before averaging power values at each time point over all looks. The condition-specific baseline period used was 2200-2000ms before look onset. Averaged power time-series occurring 2000ms before and after look onset were normalised by transforming the baseline-corrected signal to a decibel (dB) scale (71).

Cluster-based permutation analysis – EEG data

Two approaches were used for analysing the EEG data. First, 2-dimensional (frequency x time) clusters were calculated based on data collapsed in topographical space, over fronto-central electrodes (Fig. 6d). Second, 3-dimensional (frequency x time x electrode) clusters

were calculated based on the entire data. For the first analysis, normalised power was averaged over fronto-central electrodes (AF3, AF4, FC1, FC2, F3, F4, Fz; see Fig. 6d for locations), and compared between looks. This electrode cluster was chosen based on previous infant literature (72). Only participants contributing 5 usable trials or more to both look categories, in one comparison, were included in each analysis (see Fig. S1 for details on the number of epochs included before and after artifact rejection, for each type of attention episode).

For the first analysis, the normalised power time-series before and after look onset was compared for each look category, using the FieldTrip function `ft_freqstatistics` (61). The cluster-based permutation approach controls for family-wise error rate using a non-parametric Monte Carlo method. Corresponding time*frequency points were compared between conditions using paired sample t-tests, and adjacent significant time*frequency points ($p < 0.05$, two-tailed) were clustered together using the ‘maxsum’ cluster statistic, which sums together the t statistics of each significant time-frequency point in each cluster. The largest cluster was retained. This procedure was then repeated 1000 times, randomising and reshuffling participant data points between conditions on each permutation. The Monte Carlo estimate of the permutation p-value was calculated as the proportion summed test statistics larger than the observed summed t-statistic: here, clusters with a summed t-statistic $> 95^{\text{th}}$ centile (corresponding to a p-value of 0.025 (two-sided test)) were accepted as significant.

Second, in order to examine how the distribution of results varied topographically over the brain, an additional 3-dimensional cluster-based permutation analysis was conducted to examine time-frequency-electrode space for clusters of significant data points. All 32 channels, at frequencies 2-16Hz were included in the permutation. The ‘minnbchan’

parameter was set to 0. Clusters with a p-value <0.025 (two-sided test) were considered significant.

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Data availability: Due to the personally identifiable nature of our data (video and audio recordings of infants), permission to access the data will be given only by contacting the first author, EAMP, direct via email.

Code availability: All code will be made available by the authors upon request.

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Figures and Tables

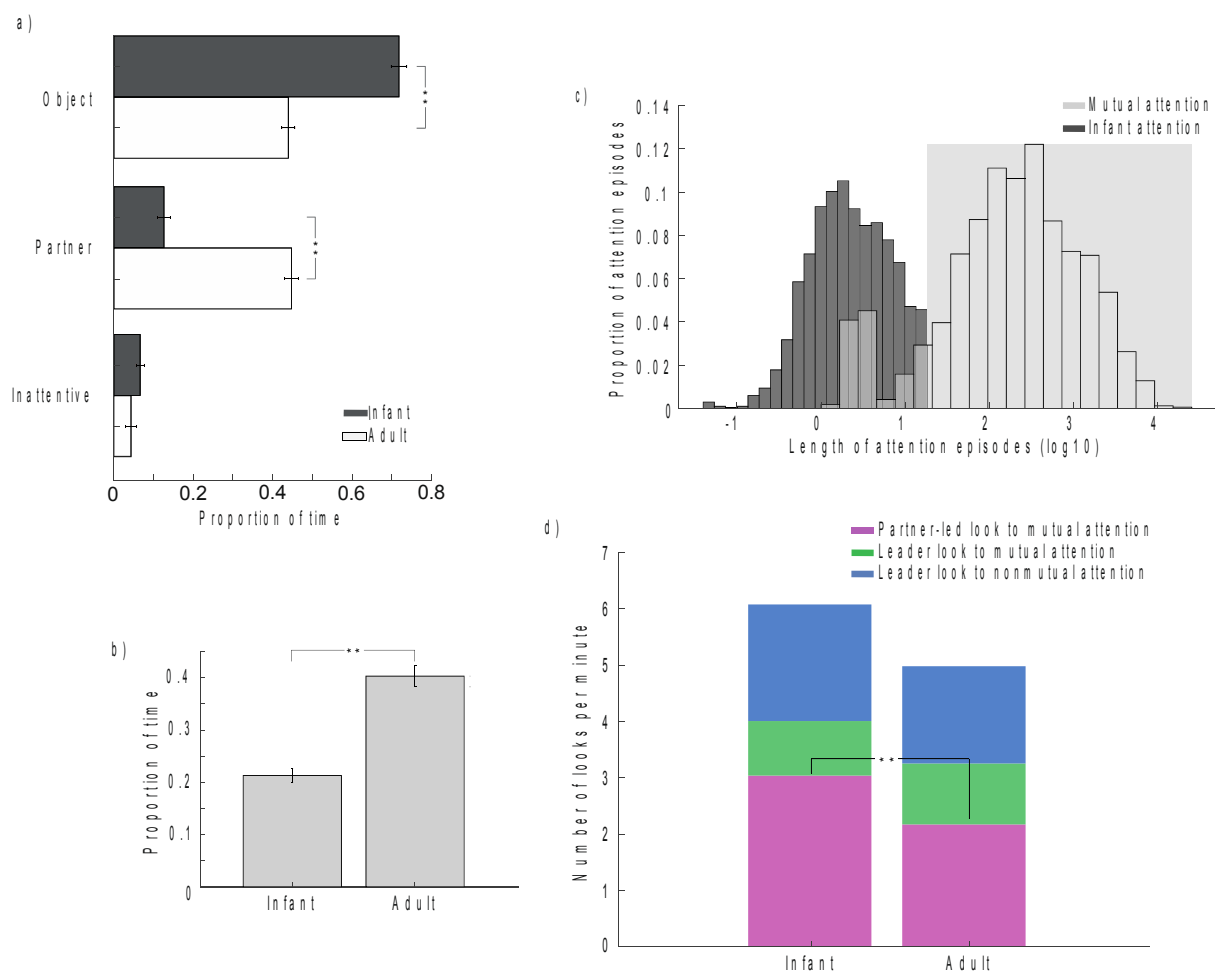


Figure 1. Caregiver and infant attention, and vocal behaviour in shared play. a) Bar plots show the proportion of time caregivers and infants spent looking to their partner, towards objects, and inattentive, during the interaction. Two-tailed independent t-tests ($n=37$) compared proportions between caregivers and infants for each look category (* $p<0.05$, ** $p<0.01$; error bars show the SEM). b) Bar plot shows the mean proportion of time caregivers and infants spent vocalising during

*the interaction. A two-tailed independent t-test ($n=37$) compared proportions between caregivers and infants ($*p<0.05$, $**p<0.01$; error bars show the SEM). c) Histograms show log-transformed infant object look durations, and length of mutual attention episodes, across all types of looks, after interpolation. d) Bar plots show the number of times infants and adults engaged in one of three possible attentional states per minute: partner-led looks to mutual attention, leader looks to mutual attention, leader looks to nonmutual attention. Two-tailed independent t-tests compared the number of attention episodes per minute between caregivers and infants, for each look category ($n=37$; $*p<0.05$, $**p<0.01$).*

