Leader-follower dynamics during early social interactions matter for infant word learning

Abstract – 150 words.

We know little about the extent to which infants' interests shape their own language acquisition. We hypothesized that infants' decisions to visually explore a specific object signal focal increases in attention, and that when caregivers respond to these manifestations of interest by naming the object this boosts word learning. To examine this, we invited caregivers and their 14-month-old infants to play with novel objects, before testing infants' retention of the novel object-label mappings, while their electroencephalogram was recorded. Results show that infants' proactive looks towards an object during play signal enhanced interest, as evidenced through greater neural signatures of endogenous attention. Furthermore, when caregivers named objects during these episodes, infants showed greater word learning, but only when caregivers also joined their focus of attention. Our findings demonstrate the feasibility of studying word learning in realistic, interactive settings, and support the idea that infants' interests guide their acquisition of a lexicon.

Introduction.

Early language learning is a social enterprise: to learn the particular set of sounds, words and syntactic rules that make up their native language, learners depend on information that can only be communicated to them by expert speakers. Yet, this does not mean that learners are passively waiting for information: they can also actively prompt their social partners to adjust their speech as a function of what they do. This bi-directional or dialogic nature of language learning is widely recognized[1,2]. Despite this, most research on language acquisition has focused on how infants perceive, memorize and interpret the information directed to them by expert speakers that are *not interacting with them* [1,3–5] (e.g., infants are listening to pre-recorded speech, or to live experimenters who do not contingently adapt their behaviour to them). As a consequence, we still know little about whether and how infants supply information to speakers to guide their own learning, how caregiver-infant dyads organize their early proto-conversation on the fly to support linguistic transmission, and how this might be supported at the neural level.

Behavioural research suggests that contingent naming situations, in which caregivers label objects or events in response to infants' behaviours, constitute key word learning opportunities[2,6,7]. Contingent naming has (at least) two very interesting properties that could be important to support word learning. First, contingent naming has the potential to drastically reduce the problem of referential uncertainty for infants. One of the key problems that language learners face when they hear a novel word is to identify which object or event this novel word refers to when several potential referents are currently available[8]. This referential uncertainty is strongly reduced when caregivers provide the label of the object their infant is already focusing on, as there is only one potential referent in infants' restricted attentional focus when they hear the object's label[9]. A second interesting but understudied property of contingent naming is that infants' proactive engagement with a specific object constitutes a potential manifestation of interest. That is, it could signal episodes during which infants are maximally attentive and focused, and therefore ready to learn[10,11]. We know that greater endogenous attention during exploration (i.e., interest) leads to better memory encoding, and this association between interest and learning can already be observed during infancy[11,12]. Thus, if caregivers are sensitive to infants' manifestations of interest and label objects during these specific episodes, they might, in effect, be presenting relevant information at times of enhanced attentional engagement that are optimal for memory encoding. Notably, these two mechanisms are not mutually exclusive, and they could both function in parallel and reinforce one another.

A rich body of lab-based and correlational studies suggests that speakers' contingent naming is associated with infants' better word learning, yet, they focused mostly on the first possibility mentioned above. First, lab-based studies have shown that infants learn the name of a novel object better when naming occurs after they looked[13], pointed[14] or babbled[10] towards it. Yet, these studies involve scripted paradigms where experimenters purposedly and systematically name objects contingent on infants' behaviours. This limits their generalizability, and leaves open the question of whether caregiver-infant dyads tend to spontaneously follow this type of leader-follower organization. Second, correlational research involving observations of spontaneous caregiver-infant interactions has shown that the degree to which caregivers' speech is contingent on their infant's behaviour during play predicts vocabulary size a few months later[15,16], beyond other measures such as the total amount of language input received by the child[16]. However, this does not show that when caregivers name specific objects contingently on their infants' interest this immediately improves word learning, and correlational evidence – by nature – cannot elucidate why social contingency positively impacts word learning.

In both lines of research, therefore, mechanistic insight has been limited. This is also because the relationship between contingent labelling and word learning has only been examined in behavioural studies, where infants' attentional engagement cannot be measured directly. Attention can vary covertly, so behaviours do not directly reflect variations in endogenous attention. Therefore, it remains unclear whether the link between contingent naming and learning is due to the fact that infants' proactive engagement with objects effectively signals greater endogenous attention, is merely caused by reduced referential uncertainty[9], or is due to both of these factors.

To examine this, here we combined a quasi-naturalistic learning situation between an infant and their caregiver with an experimental set-up that allowed us to link caregivers' contingent naming of an object during play to infants' learning of this specific object-word mapping. We invited 38 caregivers and their 14-month-old infants to play with familiar and novel objects, before testing infants' knowledge of the novel object-label mappings. Both infants' and caregivers' electroencephalograms were recorded, which allowed us to extract neural signatures of endogenous attention from both infants and caregivers' brains during the learning phase. During an initial play session, dyads briefly played with two objects (Fig. 1A). Based on parental reports, we selected objects that were either familiar (e.g., dog) or totally novel (e.g., seal) for the child. Following this play phase, infants' knowledge of the word-object mappings was immediately tested during a short test phase using a live adaptation of the looking-while-listening procedure[17]. This procedure was repeated up to 8 times. All procedures, sample sizes and analyses were preregistered.