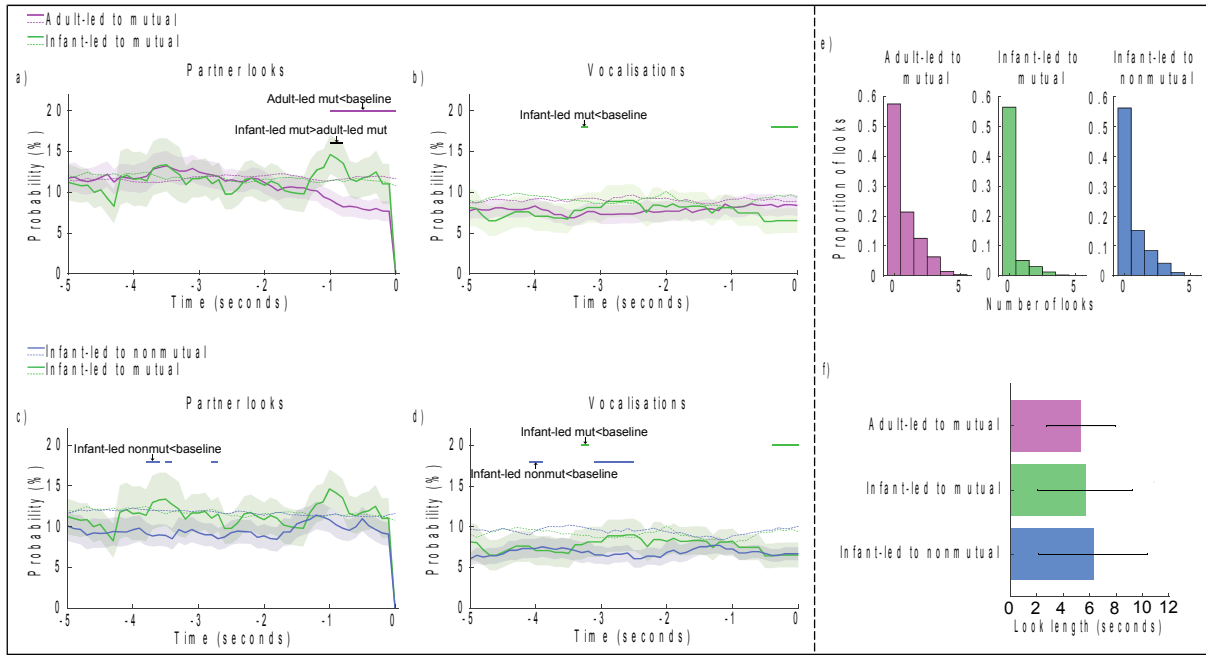


Figure 2. Probability of ostensive signals (partner looks and vocalisations) and infant attentiveness in the time-period before infant look onset. Probability time-course for: a) Partner looks before infant-led mutual attention vs adult-led mutual attention; b) Vocalisations before infant-led mutual attention vs adult-led mutual attention; c) Partner looks before infant-led mutual attention vs infant-led nonmutual attention; d) Vocalisations before infant-led mutual attention vs infant-led nonmutual attention. In each case shaded areas show the SEM ($n=37$ for a) and c), $n=19$ for b) and d)), and horizontal black lines show the areas of significant difference, between attention episodes, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). Dotted lines show the baseline time-series, plotted for each attention episode. Horizontal coloured lines show the areas of significant difference between each attention episode and baseline, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). e) Histograms show the distribution of the number of object looks in the 5s time-period before look onset for each attention episode. f) Bar plots show the mean length of infant attention towards the object immediately preceding look onset for all three attentional states. Error bars indicate the SEM ($n=37$). Two-tailed paired t -tests compared the length of infant attention towards the previous object, between each attention episode, which indicated no significant differences.

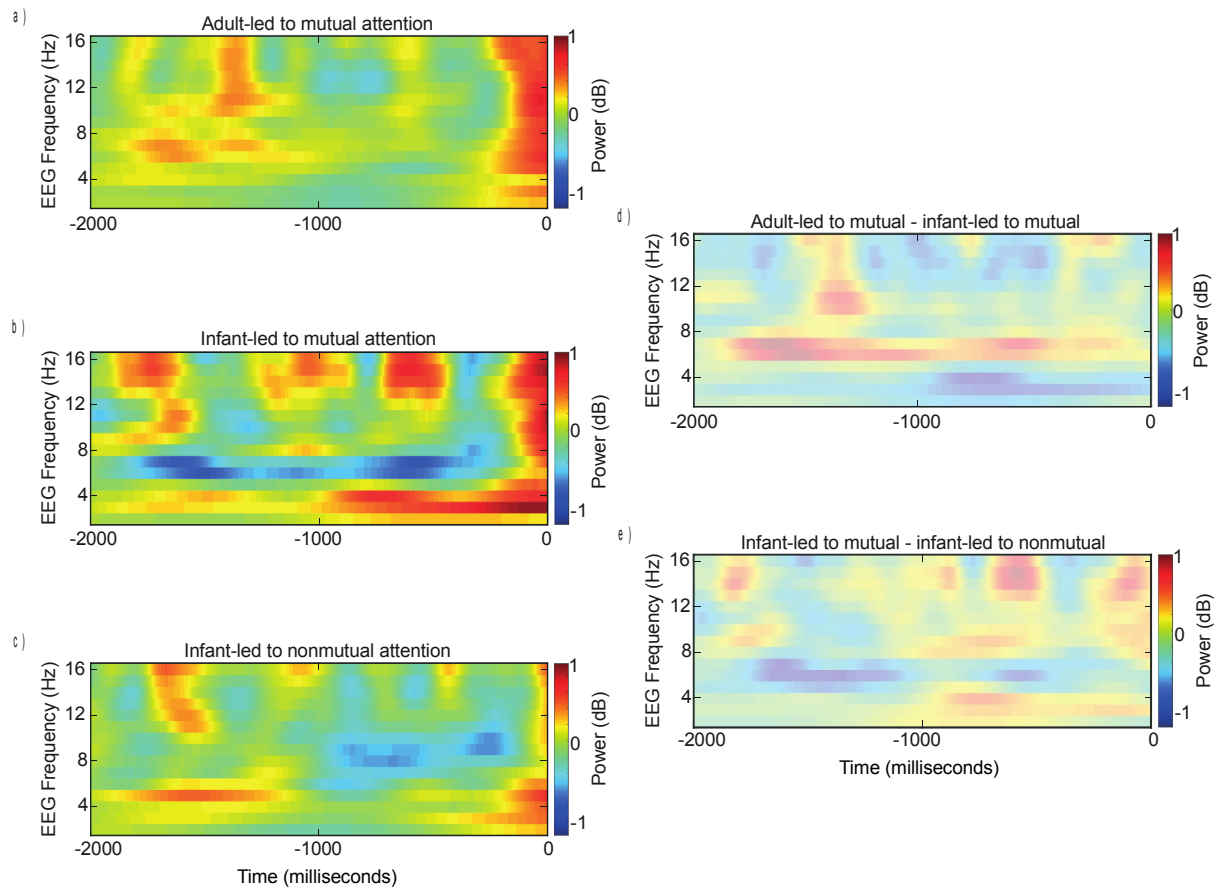


Figure 3. Comparison of infant EEG activity in the 2000ms preceding infant- and adult-led attention episodes. Time-frequency plots show infant EEG activity (2-16Hz) occurring 2000ms before look onset, for (a) adult-led looks to mutual attention, (b) infant-led looks to mutual attention and (c) infant-led looks to nonmutual attention, over fronto-central electrodes (AF3, AF4, FC1, FC2, F3, F4, Fz). Time 0 indicates infant gaze onset. d) Difference in EEG activity between infant- and adult-led looks to mutual attention (adult-led – infant-led). Cluster-based permutation analyses showed no significant clusters of time*frequency points of the difference between attention episodes. e) Difference in EEG activity between infant-led looks to mutual and nonmutual attention (infant-led to mutual - infant-led to nonmutual). Cluster-based permutation analyses showed no significant clusters of time*frequency points of the difference between attention episodes.

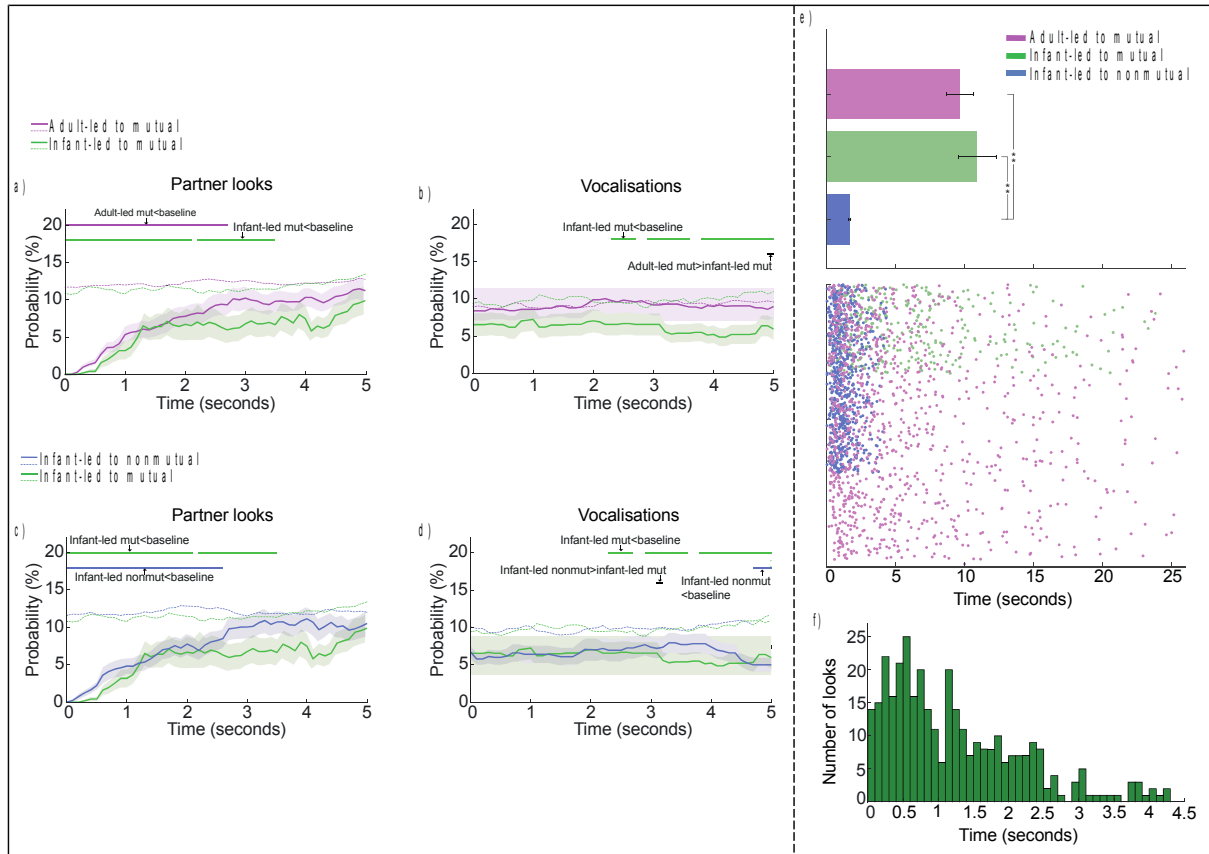


Figure 4. Probability of ostensive signals (partner looks and vocalisations), infant attentiveness, and the time adults took to follow infant attention in the time-period after infant look onset.