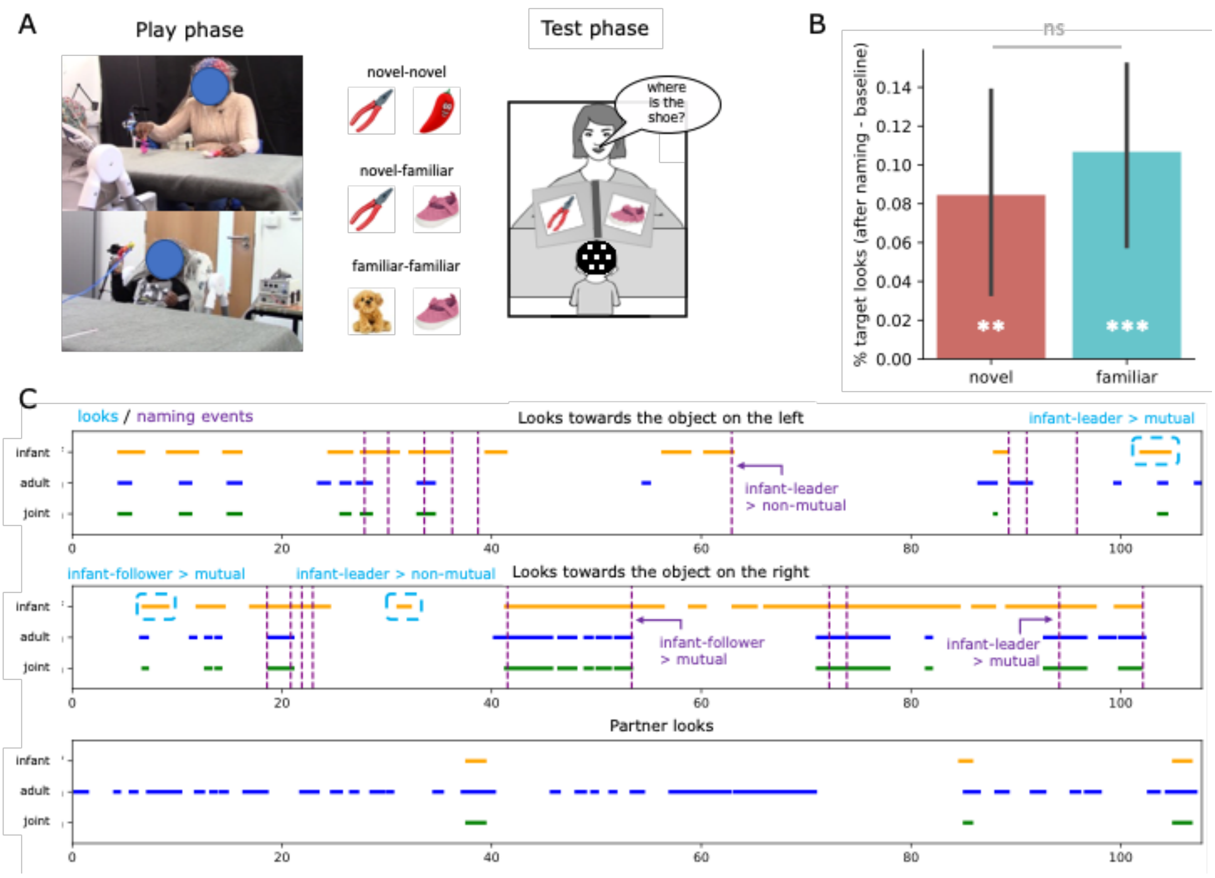

Figure 1. A) *Schematic description of the experimental set-up.* ***B)*** *Learning performance during the test phase for familiar and novel toys. Error bars show the 95% CI.* ***C)*** *Example data and depiction of the different types of looks (cyan) and naming events (purple). Adult and infants' looks are shown separately for looks towards the object placed on the left of the table (top), right of the table (middle), and looks towards the partner's face (bottom). Infants looks towards objects are shown in yellow, adult looks in blue and joint attention episodes in green. Periods where no looks are shown for a partner correspond to periods of inattention. Look types (infant-leader to non-mutual, infant-leader to mutual, infant-follower to mutual) derived from the raw data are shown in cyan (dashed boxes), and naming events types are shown in purple (dashed lines).*

This unique set-up allowed us to address three research questions. First, we hypothesized that caregivers should be sensitive to their infants' manifestations of interest towards objects, and name them more often following looks towards objects that were initiated by the infant (infant-leader looks) compared to looks that were initiated by the adult (infant-follower looks). We also hypothesized that the novelty of the objects should influence how and when caregivers named objects in response to infants' interests. To examine this, we compared the behaviour of caregivers and infants towards familiar objects with their behaviours towards novel objects during the play. Second, we predicted that infants should display better word learning when caregivers tended to name novel objects contingently after they proactively focused their visual attention upon it, regardless of the number of times they heard the novel label overall. Third, we asked whether infants learn better in these instances because proactive engagement with objects signals enhanced attentional engagement. We hypothesized that neural signatures of endogenous attention should increase when infants proactively look towards objects, as compared to when they passively follow their caregivers' attentional focus. Further, we hypothesized that this would result in increased neural signatures of endogenous attention in infants' brains when caregivers name objects around these manifestations of interest, which should in turn lead to greater word learning.

Results.

Infants learning of the novel objects' names. First, we checked that infants were able to learn novel words in this setting (Fig.1B). Infants' recognition performance was computed as the percentage of time spent looking towards the target object after hearing the target word minus the percentage of time spent looking towards the target object before hearing the target word[17]. Infants showed above-chance performance during the test phase for both novel ($M = 0.08$, $SD = 0.16$, $t(36) = 3.15$, $p = 0.003$, $d = 0.52$) and familiar ($M = 0.11$, $SD = 0.15$, $t(37) = 4.26$, $p < 0.001$, $d = 0.7$) objects, with no significant difference between conditions ($t(36) = 1$, $p > 0.3$, $d = 0.2$). This above-chance performance reflected imperfect recognition, with 2.97 (SD = 1.75) correct (greater % target looks after as compared to before naming onset) and 2.06 (SD = 1.07) incorrect (smaller % target looks after as compared to before naming onset, or no change) trials on average for each infant in the novel condition, and 3.52 (SD = 1.85) correct and 1.77 (SD = 1.02) incorrect trials on average in the familiar condition. This distribution provided us with the opportunity to investigate whether naming contingent on infants' interest during the play phase predicted their recognition of the novel target word during the test phase. In the following, the analyses concerning the play phase contrast novel and familiar toys to examine how infant-caregiver exchanges during play are affected by whether or not the word label was known by the infant beforehand. The analyses involving infants' recognition performances during the test phase are restricted to novel words because it is only for those cases in which a word label was not known beforehand that genuine learning can be measured.

Leader-follower dynamics of caregiver-infant play. To investigate how infants' learning of novel word-object mappings was predicted by their proactive engagement with objects and by caregivers' contingent naming, we focused on infants' gaze shifts towards objects. For each target object and dyad, we classified each of their looks and each naming event as a function of leader-follower dynamics (see Fig.1C and Methods). Infants were more likely to proactively initiate a look towards an object rather than following their caregiver's gaze ($M = 62\%$, $SD = 7.6$; $N = 133.18$ infant-leader looks, $SD = 40.8$, see Fig.2A). By contrast, adults tended to join their infant's focus of attention rather than initiating gaze towards objects proactively ($M = 41\%$, $SD = 8.7$; $N = 94$ adult-leader looks, $SD = 29.54$). Thus, infants proactively led looks towards objects more often than adults here ($t(37) = 9.95$, $p < 0.001$, $d = 2.6$; see Fig.S3 for a complementary analysis relying on Granger causality).

Next, we examine gaze shifts not only as a function of whether each agent led a look towards an object, but also as a function of their partner's reaction to this (see Fig.2B). We identified four types of looks (see Methods): looks led by the infant that resulted in a mutual attention episode (*infant-leader looks > mutual attention*), looks led by the adult that resulted in a mutual attention episode (*infant-follower looks > mutual attention*), and finally, looks led by the infant that did not result in a mutual attention episode because the caregiver either carried on looking towards the child (*infant-leader looks > partner*), or carried on looking elsewhere (*infant-leader looks > non-mutual attention*) for the duration of the infant's look. To examine how the four different types of looks were distributed for each actor, we ran hierarchical model comparisons contrasting nested linear mixed regression including the percentage of looks as a dependent variable, dyad as a random factor, and look type, actor (infant vs. adult) and their interaction as a fixed factor. This revealed a significant improvement of the model fit when the fixed effect of look type was included ($X2 = 187$, $p < 0.001$) as compared to the null model, and a further significant improvement of the model fit when the interaction term was added to the model ($X2 = 1403$, $p < 0.001$). The output of this best fitting model revealed that all cross-partner comparisons were highly significant ($p < 0.001$). All comparisons as a function of look types within each actor were also highly significant ($p < 0.001$), apart from the comparison between infant-follower > mutual and infant-leader > partner for infants looks ($p > 0.8$).

During most infant-leader looks towards objects, caregivers carried on looking towards their infant's face (infant-leader>partner condition: 38%, SD=10; N = 81.4, SD = 30.8). Instances in which the adult followed their infant's interest by joining them in looking towards the same object (infant-leader > mutual: 19%, SD=5; N = 40.8, SD = 14.6) were more common than instances in which they shifted their gaze towards another location instead (infant-leader > non-mutual: 5%, SD = 3; N = 10.9, SD = 5.9; beta = 14,5%, se = 1, t = 14.4, $p < 0.001$). By contrast, when the adult led a look towards an object, most of the time the infant did not follow their interest and chose to look somewhere else instead (adult-leader>non-mutual condition: 19%, SD=6; N = 44.7, SD = 16.4), while they followed their caregiver's gaze only 14% of the time (adult-leader> mutual condition: SD= 4; N = 30.9, SD = 9.8). The difference between these two configurations was highly significant (beta = 6%, se = 1, t = 6, $p < 0.001$), which means that infants did not tend to follow their caregivers' focus of attention here. Adults gaze-shifts were mostly reactive, with the adult following the infants' interest 59% (SD = 9) of the time (adult-follower>mutual condition: N = 126.8, SD = 46.2). Finally, the frequency with which infants looked towards their caregivers' face while they were looking towards an object was relatively low (adult-leader>partner: M = 8%, SD = 6; N = 18.6, SD = 12.8), highly significantly lower than for caregivers (infant-leader>partner: beta = 30,3%, se = 0,9, t = 32, $p < 0.001$), a pattern that has been reported in other studies examining free-flowing play interactions[9,18,19]. Infants were also slower to join their partner's focus of attention: infants took on average 1.3 (SD = 0.35) seconds to join an adult-led episode of mutual attention, while adults' latency to join an infant-led episode of mutual attention was 0.81 (SD = 0.24) seconds ($t(37) = 6.99$, $p < 0.001$). Thus, overall, the interactional pattern was extremely asymmetric here, reflecting a dyadic process where caregivers tend to follow their infants' focus of attention more than the other way around.

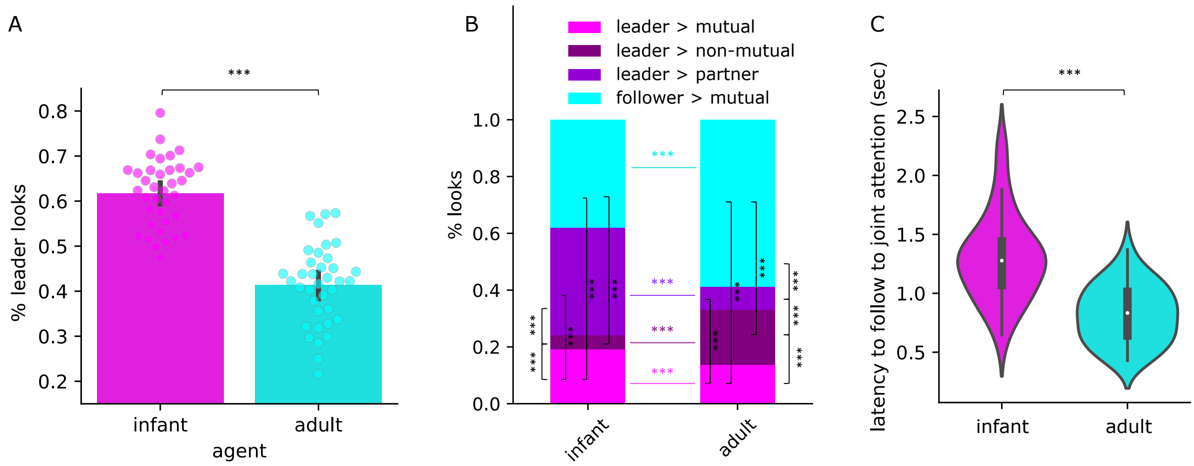

Figure 2. A) Percentage of object directed looks that were proactively initiated by each partner. *For each actor (infant or adult), dyad and target object, we computed the percentage of leader looks as the number of actor-led looks over the total number of looks towards that object for this actor during the trial. Error bars show the 95% CI.* ***B) Distribution of looks as a function of look type and partner.*** *Splitting down leader and follower looks as a function of what the partner was doing during the actor's look led to four configurations for look types: 1) actor-led look towards the object that led to a matching look by the partner (i.e., mutual attention); 2) actor-led look towards the object that did not lead to a matching look by the partner (i.e., non-mutual attention); 3) actor-led look towards the object where the partner kept on looking towards the actor's face; 4) other-led - or follower - look towards the object leading to mutual attention.* ***C) Latency to join the partner's attentional focus*** *shown separately for infants (magenta) and adults (cyan) in seconds. Violin plots show the distribution of the data, box plots the quartiles, black bars the interquartile range, and white dots the medians.*

Infants' proactive looks signal increased endogenous attention during play. Next, we wanted to examine our main hypothesis, which was that infants' proactive gaze shifts towards objects might signal greater attentional engagement. Attention cannot be inferred from behaviour alone, because it can also be deployed covertly, and fluctuates regardless of overt behaviours (e.g., attention blanking or mind wandering). To measure infants' attentional engagement more directly, we therefore turned to brain data. We examined infants' brain activity around infant-leader and infant-follower gaze shifts in the time and frequency domains. In the time domain, we focused on the P400 and Nc components, that have both been associated with greater endogenous attention during infancy in a variety of tasks[20–22]. Using infants' brain activity, we computed event-related-potentials (ERPs) around gaze shifts (-500 to +1500ms) separately for infant-leader and infant-follower looks towards objects during the play phase (collapsed over both types of objects, see S8 for a break-down as a function of novelty). The resulting ERPs were averaged in a fronto-central and an occipital-temporal cluster of electrodes to estimate the amplitudes of the Nc and P400 components respectively. The resulting ERPs presented a typical profile for visually evoked potentials[20,23], including a P1/N290/P400 complex in the occipito-temporal cluster, and a Nc component in the frontocentral cluster of electrodes (see Fig.3A). Using a ROI approach[20,23], we averaged the amplitude of the P400 and Nc components around each peak, separately for infant-leader and infant-follower looks. This revealed a greater amplitude of the infant Nc and P400 components for infant-leader looks (Nc: M = -2.98 µV, SD = 1.78; P400: M = 8.2 µV, SD = 4.67) as compared to infant-follower looks (Nc: M = -2.25 µV, SD = 2.21; P400: M = 5.87 µV, SD = 5.33). A hierarchical model comparisons comparing nested linear mixed regression revealed a significant improvement of the model fit when the effect of leadership was included as compared to the null model for both components (P400: X2 = 7.17, p = 0.007; Nc: X2 = 4.42, p = 0.03). This reflected the fact that for infant-leader looks the amplitude of the P400 was significantly more positive (beta = 1.6, se = 0.61, t = 2.6, p = 0.009), and the amplitude of the Nc more negative (beta = -0.72, se = 0.34, t = 2.11, p = 0.035) than for infant-follower looks. Notably, we found no significant difference between look types for the P1 component (infant-leader looks: M = -2.16 µV, SD = 5.6; infant-follower looks: M = -2.07 µV, SD = 4.62; X2 = 0.01, p = 0.9, beta = -0.08, se = 0.68, t = 0.12), which is consistent with the idea that this effect is related to greater endogenous engagement for infant-leader looks rather than to other (lower-level) factors.