Probability time-course for: a) Partner looks after infant-led mutual attention vs adult-led mutual attention; b) Vocalisations after infant-led mutual attention vs adult-led mutual attention; c) Partner looks after infant-led mutual attention vs infant-led nonmutual attention; d) Vocalisations after infant-led mutual attention vs infant-led nonmutual attention. In each case shaded areas show the SEM and horizontal black lines show the areas of significant difference, between attention episodes, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). Dotted lines show the baseline time-series, plotted for each attention episode. Horizontal coloured lines show the areas of significant difference between each look type and baseline, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). e) Length of infant attention towards an object after look onset, for each type of attention episode. The bar plot shows the mean length of infant attention averaged over participants (error bars show the SEM ($n=37$)); scatter plot shows the length

*of each individual look contributing to each object look category, across all participants, after outlier removal. Two-tailed paired t-tests ($n=37$) compared the difference in the length of infant attention between each type of attention episode ($*p<0.05$, $**p<0.01$). f) Histogram shows the distribution of the time it took caregivers to follow infant-led looks to mutual attention, across all looks, for all participants, after outlier removal.*

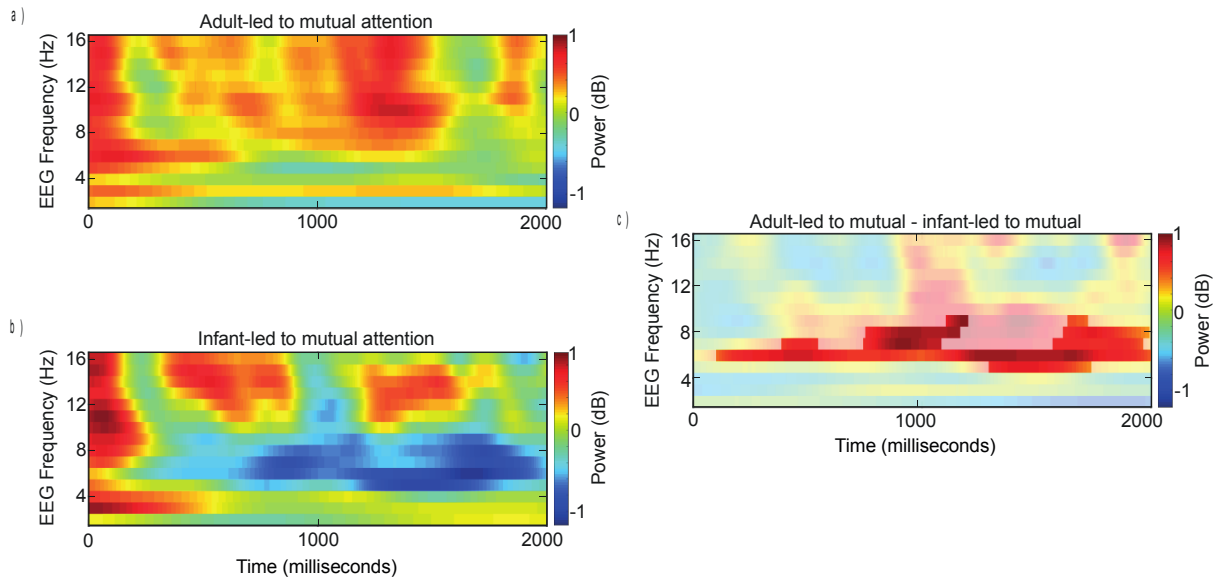


Figure 5. Comparison of infant EEG activity in the 2000ms following infant- and adult-led attention episodes. Time-frequency plots show infant EEG activity (2-16Hz) occurring 2000ms after look onset, for (a) adult-led looks to mutual attention and (b) infant-led looks to mutual attention, over fronto-central electrodes (AF3, AF4, FC1, FC2, F3, F4, Fz). Time 0 indicates infant gaze onset. c) Difference in EEG activity between infant- and adult-led looks to mutual attention (adult-led – infant-led); highlighted area shows the significant positive cluster identified by the cluster-based permutation analysis ($p=0.003$). The cluster ranges from 5-9Hz, from 92-2000ms post look-onset.

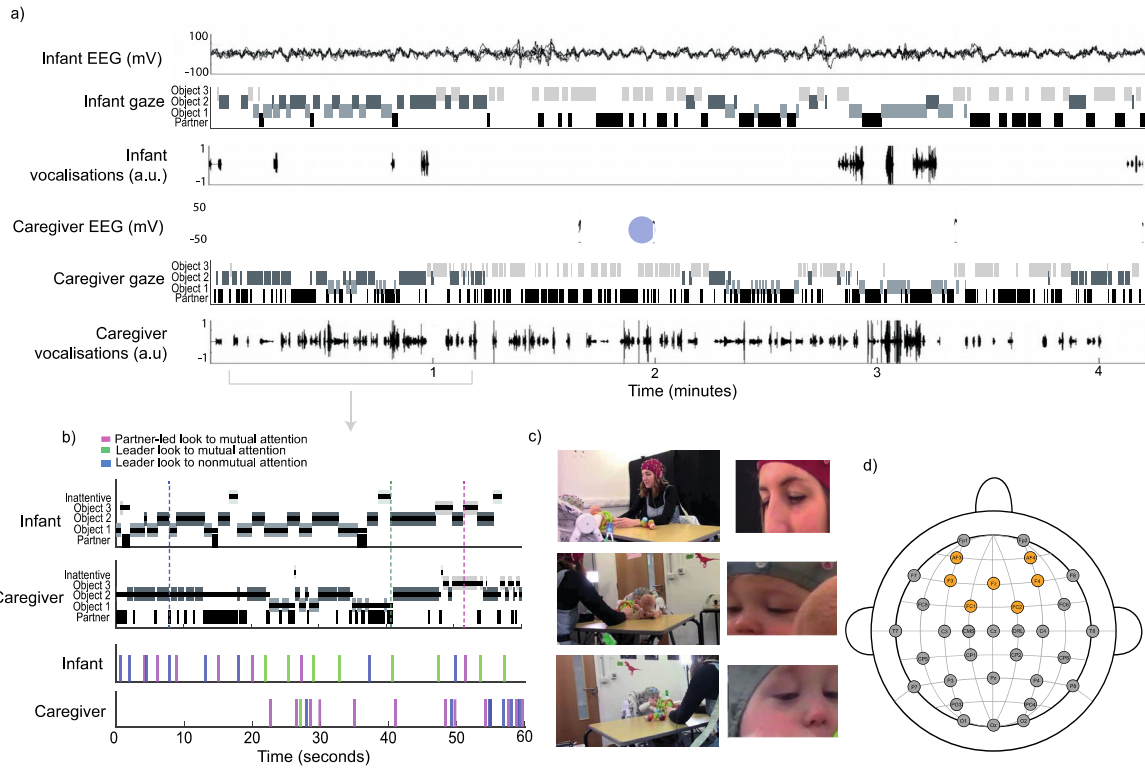


Figure 6. Example data collected during one five minute interaction for one dyad, camera angles used for coding and EEG montage. a) Raw data sample, showing (from top) infant EEG over fronto-central electrodes, after pre-processing, infant gaze behaviour, infant vocalisations, adult EEG over fronto-central electrodes, adult gaze behaviour, adult vocalisations. b) Example of interpolated looks (thin black lines) superimposed on caregiver and infant looking behaviour before interpolation (thick grey lines). Coloured dashed lines indicate examples of different look types in the infant gaze time series (top). Spike trains for infant and caregiver looks, coloured according to look type (bottom). c) Example camera angles for caregiver and infant (right and left), as well as zoomed-in images of caregiver and infant faces, used for coding. d) Topographical map showing electrode locations on the bio-semi 32-cap; fronto-central electrodes included in the infant time-frequency analysis are highlighted in orange (AF3, AF4, FC1, FC2, F3, F4, Fz).

Table 1. Definition of infant attention episode categories

Attention episode	Definition
Adult-led looks to mutual attention	The start of the attention episode was taken from the frame that the infant first shifted their gaze towards an object that the adult was already looking towards, at any point in the time that the adult was still attending towards the object.
Infant-led looks to mutual attention	The start of the attention episode was taken from the frame that the infant first shifted their gaze towards an object that the parent was not already looking at, and the adult subsequently joined the infant's gaze towards the object, at any point in the time that the infant was still attending towards the object.
Infant-led looks to nonmutual attention	The start of the attention episode was taken from the frame that the infant first shifted their gaze towards an object that the adult was not already looking at, and the adult did not follow the infant's look towards the object at any point in the time that the infant was still attending towards the object.

Supplementary Information for:

Proactive or reactive? Neural oscillatory insight into the leader-follower dynamics of early infant-caregiver interaction

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This PDF file includes:

Figures S1 to S12

Materials and Methods

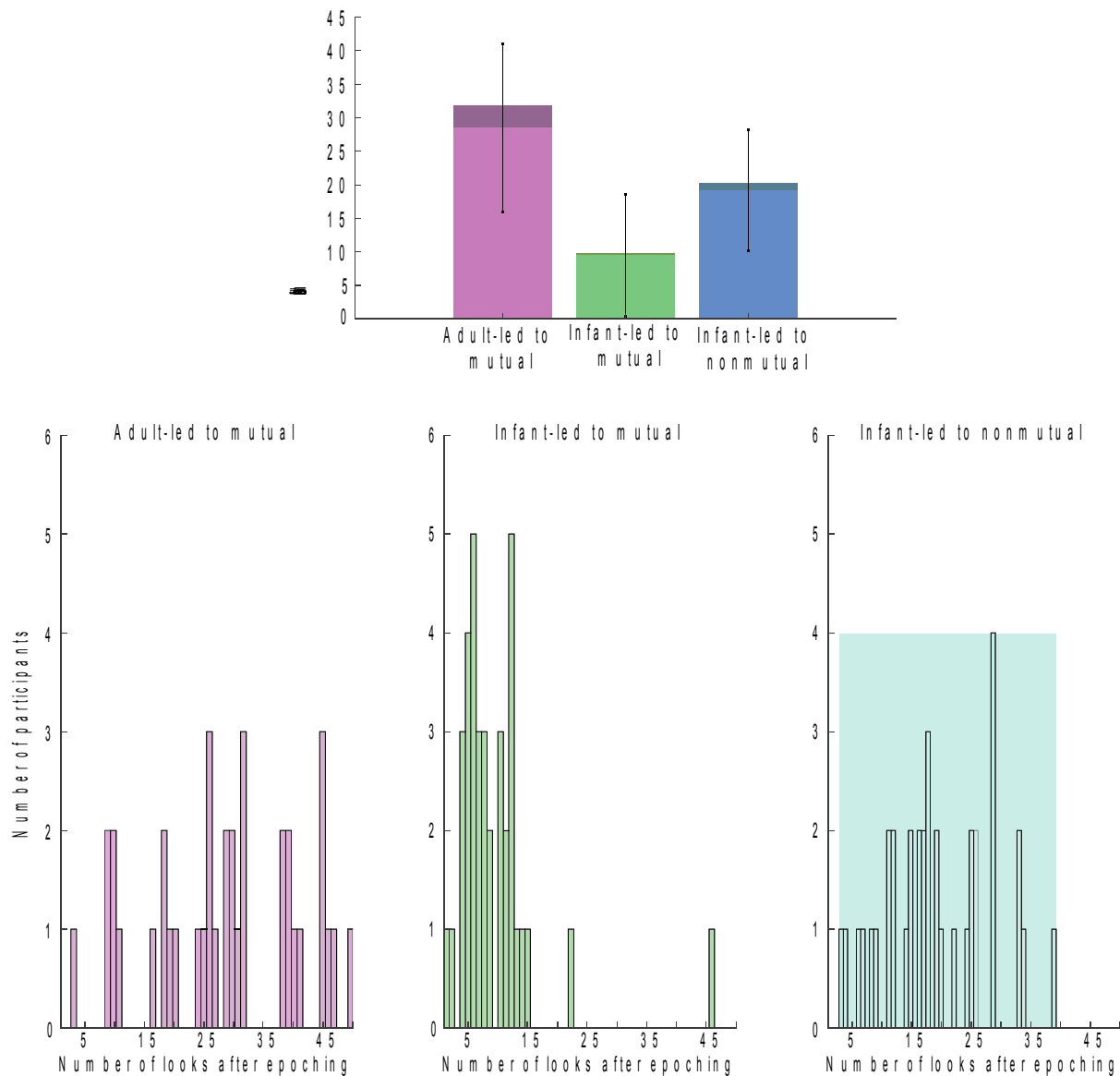


Fig. S1. a) Bar plot shows the mean number of looks included in each category after EEG epoching. Error bars show the standard deviation ($n=37$). b) Histograms show the number of participants contributing a certain number of look epochs for each attention episode. One participant contributed fewer than five trials for adult-led looks to mutual attention; 5 for infant-led looks to mutual attention, and 2 for infant-led looks to nonmutual attention. Participants contributing fewer than 5 looks for one attention episode in each comparison (e.g., infant-led mutual attention compared to adult-led mutual attention) were excluded from the cluster-based permutation analysis.

Results

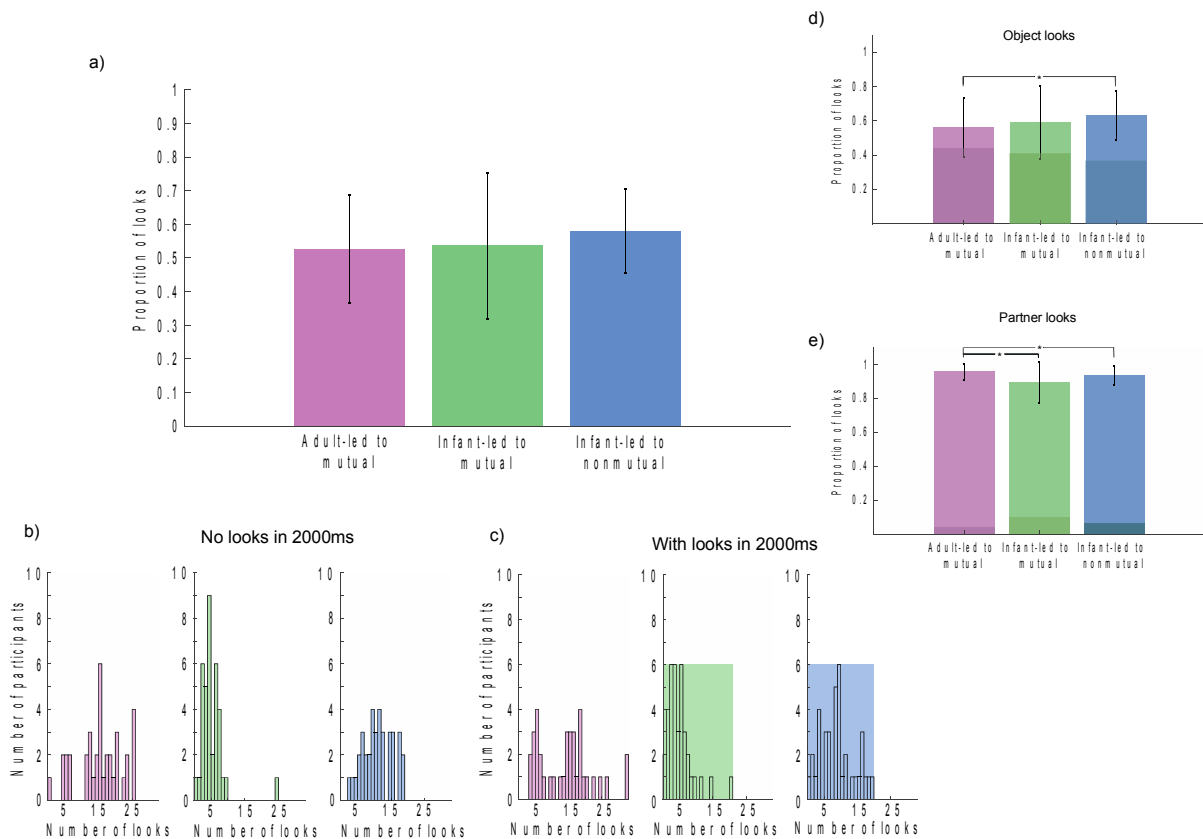


Fig. S2. a) Bar plots show the proportion of looks without an object or partner look in the **2000ms preceding look onset** for each type of attention episode (error bars show the standard deviation ($n=37$)). Paired t -tests indicated no differences between attention episodes in the number of looks with an object or partner look occurring in the 2000ms before look onset (all $p>0.05$). Histograms show the number of trials that participants contributed without (b) and with (c) object or partner looks. d) and e) show the breakdown of proportions without object and partner looks, respectively; shaded areas show average proportions with looks for each attention episode (error bars show the standard deviation ($n=37$)). Paired t -tests showed that adult-led attention episodes have significantly fewer partner looks in the 2000ms before look onset compared to infant-led looks to mutual attention ($p<0.05$), and non-mutual attention ($p<0.05$). Adult-led looks also have fewer object looks compared to infant-led looks to nonmutual attention ($p<0.05$). All other comparisons ($p>0.05$).