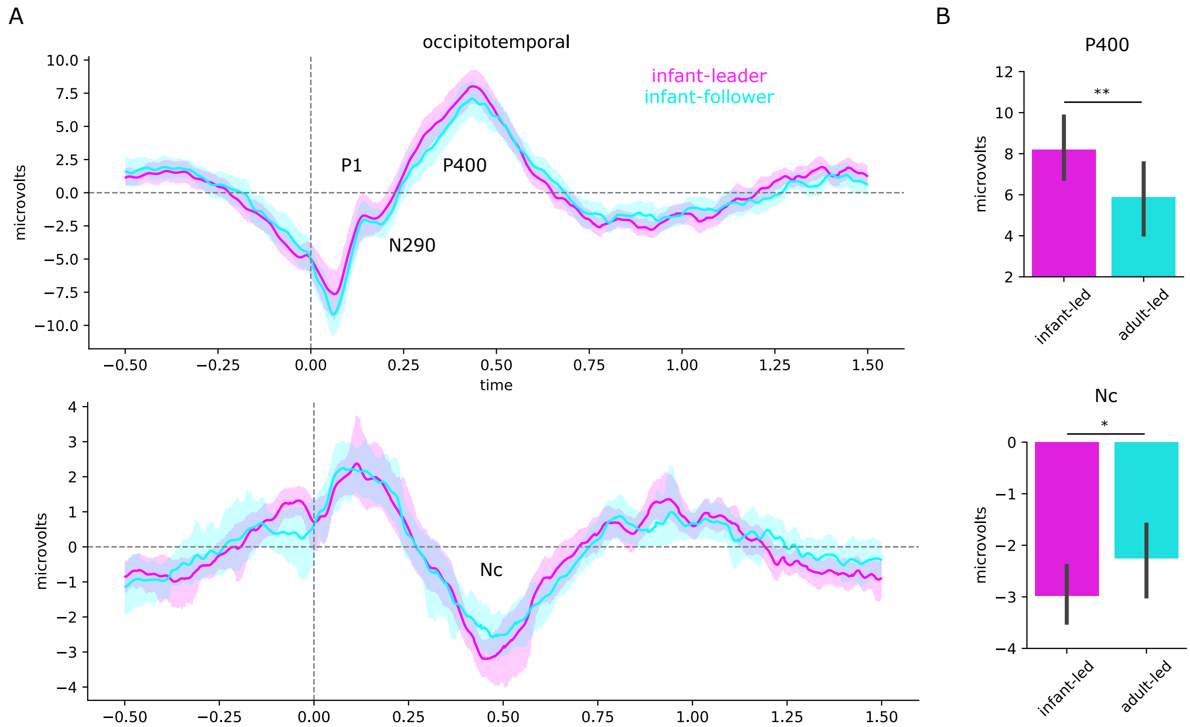

__Figure 3. A)__ ERPs computed around gaze-shifts towards objects for infant-leader (pink) and infant-follower (cyan) looks in an occipito-temporal (top) and fronto-central (bottom) cluster of electrodes. Shaded areas show the 95% CI. The vertical dashed line shows look onsets. __B)__ Amplitude of the P400 and Nc components averaged in a 100ms windows around each of the components of interest's peaks. Error bars show the 95% CI.

Next, we examined brain activity around gaze shifts in the frequency domain, because previous research has shown that oscillatory activity also reflects variations in endogenous attention. More specifically, increased endogenous attention has been associated with greater theta power over fronto-central electrodes when infants passively view stimuli on a computer screen[24] or actively explore objects during play[12,25]. Building on this literature, we examined whether infants' proactive looks towards objects during play associate with greater neural signatures of endogenous attention. To do so, we ran time-frequency decompositions using continuous Morlet wavelet convolution for frequencies between 1 and 16Hz in a -1000 to +1500ms window around look onset, separately for infant-leader and infant-follower looks. Similar to previous studies[12,25], data were averaged in a fronto-central cluster of electrodes. A 2-D (frequency * time) cluster-based-permutation analysis comparing both conditions revealed a significant cluster ranging from 541ms before look onset until 730ms following look onsets in frequencies between 1 to 13Hz (Fig. 4A). Averaging power in this cluster showed a highly significant difference between the two conditions ($t(37) = 3.77$, $p < 0.001$, $d = 1.03$, Fig. 4B), with stronger power around infant-leader ($M = 0.29$ dB, $SD = 0.52$) as compared to infant-follower ($M = -0.22$ dB, $SD = 0.49$) looks. Notably, there was a highly significant negative correlation between power in this cluster and the amplitude of the Nc component (spearman's rho = -0.09, $p < 0.001$), and symmetrically, a positive relationship with the amplitude of the P400 (spearman's rho = 0.06, $p < 0.001$), supporting the idea that these three neural measures reflect the same underlying construct of increased endogenous attention. Because previous research has suggested that theta power over frontocentral electrodes especially reflects increased endogenous attention during infancy[12], we also conducted a supplementary analysis using restricted frequency bands. Power around gaze shifts was averaged in the theta band (3-6Hz) separately for infant-leader and infant-follower looks in the time window identified by the cluster-based analysis. We found stronger theta power around infant-leader ($M = 0.19$ dB, $SD = 0.58$) as compared to infant-follower ($M = -0.32$ dB, $SD = 0.72$) looks, with a significant difference between the two conditions ($t(37) = 3.24$, $p = 0.002$, $d = 0.79$, Fig. 4C). There was also stronger power around infant-leader ($M = 0.22$ dB, $SD = 0.61$) as compared to infant-follower ($M = -0.28$ dB, $SD = 0.51$) looks in the alpha band ($t(37) = 3.27$, $p = 0.002$, $d = 0.91$).

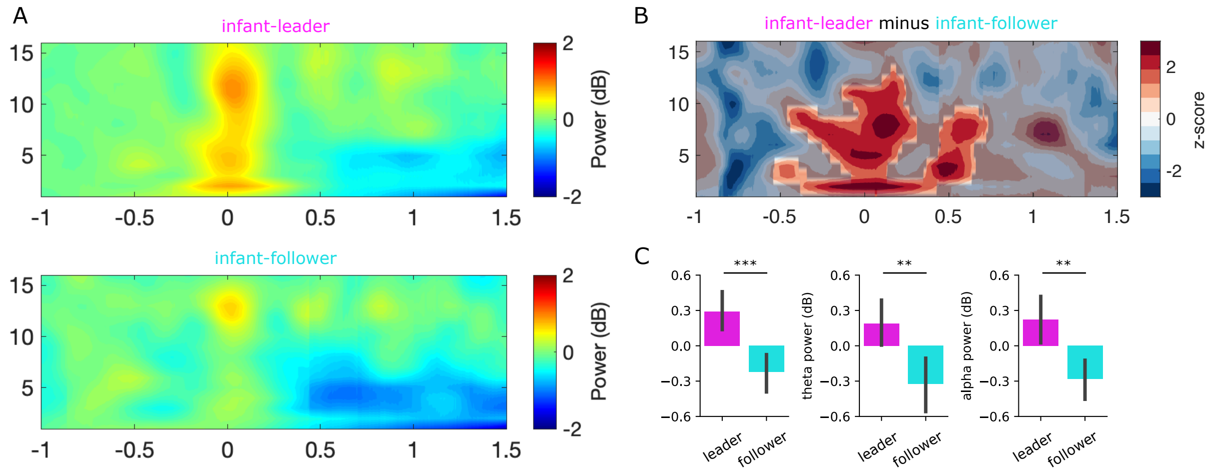

Figure 4. A) *Time-frequency plots show infant EEG activity (1-16Hz) occurring between 500ms before look onset and 1500ms after look onset, separately for infant-leader looks (top) and infant-follower looks (bottom).* ***B)*** *Difference plot showing power computed around infant-leader looks minus power around infant-follower looks. The superimposed area shows the significant 2D cluster identified by the permutation analysis.* ***C)*** *Power was averaged within the time-frequency cluster (left), or within the time window of the cluster separately for the theta band (middle) and alpha band (right). Error bars show the 95% CI.*

In sum, we found evidence for enhanced neural signatures of endogenous attention around proactive looks in the infant brain in both the time and frequency domains. This is compatible with our hypothesis that infants' proactive looks towards objects can be meaningful cues for caregivers, as they reflect a greater attentional focus. An additional indication that infant-leader looks reflect greater interest can be found in the fact that infants were also more likely to gesture towards toys when initiating a look towards it (mean % of gestures around infant-leader looks: 41.8, $SD = 10.5$; infant-follower looks: 34.4, $SD = 11.4$, $t(37) = 5.22$, $p < 0.001$, $d = 0.72$). Importantly, this cannot explain the EEG findings: as can be seen on Fig.S4, neural activity (ERP amplitudes and EEG power) was not greater around looks that were accompanied with gestures as compared to looks not accompanied with gestures. Overall, our data are thus consistent with the idea that proactive looks by infants signal increased interest during play, and that, as such, they constitute relevant cues for informants.

Notably, similar analysis with adult data suggested that, unlike infants, caregivers did not seem to engage their attention differentially as a function of whether they, or their infant, initiated a look: there were no differences between ERPs amplitudes and power averaged separately around adult-leader and adult-follower adult looks (see Fig.S2). This is a null result that requires cautious interpretation, but it might suggest that caregivers are equally attentive when they themselves lead the interaction and when they follow their child's interest.