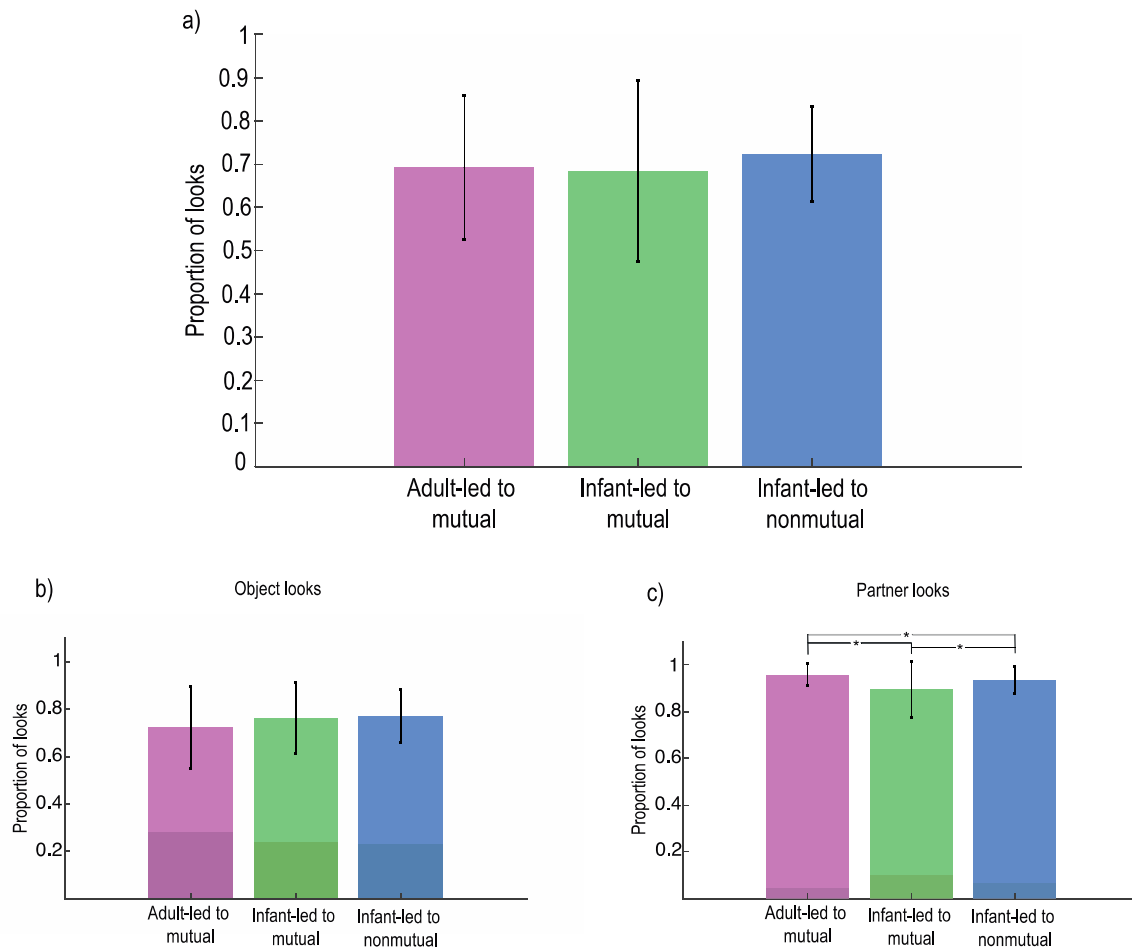


Fig. S3. a) Proportion of looks without an object or partner look in the **2000-1000ms preceding look onset** for each type of attention episode (error bars show the standard deviation($n=37$)). Paired t -tests indicated no differences between attention episodes (all $p>0.05$). b) and c) show the breakdown of proportions for object and partner looks, respectively, for each type of attention episode (error bars show the standard deviation($n=37$)). Paired t -tests indicated no differences between attention episodes in the proportion of looks with object looks; partner looks differed between all three attention episodes ($p<0.05$).

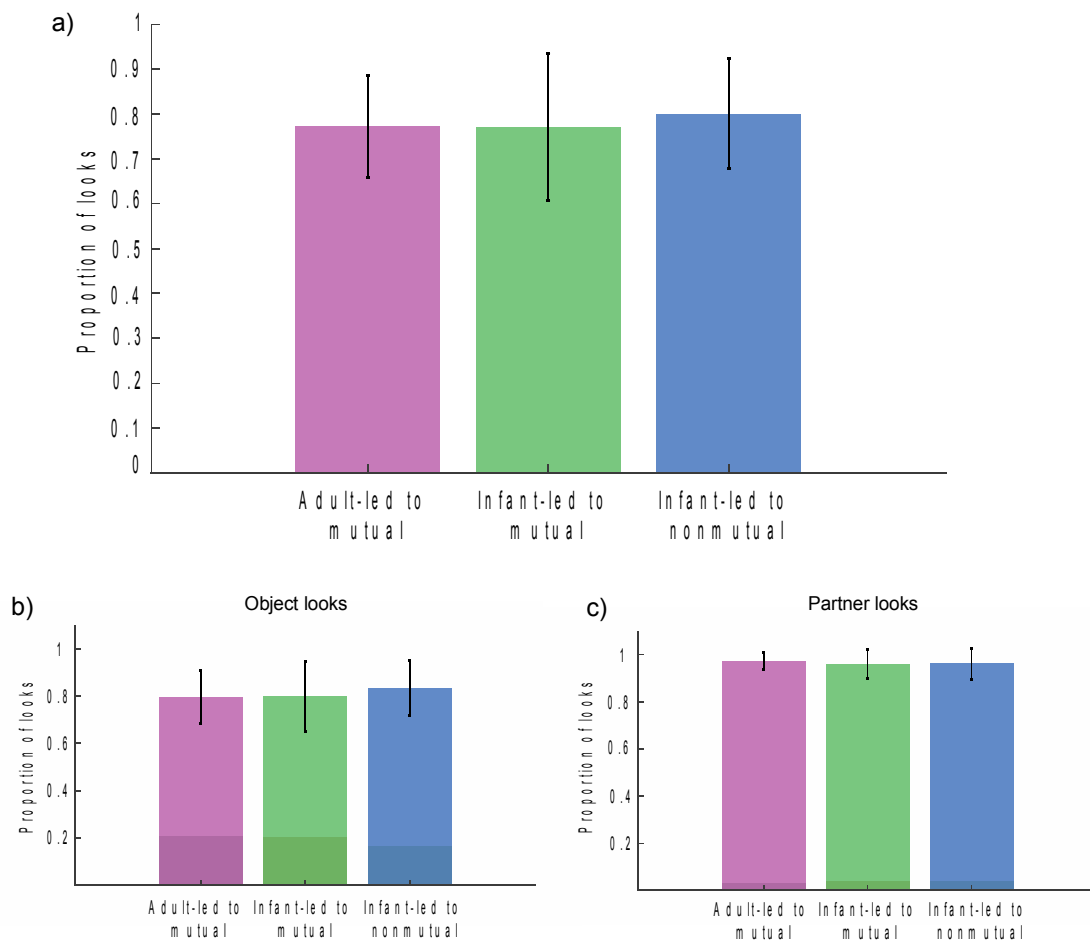


Fig. S4. a) Proportion of looks without an object or partner look in the 1000-0ms preceding look onset for each type of attention episode (error bars show the standard deviation($n=37$)). Paired t -tests indicated no differences in proportions between attention episodes (all $p>0.05$). b) and c) show the breakdown of proportions for object and partner looks, for each type of look (error bars show the standard deviation($n=37$)). Paired t -tests again indicated that there were no differences between attention episodes in the number of object or partner looks (all $p<0.05$).