Do caregivers often name novel objects contingently as a function of infants' interests during play?
We now turn to our next series of hypothesis, which concerned caregivers' ability to pick up on those cues of interest, and name objects for their child during proactive looks. We found mixed evidence regarding our hypothesis that caregivers should often respond to their infants' manifestations of interest for a novel object by naming it for them. First, we examined how caregivers named objects as a function of where their infant was looking (at the named object: match, at the other object: mismatch, at them: partner, or away; Fig.5A). Caregivers were most likely to name an object when their infant was looking towards it (M = 56.28%, SD = 12.33), as compared to naming the other object (M = 13.99%, SD = 8.1), naming an object while their infant was looking away (i.e., neither at the partner nor one of the objects, M = 15.04%, SD = 8.06), or while their infant was looking towards them (M = 14.68%, SD = 9.06). This was true for both conditions (novel vs. familiar objects), with naming events occurring more often when infants were looking at the corresponding object (match) than in all the other cases (all p-values < 0.001, other comparisons between look types were non-significant, all p-values > 0.13). Still, hierarchical linear mixed model comparisons revealed an interaction between look types and condition (X2 = 10.86, $p = 0.03$) which was due to the fact that, when infants where looking towards an object, caregivers named this object more often if this object was novel than when it was familiar (beta = 0.6, se = 0.18, t = 3.26, $p < 0.002$), while they were marginally more likely to name familiar objects than novel objects when infants were looking towards their face (beta = 0.03, se = 0.019, t = 1.74, $p = 0.08$; other comparisons were not significant). This reveals functional distinctions between speech directed towards familiar and novel toys during play (also see[6]), and it is partially consistent with our hypothesis that caregivers tend to name novel objects for their infants when they are showing interest for it. In Fig.S1 we present complementary analyses showing when exactly caregivers name objects as a function of infants' gaze shifts towards a novel or a familiar object (similar to a response time analysis). These analyses show that, overall, naming events are mostly reactive (caregivers tend to label objects after infants' gaze shifts), for both novel and familiar toys. Yet, naming events are timelier for familiar toys as compared to novel toys overall (they occur closer in time to infants' gaze shifts towards familiar toys on average, see Fig.S1).

Our more specific hypothesis however was that caregivers should tend to name novel objects for their child when they proactively show interest for it, so, next we examined whether caregivers were more likely to name an object that the infant was currently looking at versus not looking at (match or mismatch), as a function of who initiated this look (the infant or the adult), and object type (novel or familiar). Across both conditions and look types (match/mismatch), caregivers were more likely to name objects following infant-leader looks (M = 38.32%, SD = 11) as compared to infant-follower looks (M = 28.9%, SD = 9.5, $t(37) = 3.57$, $p = 0.001$, $d = 0.94$, see Fig.5B). However, hierarchical model comparisons contrasting nested linear mixed regressions including dyad as a random factor, object type (novel or familiar), leadership (infant or adult), and look types (match or mismatch) as fixed factor, as well as the interaction terms between these three factors, revealed that the best fitting model was the model including the triple interaction (X2 = 10.45, $p = 0.001$). Caregivers were more likely to name the target object (match) than the other object (mismatch) for infant-leader and infant-follower looks in both familiar and novel (Fig.5C, all p-values > 0.001) conditions, but they were only more likely to name the target object (match) after an infant-leader look as compared to an infant-follower look for familiar toys (beta = 0.08, se = 0.02, t = 4.2, $p < 0.001$), and not for novel toys (beta = -0.03, se = 0.02, t = 1.37, $p = 0.17$); caregivers were therefore more likely to name the target object following an infant-follower look for novel objects than for familiar objects (beta = -0.08, se = 0.02, t = 3.93, $p < 0.001$). This is the opposite of what we would predict if caregivers were inclined to provide labels when their infant displays interest towards novel objects specifically, but it is what we might predict if caregivers were actively trying to teach their child labels by redirecting their attention towards novel objects. In addition, in both conditions, adults gave the label of the other object (mismatch) more often after an infant-leader look than after an infant-follower look (novel: beta = 0.07, se = 0.02, t = 3.58, $p < 0.001$; familiar: beta = 0.05, se = 0.02, t = 2.73, p = 0.006). This means that, for infants, the information received after a proactive look is more ambiguous than the information received after a reactive look. A complementary analysis based on response times presented in Fig.S1 also shows that naming events occurred later after look onset for looks initiated by the infant as compared to follower looks.

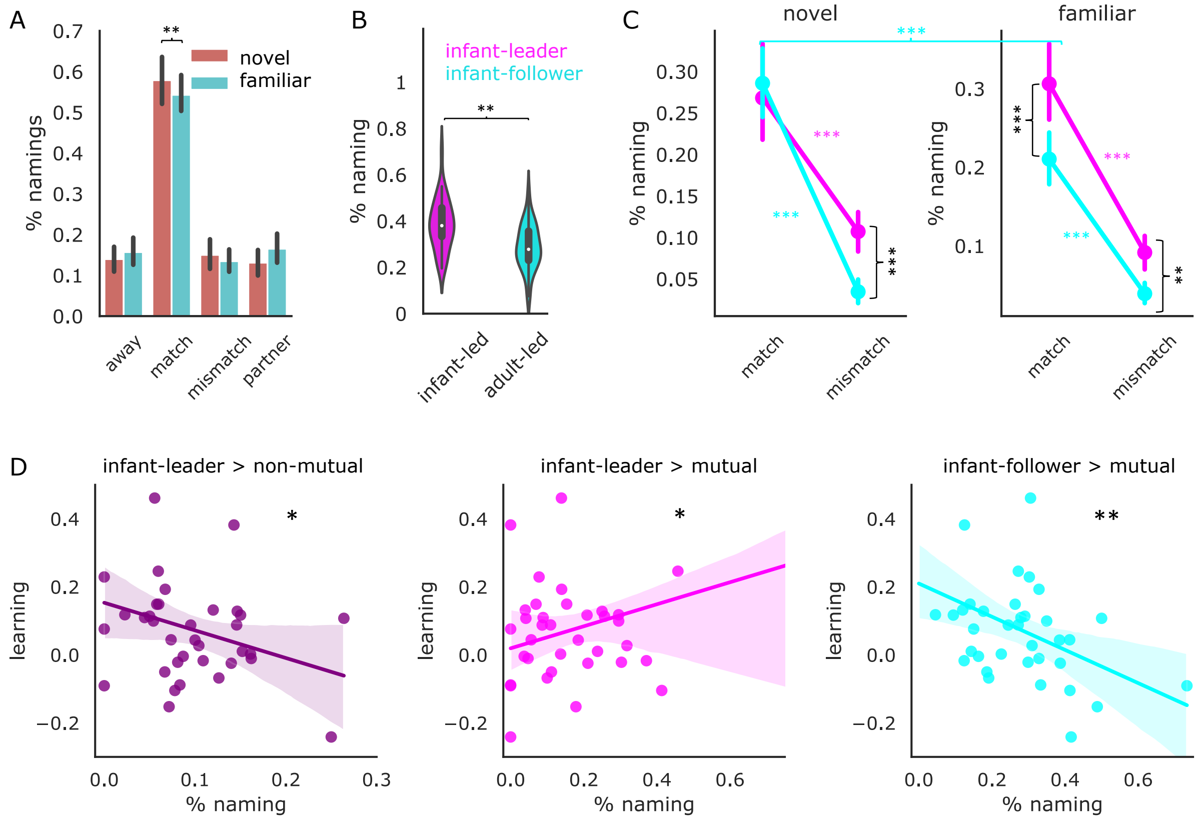

Figure 5. A) *Percentage of naming events that occurred while infants were looking away, towards the target object (match), towards the other object (mismatch), or towards their parents' face (partner), split for novel (red) and familiar (cyan) objects.* ***B)*** *Percentage of naming events that occurred during infant-leader or infant-follower object directed looks overall.* ***C)*** *Percentage of naming events that occurred during infant-leader or infant-follower looks, broken down by the type of look (match/mismatch) and condition.* ***D)*** *Relationship between word learning (measured during the test phase) and the proportion of naming events that occurred during each type of look towards novel objects (measured during the play phase; this only includes novel objects for which we can measure word learning). Note that experimental settings where a positive link between contingent naming and word learning have previously been observed[10,13,26] artificially reproduce the ideal situation in the middle (infant-leader > mutual attention). Error bars and shaded areas show the 95% CI.*