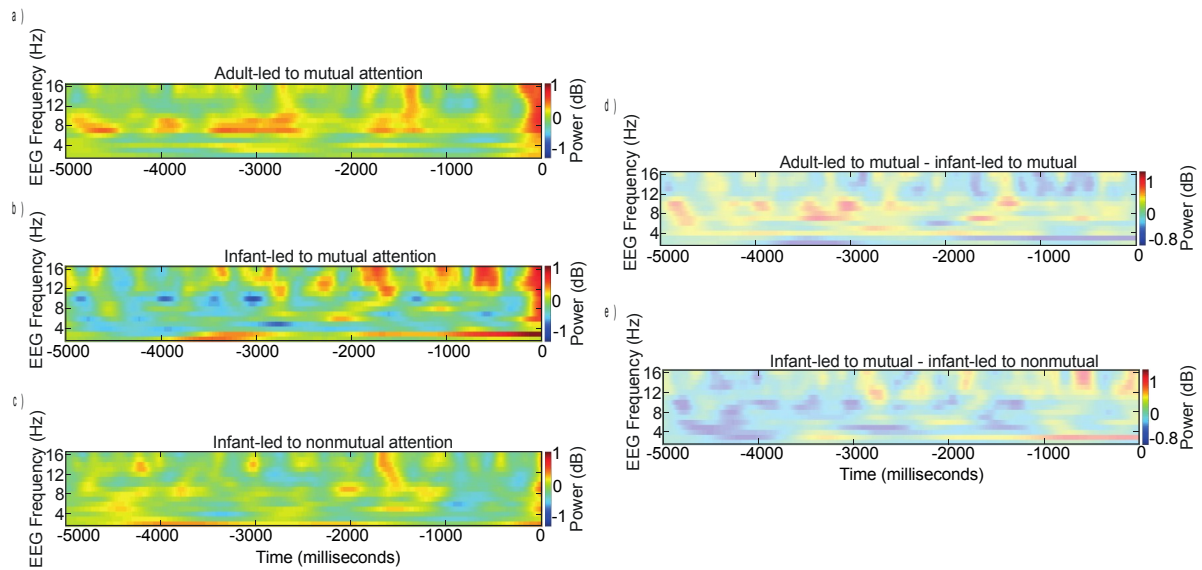


Fig. S5. Time-frequency plots show infant EEG activity (2-16Hz) occurring 5000ms before look onset, for (a) adult-led looks to mutual attention (b) infant-led looks to mutual attention and (c) infant-led looks to nonmutual attention, over fronto-central electrodes (AF3, AF4, FC1, FC2, F3, F4, Fz). d) Difference in EEG activity between infant- and adult-led looks to mutual attention (adult-led – infant-led). Cluster-based permutation analyses showed no significant clusters of time*frequency points of the difference between attention episodes. e) Difference in EEG activity between infant-led looks to mutual and nonmutual attention (infant-led to mutual - infant-led to nonmutual). Cluster-based permutation analyses showed no significant clusters of time*frequency points of the difference between attention episodes.

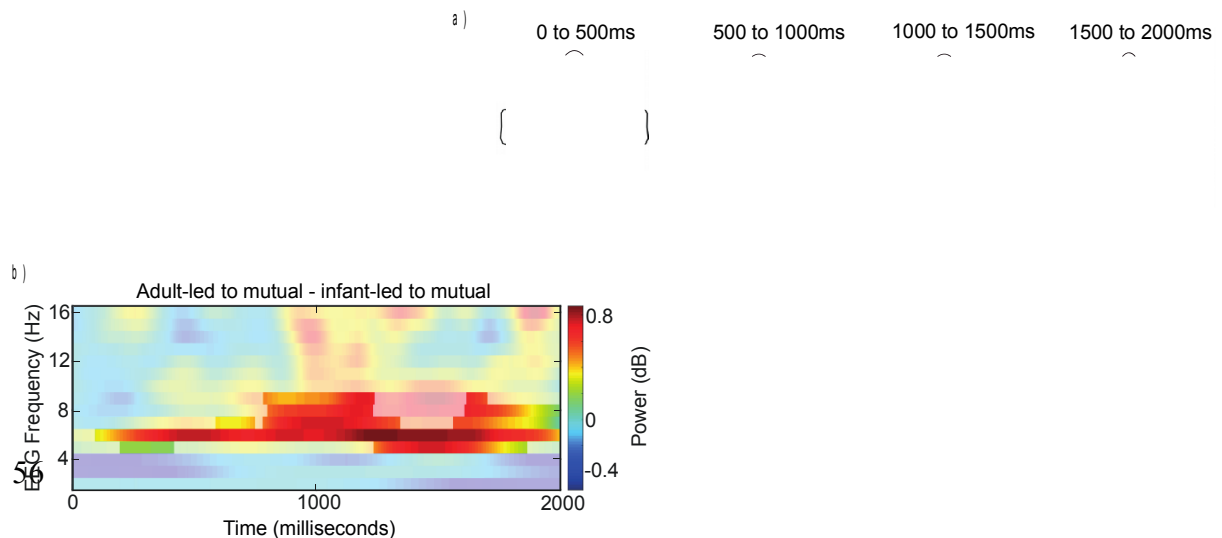


Fig. S6. a) Time-course of the trend-level time*frequency*electrode positive cluster identified by the 3-dimensional cluster-based permutation analysis, in time*electrode space, in 500ms time-windows; channels included in the cluster at each time-point are highlighted in black. b) Time-frequency plot shows the difference between looks in time*frequency space averaged over electrodes included in the cluster (adult-led mutual – infant-led mutual). Highlighted area shows time-course of the cluster ($p=0.099$).

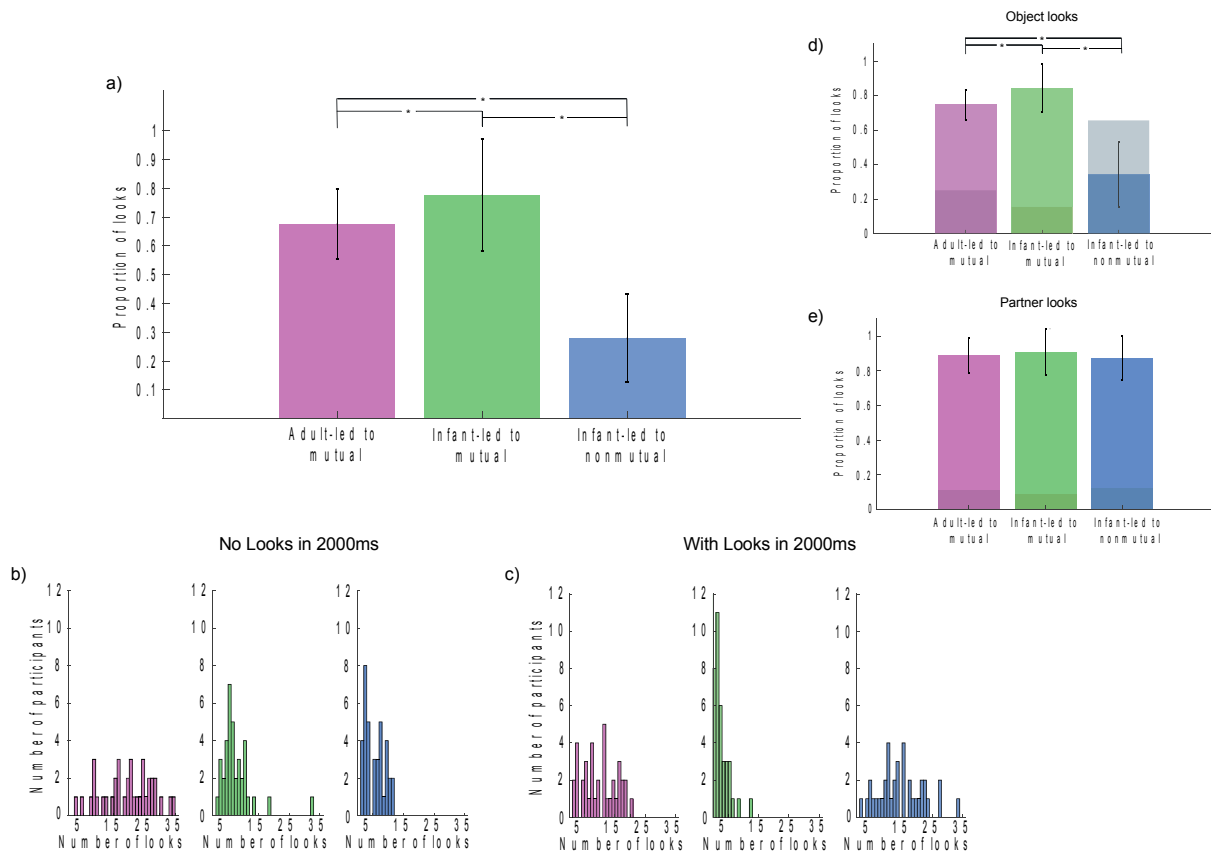


Fig. S7. a) Bar plots show the proportion of looks without an object or partner look in the **2000ms post look onset** for each type of attention episode (error bars show the standard deviation ($n=37$)). Paired t -tests indicated significant differences between all attention episodes in the proportion of looks with object and partner looks combined occurring in the 2000ms after look onset (all $p<0.05$). Histograms show the number of trials that participants contributed without (b) and with (c) object or partner looks. d) and e) show the breakdown of proportions without object and partner looks, respectively; shaded areas show average proportions with looks for each attention episode (error bars show the standard deviation ($n=37$)). Paired t -tests showed that infant-led looks to nonmutual attention had significantly more looks with object looks in the 2000ms post look onset compared to adult-led looks and infant-led looks to mutual attention ($p<0.05$). Comparisons also showed that infant-led looks to mutual attention involved significantly fewer object looks, compared to adult-led looks ($p<0.05$). No differences in the number of partner looks were observed (all $p>0.05$).

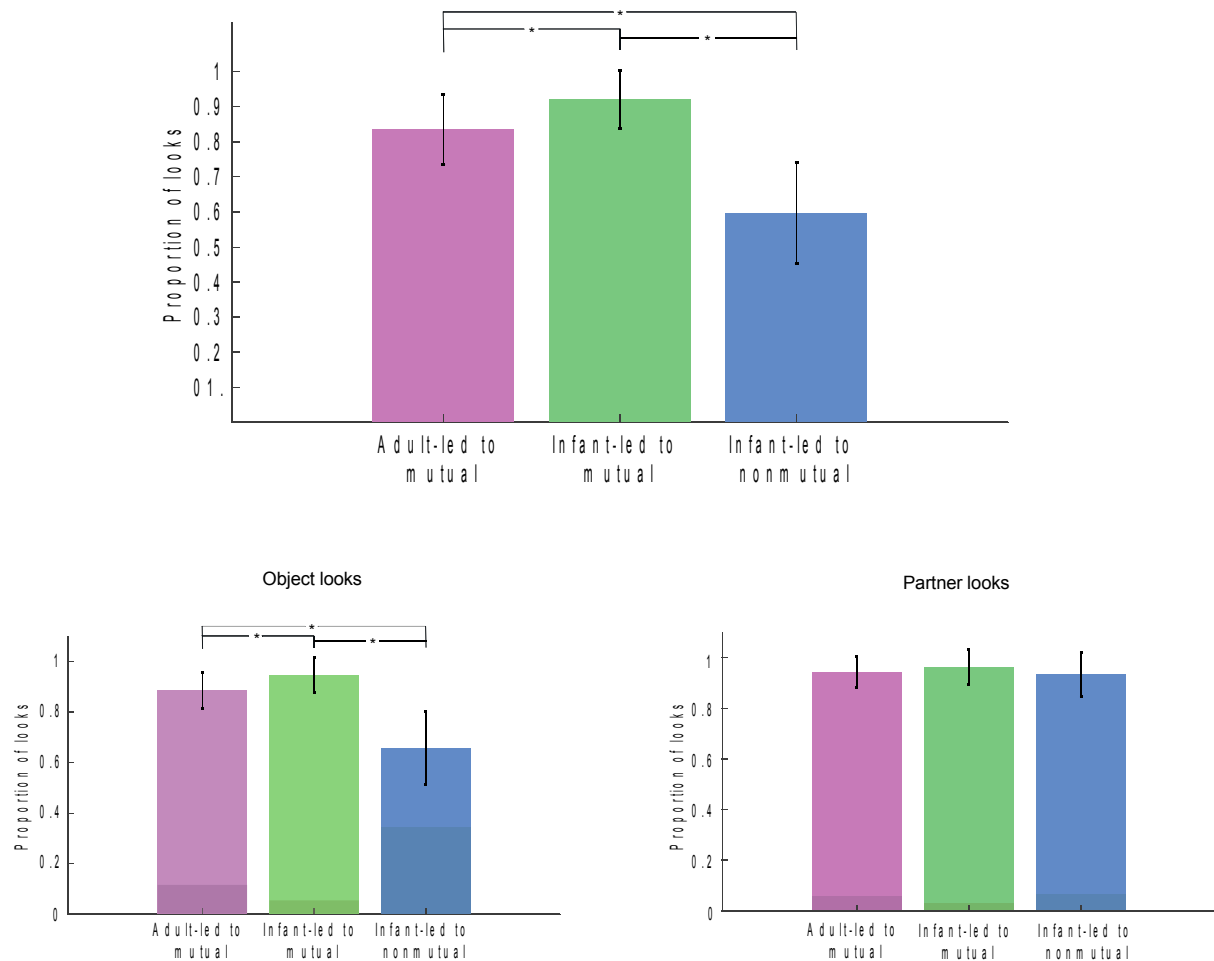


Fig. S8. Proportion of looks without an object or partner look in the **0-1000ms post look onset** for each attention episode (error bars show the standard deviation ($n=37$)). Paired t-tests indicated significant differences between all attention episodes in the proportion of looks with object and partner looks combined occurring in the 1000ms after look onset (all $p<0.05$). b) and c) show the breakdown of proportions for object and partner looks for each attention episode. Paired t-tests showed that all looks have significantly different proportions of looks with object looks in the time-period 1000ms after look onset (all $p<0.05$). There were no differences in the proportion of looks involving partner looks (all $p>0.05$).

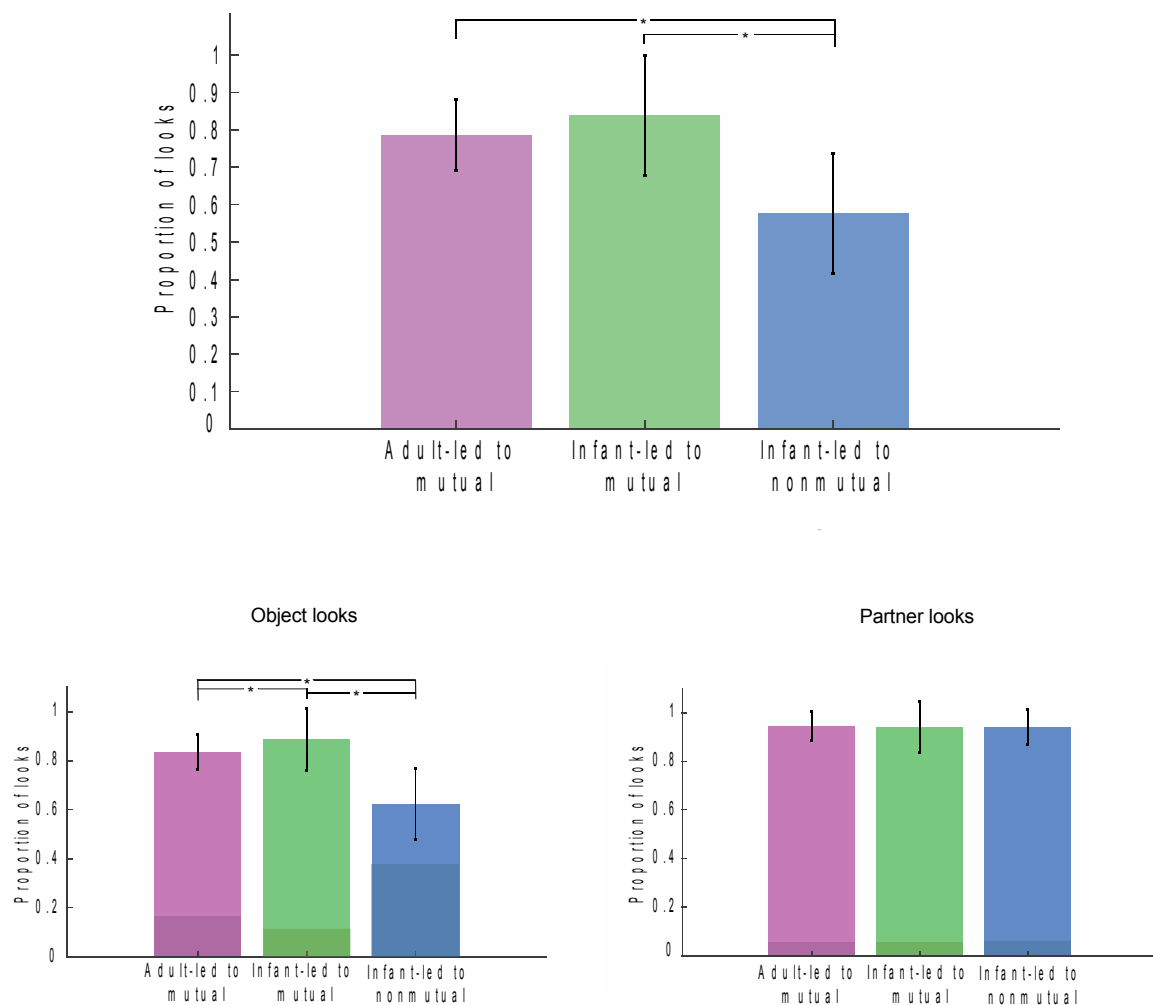
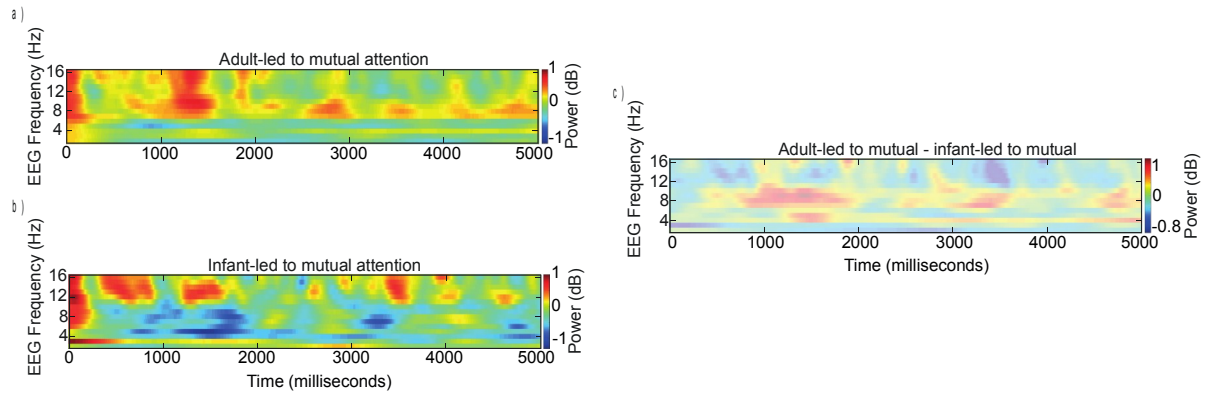


Fig. S9. Proportion of looks without an object or partner look in the **1000-2000ms post look onset** for each attention episode. Paired *t*-tests showed that infant-led looks to nonmutual attention included significantly more looks with object and partner looks compared to infant-led looks to mutual attention, and adult-led looks ($p < 0.05$). b) and c) show the breakdown of proportions for object and partner looks for each type of look. All looks have significantly different proportions of looks including object looks in the time-period 1000-2000ms after look onset (all $p < 0.05$). There were no differences in the proportion of partner looks, $p > 0.05$).