Contingent naming during play associates with greater word learning. Next, we examined the link between the timing of caregivers' labelling during the play phase and infants' word learning measured during the test phase (Fig.5D). We computed the percentage of naming events that occurred during infants' looks towards novel objects that were led by the infant and resulted in mutual-attention, looks that were led by the adult and resulted in mutual-attention, and looks that were led by the infant and did not result in mutual-attention (either because the adult kept on looking towards their infant's face, or looked elsewhere during the infant's look, see Methods). Hierarchical model comparisons contrasting nested linear mixed regressions including dyad as a random factor, look type (infant-leader > mutual attention, infant-follower > mutual attention, and infant-leader > non-mutual attention), and naming rate as fixed factor, as well as the interaction term between these two factors, revealed that the best fitting model was the model including the interaction (X2 = 8.92, $p < 0.001$). This interaction reflected the fact that, while the naming rate during infant-leader > mutual attention episodes was positively related to learning (beta = 0.328, se = 0.13, t = 2.4, p = 0.02), the naming rate during infant-follower > mutual attention episodes (beta = -0.49, se = 0.17, t = 2.82, p = 0.006) and infant-leader to non-mutual attention episodes (beta = -0.81, se = 0.04, t = 2.02, p < 0.05) was negatively related to learning. In sum, infant word learning was fostered when caregivers tended to join their infants' focus of attention while naming the object, while redirecting the infant's attention to an object that the adult already focused on, or naming a novel object while looking elsewhere associated with worse learning.

Notably, no individual-level (as opposed to dyadic) measures collected during the play phases (greater looking toward target objects for either the infant or the caregiver, higher rates of infant-leader looks overall, higher rates of adult looks towards their infant's face, higher rates of infant looks towards their caregiver's face, or greater neural signatures of endogenous attention recorded in infants' brains) predicted greater learning during the subsequent test phases. This suggests that the effects uncovered here were not mediated by another hidden measure (see Table.S1). The fact that the percentage of infant-leader looks did not directly predict learning in and by itself also reinforces the idea that proactively engaging with objects is not sufficient to learn novel words, because caregivers are not always attuned to these manifestations of interest. Finally, longer episodes of mutual attention also did not predict greater learning here (see Table.S1), suggesting that this symmetric dyadic measure (both actors doing the same action) is less important for infant learning than the asymmetric (both actors doing different actions) measure we described above.

Neural signatures of speech processing during contingent and non-contingent naming.
Finally, we examined infants' brain activity around naming events to see whether the greater neural signatures of endogenous attention we observed during infant-leader looks had an influence on speech processing during these episodes, and ultimately, on infant word learning. Contrary to our initial hypothesis, we did not find greater theta power around naming onsets that occurred during infant-leader> mutual attention episodes (Fig.6A). Instead, we found a marginally significant cluster ranging from 62 to 478ms after naming onsets when comparing the infant-leader > mutual attention and the infant-follower > mutual attention conditions (Fig.6B, no clusters were identified for the other two comparisons, all p-values > 0.1). Averaging power in this 2D cluster (Fig.6C) confirmed that there was a main effect of look type (X2 = 6.45, p = 0.002) reflecting stronger power suppression during labelling in the infant-leader > mutual (M= -1.11, SD = 1.36) as compared both to the infant-follower > mutual (M= -0.05, SD = 1.03; beta = 1.06, se = 0.3, t = 3.53, p < 0.001) and the infant-leader>non-mutual attention conditions (M= -0.41, SD = 1.46; beta = 0.7, se = 0.3, t = 2.34, p = 0.02, the difference between the other two conditions was not significant: beta = 0.36, se = 0.3, t = 1.19, p = 0.23). The difference between the infant-leader > mutual (M=-0.98, SD = 1.91) and the infant-follower>mutual (M=-0.002, SD = 1.16) attention conditions was also significant when restricting the analysis to the alpha-band (beta = 0.98, se = 0.4, t = 2.45, p = 0.01; other comparisons were not-significant, all p-values > 0.08; infant-leader > non-mutual: M=-0.7, SD = 1.96), but not when restricting the analysis to the theta-band (infant-leader to mutual: M-1.39, SD = 2.38; infant-follower to mutual: M=-0.53, SD = 1.32; infant-leader to non-mutual: M=-0.6, SD = 2.08; all comparisons p > 0.06), which suggests that the effect is restricted to the alpha-band here.

This effect is not strictly in line with our hypothesis, since we had predicted stronger theta power in the infant-leader > mutual attention condition, similar to the effect we observed around gaze shifts. However, this result is still interesting given that stronger alpha suppression has previously been related to speech processing in both adults and children[27,28], and with sustained attention during infancy[24]. We therefore decided to still conduct our pre-registered analysis to see whether neural activity in this cluster related to infant word learning, but found no evidence that this was the case (see S.7).

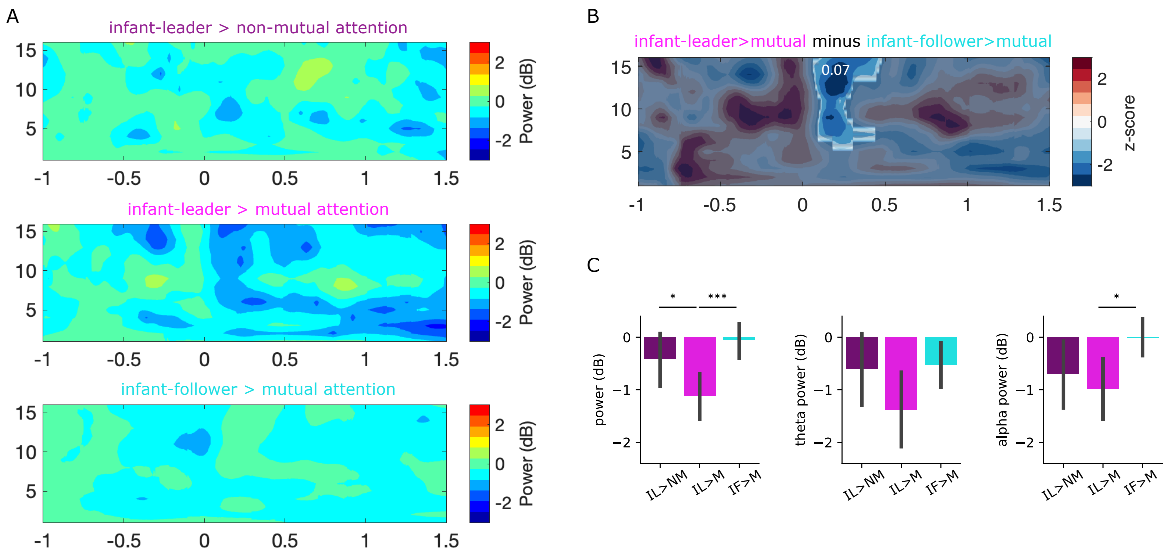

Figure 6. A) *Time-frequency plots show infant EEG activity (1-16Hz) occurring between 1000ms before naming events and 1600ms after naming events, separately for naming events that occurred during infant-leader looks to non-mutual attention (top), infant-leader looks to mutual attention (middle), and infant-follower looks to mutual attention (bottom).* ***B)*** *Difference plot showing power computed during infant-leader > mutual attention naming onsets minus power computed around infant-follower > mutual attention naming onsets. The superimposed area shows the marginally significant 2D cluster identified by the permutation analysis.* ***C)*** *Power averaged within the time-frequency cluster (left), within the time window of the cluster for the theta- (middle) and alpha-bands (right). Error bars show the 95% CI.*

Discussion.

We examined whether caregivers tend to name novel objects contingently on infants' interest during free-flowing play, whether this associates with better infant word learning, and whether this is related to the fact that naming objects contingent on infants' interests ensures that novel information is presented when they are maximally attentive. Overall, our findings are compatible with the idea that infants' increased interest when they visually explore novel objects can boost their learning of the objects' names. However, this is only true when speakers are sensitive to these manifestations of interest, and respond to them by following their infants focus of interest and naming objects contingently, which - as our findings also illustrate - is a challenging task for caregivers.

Our results show that previous findings linking contingent naming and word learning in scripted experimental paradigms[10,13,26] can be generalized to free-flowing interactions between infants and their caregivers. We have mentioned two main mechanisms that might explain why contingent naming can be beneficial for word learners. First, naming contingent on infants' interest results in low referential uncertainty regarding the referent of the novel word. Second, it might allow speakers to present information at times when learners are more attentive. Previous research had provided evidence supporting the existence of the first mechanism[9], and here, we provide evidence that the second mechanism is also important: neural signatures in both the time and frequency domains revealed that infants' proactive looks towards objects indeed signal enhanced endogenous attention during free-flowing play. Thus, proactive looks can be a meaningful behaviour for caregivers to decide when to provide information to their infant, because they are associated with cognitive states that are favourable for memory encoding[12]. Our findings therefore speak against a purely bottom-up view according to which better word learning following contingent naming simply results from the fact that infants' visual field contains only one referent during these episodes[9]. Instead, our results suggest that contingent naming also enhance learning because when infants show interest for specific objects in their environment, they already demonstrate top-down attentional control, which can increase memory encoding if information is presented by speakers contingently on these events. They are also compatible with the idea that joint attention, or perhaps more specifically the sensitivity to having one's own gaze being followed by a social partner[29], is important for word learning[1,30], perhaps because it supports infants' understanding of the referential nature of words[2,7]. Together, this shows that bottom-up referential uncertainty reduction is not the only mechanism through which contingent naming can boost word learning.

Strikingly, though, our findings also indicate that active exploration can be a risky strategy for infants in the context of word learning: looking proactively at objects often led to receiving ambiguous information (i.e., infants often heard a mismatching label after leading a look towards a novel object). By contrast, following caregivers' focus of attention (which rarely occurred) typically led to less ambiguous information (because caregivers talked about their current focus of attention more than 80% of the time). We also found mixed evidence regarding our hypothesis that caregivers should often respond to their infants' manifestations of interest for a novel object by naming it for them[6]. Thus, although they are broadly consistent with the idea that interactions in which infants proactively explore and caregivers contingently name objects can be beneficial for word learning, our results also reveal that coordinating their speech as a function of infants' behaviour and knowledge on the fly is a challenging task for caregivers.

A limitation of our study, and this is true for all of the previous studies cited in this paper, is that our findings are likely to reflect the specific "child-centered" caregiving style that is prominent in western middle to upper class samples[31]. It is and open question whether our findings would hold true in other cultural settings where joint attention is less gaze-centric[32], where leader-follower roles are more flexible and negotiated on the fly during social interactions[33], where direct instruction or observational learning are more common[34], and/or where child-directed speech is less common[35]. As a consequence, our findings here cannot be normative nor prescriptive: child-led contingent naming is likely to be only one out of the many strategies that expert speakers can deploy to support infants word learning, and further research should aim to document other strategies in more diverse samples.

Overall, our findings are compatible with the idea that early language learning can build upon infants emerging exploratory skills and interests. The metaphors according to which infants are « little plants that grow » or « little sponges that absorb information » might have influenced our tendency to study language acquisition in non-interactive settings, and to neglect the role that infants can play in their own language acquisition. Here, we demonstrate that adopting a dyadic approach to study both sides of early social interactions between infants and their caregivers is possible, and that it provides evidence that infants can be – whether it is intentional or not – active agents of their acquisition of a lexicon.

Methods.

Participants. In total, we tested 63 dyads, of whom 38 were included in the final sample (mean age of the infants included: 14.31 months, SD = 0.65, 21 girls; mean age of the mothers: 36.33 years, SD = 4.11, 4 mothers refused to communicate their age; one pair of twins was included in the study, they played with their mothers on separate days). Another 25 dyads were tested but could not be included in the final sample because infants did not accept to wear the EEG cap (6), never looked in the book during the test phase (9), because EEG data were not usable (1), because of fussiness (5), or because of a technical error (4). Mothers identified as white British (19), black British (2), Indian British (3), Latin British (3), white European (11). 18 infants were monolinguals (only heard English), 17 infants heard at least one other language more than 5% of the time, and 3 of them heard at least two other language more than 5% of the time. During the study, mothers spoke in the language they typically used with her child, which was understood by the experimenter for all of the participants speaking English (29), French (1), Spanish (2), Italian (3) or Portuguese (1), but not for the mothers speaking in Hindi (1) and Dutch (1). Most of them had a degree (22), 13 were post-graduate, 2 had no formal education, and 1 had a PhD. They worked full time (12), part-time (18), were unemployed (6), or still studying (2). Three of them were single mothers. Yearly household income was inferior to the national average in the UK for 3 dyads, and above £50K for 29 dyads. All mothers provided informed consent prior to the study. Families were mostly recruited through baby groups in East London, as well as through social media. The experimental procedure was approved by the University of East London Ethics Committee. Data from the 38 dyads were used for all analyses except for the analyses on learning for which 1 dyad could not provide data because the infant's performance during the test phase was at ceiling (only correct recognition). In our pre-registration we planned to test 90 dyads in order to include 60 dyads, but this was made impossible because of the covid-19 pandemic.

Procedure. We recorded dual EEG from 14-month-olds and their parents while they freely played with pairs of objects (play phase), before engaging in short book-reading sessions allowing us to assess word learning using an adaptation of the looking-while-listening procedure[17] (test phase). All procedures, sample sizes and analyses were preregistered.

Play phases. Dyads freely played with pairs of objects, until the parent named each object 8 times. Prior to the study, parents were asked to freely play with their infant and the objects, but they were not explicitly told to "teach" their infants words. They were simply told that *"the aim of the study is to observe how they both play with different toys"*, and asked to *"play as naturally as possible, as they would at home"*. Pilot testing revealed that parents did not always speak during the play, so we also explained that *"we study how the infant brain reacts to spoken words and because of that we need the same number of naming instances for both objects",* and that *"we are particularly interested in speech and vocalizations*", to prime them to talk and engage their child in conversation. Importantly however, there was no reference to novelty, teaching, speech or word-learning in the instructions, in order to remain as close to usual play as possible and not influence parents' behavior. Parents were informed about the details and aims of the study at the end of the session.

Parents wore earphones so that we could help them navigate in the procedure without interfering with the play (see similar procedures in[36,37]). At the beginning of the play, parents received instructions through headphones ("You can now put the X and the Y on the two crosses on the table and start playing") to place the two toys on two crosses placed on each side of the table (counterbalanced across infants). This was also done so as to implicitly prime the parents to name the objects in a certain way. Initial locations were chosen so that toys should initially be out of reach for the infant, to provide them with the opportunity to point towards a toy of interest (either through a gesture or gaze).