*Fig.S10. Time-frequency plots show infant EEG activity (2-16Hz) occurring 5000ms after look onset, for (a) adult-led looks to mutual attention and (b) infant-led looks to mutual attention, over fronto-central electrodes (AF3, AF4, FC1, FC2, F3, F4, Fz). d) Difference in EEG activity between infant- and adult-led looks to mutual attention (adult-led – infant-led). Cluster-based permutation analyses showed no significant clusters of time*frequency points of the difference between attention episodes.*

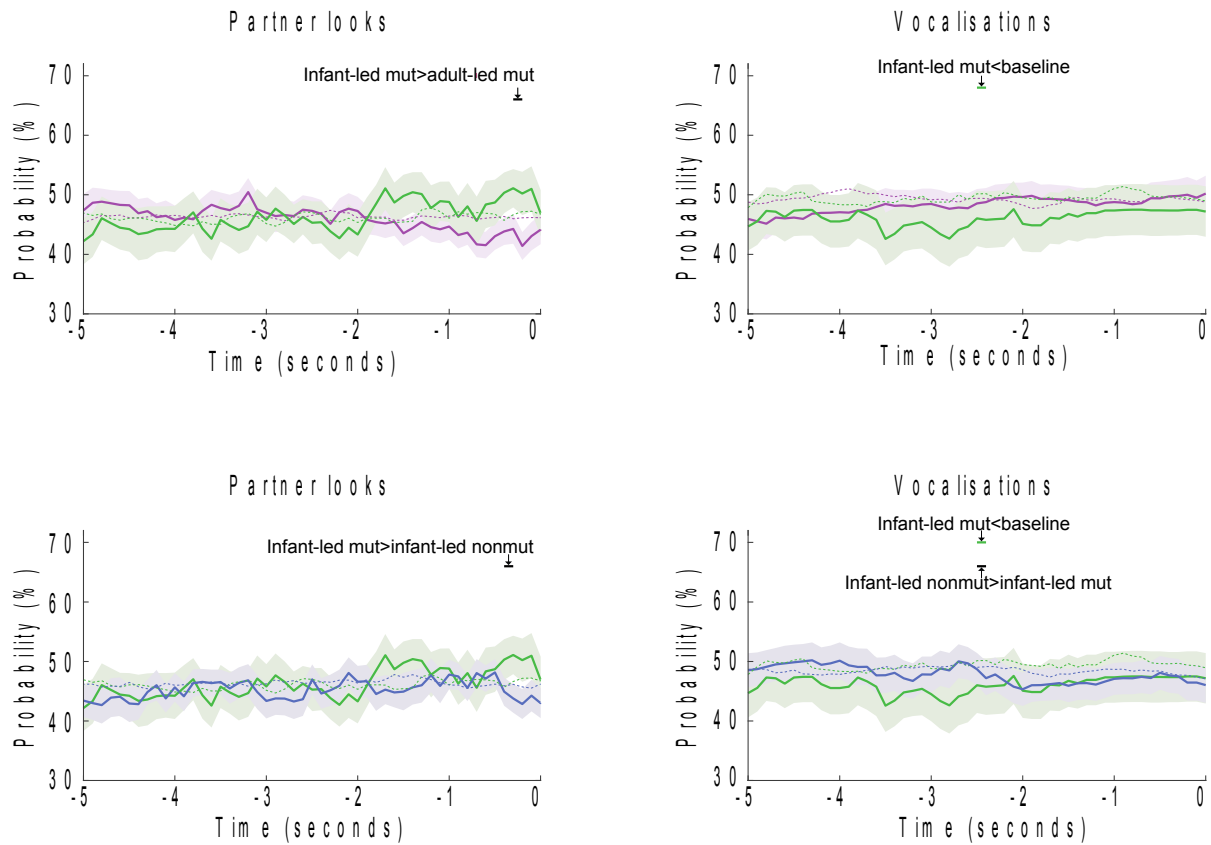


Fig. S11. Probability of caregiver ostensive signals (partner looks and vocalisations) occurring in the time-period before attention episodes. a) Partner looks after infant-led mutual attention vs adult-led mutual attention; b) Vocalisations after infant-led mutual attention vs adult-led mutual attention. c) Partner looks after infant-led mutual attention vs infant-led nonmutual attention. d) Vocalisations after infant-led mutual attention vs infant-led nonmutual attention. In each case shaded areas show the SEM and horizontal black lines show the areas of significant difference, between attention episodes, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). Dotted lines show the baseline time-series, plotted for each attention episode. Horizontal coloured lines show the areas of significant difference between each look type and baseline, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05).

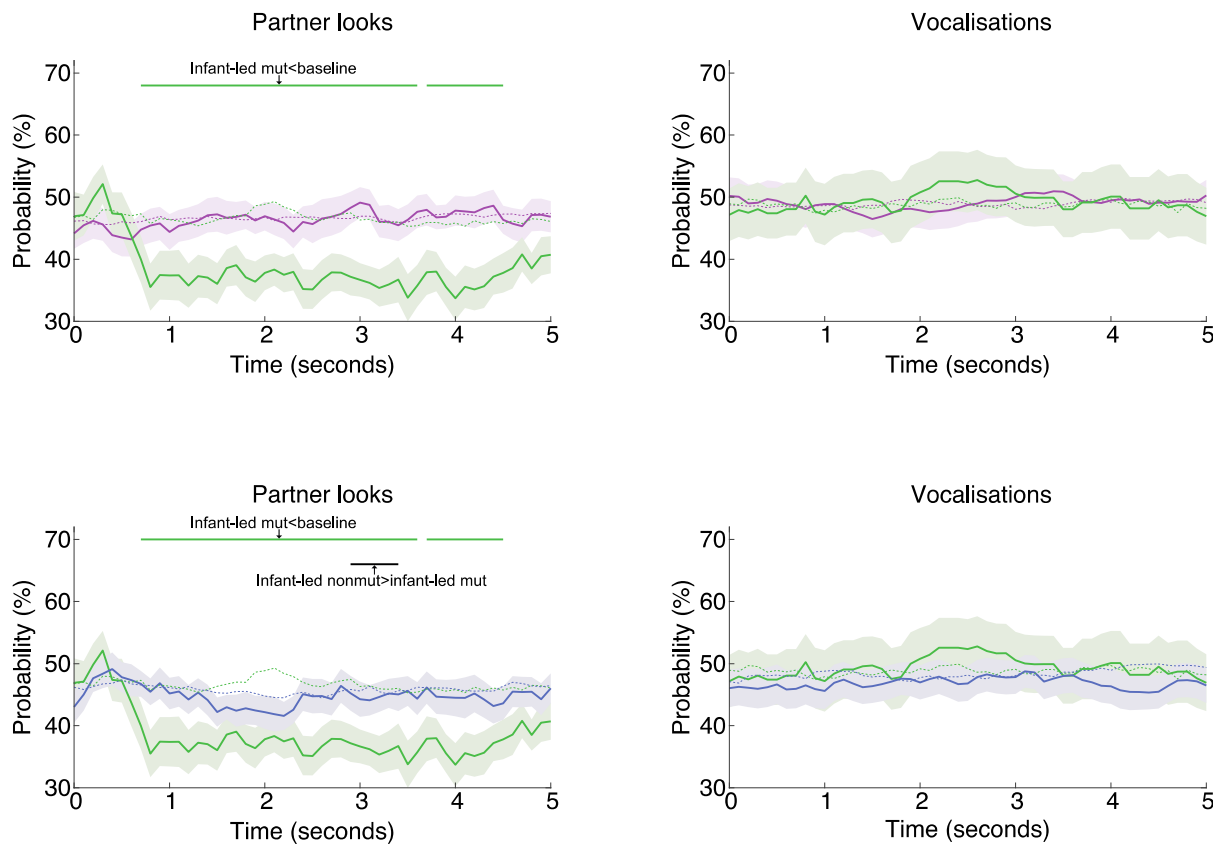


Fig. S12. Probability of caregiver ostensive cues (partner looks and vocalisations) occurring in the time-period after attention episodes. a) partner looks after infant-led mutual attention vs adult-led mutual attention; b) vocalisations after infant-led mutual attention vs adult-led mutual attention. c) partner looks after infant-led mutual attention vs infant-led nonmutual attention. d) vocalisations after infant-led mutual attention vs infant-led nonmutual attention. In each case shaded areas show the SEM and horizontal black lines show the areas of significant difference, between attention episodes, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05). Dotted lines show the baseline time-series, plotted for each attention episode. Horizontal coloured lines show the areas of significant difference between each look type and baseline, identified by the cluster-based permutation analysis (Monte-Carlo p value < 0.05).