Toys were presented according to 3 possible combinations: either two familiar toys (FF), two novel toys (NN), or a familiar and a novel toy (FN), selected as explained below on the basis of parental reports. Conditions (NN / FN and FF) were counterbalanced within blocks of 4 trials, so that the homogenous (NN and FF) conditions appeared only once per block, and the heterogenous (FN) condition twice. Each object appeared once in the heterogenous condition (FN) and once in one of the homogenous conditions (FF or NN). Each object type (e.g., dog) appeared twice, in a different exemplar (e.g., a brown or a grey dog), and was initially introduced either on the left or on the right of the table. Objects were attached to the table with ribbons so that caregivers could bring them back on the table without standing up.

During the play, an experimenter (present behind a screen) pressed a button each time a label was pronounced by the parent. When a set number of naming instances (8) was reached, an auditory prompt was automatically delivered through the earphones ("please stop saying dog"). If the parent uttered the label again after hearing the auditory prompt, the prompt was repeated. The aim of this procedure was to equalize the number of times that children hear novel names, because the amount of linguistic experience with a word can be related to children's ability to retain novel labels[38].

The play phase continued until the parent had labelled each object 8 times, or until the time exceeded 3 minutes. Play phases lasted for 175.5 (SD = 31.98) seconds on average, and caregivers named objects 7.87 (SD = 4.05) times on average. There was no significant relationship between the number of naming events and the duration of the play phase (Spearman's rho = 0.06, $p > 0.2$). At the end of the test phase the parent received an auditory prompt to proceed to the test phase.

Test phases. Following each play phase, a short book reading session involving the looking-while-listening method[39] allowed us to assess infants' learning of the novel word-object mappings. The parent was presented with a book which contained pictures of the play objects, one on each side. The parent received an auditory prompt to open the book, facing towards the infant, and to repeat auditory prompts (e.g., 'Waow look at these! Can you find the banana? Where is the banana? Can you see the banana?'). Parents were not able to see what was in the book during this phase, and were instructed to look directly towards their infants.

Post-hoc coding of parents' looking behaviours during the test phase (see below for details) confirmed that they were looking towards their infant and not into the book during this phase: 21 caregivers never looked inside the book after naming the objects (i.e., always looked towards their infant), as instructed; 17 caregivers sometimes glanced inside the book during the test phase (e.g., to turn pages or redirect their infants' attention to the book), but did so equally often towards the correct or incorrect sides (M= 48.2% target looks post-naming, SD = 0.32, not different from % target looks pre-naming, M = 48.1%, SD = 0.06, $t(16) = 0.62$, $p > 0.5$).

The side and order in which objects appeared during the two trials of the test phase was counterbalanced[39]. For each test phase, each object was presented once as a distracter (not labelled) and once as a target (labelled). Each type of object appeared once on the left and once on the right, and served as the target during the first or second test trial once over the course of the experiment. Thus, novel and familiar target objects appeared half of the time on the right and half of the time on the left; the first target was half of the time a novel object, and half of the time a familiar object; and the first target was half of the time on the left, and half of the time on the right. Finally, the object that was introduced on the left during the play phase appeared as a target for the first test trial half of the time, and as a target during the second test trial for the other half. Infants completed 9.71 (SD=3.57) test trials on average.

Stimuli. For each session, 8 objects in total were used: 4 exemplars of familiar objects, and 4 exemplars of novel objects. They were "real" novel objects (as opposed to custom made objects) so as to allow parents to spontaneously and easily name the objects (e.g., as in[40]) without formal instruction. This is important because using custom-made objects introduces a confound in the sense that they are novel both for the child and for the parent, who might name them in different ways (e.g., slower[6]) as compared to familiar objects not because they are novel for the child, but because they are novel for themselves. Objects were pooled for each dyad from a set of 28 different objects (corresponding to 14 different object names) depending on mothers' reports about their infants' receptive vocabulary and familiarity. A pool of 14 potential words were selected on the basis of *Wordbank* vocabulary norms (parental Oxford CDI database). Familiar words (banana, ball, dog, cat, car, shoe, duck) were selected so as to be understood by roughly 2/3 of 14-month-olds according to *Wordbank*. In addition, previous research using eye-tracking[37,41] or neural markers of semantic processing[36] suggests that infants understand most of these words before their first birthday. Novel words (acorn, anchor, worm, crab, seal, chili, pliers) were equivalent real animal, fruit or object names that infants of this age are unlikely to know already according to the same database (less than 10% of 14-month-olds understand them, less than 50% of 24-month-olds produce them), selected so as to not have close phonological neighbors in the supposed lexicon of a 14-mo. We selected objects that are maximally distant to the words and objects that infants already know at this age either conceptually (e.g., not including a fox, too close to a cat) and/or phonologically (e.g., excluding deer/bat, too close to dear/cat). Familiar and novel words were matched for bigram frequencies (F: M = 1617 +/- 889; N: M = 2015 +/- 506; $t(13) = 1$, $p = 0.33$) and bigram frequencies sensitive to positions within words (F: M = 1140 +/- 520; N: M = 1618 +/- 809; $t(13) = 1.25$, $p = 0.23$). They were mono- (10; F:6; N:4), bi- (N:3) or tri- (2: F:1; N:1) syllabic words. Number of syllables was not significantly different between both pools (F: M = 1.3 +/- 0.7, range 1 to 3; N: M = 1.6 +/- 0.7, range 1 to 3; $t(13) = 0.87$, $p = 0.4$).

From this initial pool of 14 possible objects, four objects were selected for each dyad after asking parents to rate how sure they were that their infant 1) understands and 2) is familiar with each of these words on two separate 5-points scale (*1 = I am sure that my baby does not understand X / 3 = I don't know whether my baby understands X / 5 = I am sure that my baby understands X; 1 = My baby has never seen this / 3 = I don't know whether my baby has already seen this or not / 5 = My baby often sees this*). The questionnaire showed pictures of the items (1 real exemplar and 3 toy exemplars), which implicitly showed parents how the objects are called (e.g., a cat not a kitten; pliers not claws, etc.). This was meant to prime them to label the items consistently during the play sessions without formal instruction. For each dyad and trial, the selected objects were paired to maximize phonological and conceptual distances while minimizing differences in surface properties (e.g., pairing plastic objects with plastic objects…) and attractivity (based on adults' ratings of attractiveness). When possible, exemplars from the same pairs were of different colors and categories (e.g., food vs. animal) to help object individuation. Finally, we tried to equalize the number of toy types (e.g., stuffed vs. plastic) per condition (novel/familiar) as far as it was possible given the other constrains and the limited number of toys available overall.

For each session, each object was presented twice, but there were 2 exemplars (e.g., 2 different toy cars) for each object, as varying exemplars have been found to facilitate word learning[42]. However, in our study there was no significant difference between the 1st and 2nd presentation of a similar object (mean performances for the 1st presentation = 0.10, SD = 0.13; mean performances for the 2nd presentation = 0.035, SD = 0.18; $t(32) = 1.64$, $p = 0.11$; only 33 infants actually saw at least one object twice).

The images in the book for the test phase were pictures of the actual toys. The size of the objects within the images (18*18cm) was resized to equalize the percentage of the image occupied by each object, so that they occupied less than 2/3 of the image but more than 1/3th of the image. Brightness and contrast were normalized using the cv2 toolbox in python.

Measures and pre-processing.

Questionnaires. Before coming to the lab, parents filled in a consent form, the MacArthur CDI, the IBQ, the GAD-7 and PhQ-9, and provided information about their household (number of children, SES…), and about the languages spoken in their homes. They also filled in a questionnaire asking them whether their infant was familiar with the 14 potential objects described above.

Audio recording and coding. Dyads were recorded with two wireless Sennheiner EW 112P G4-R microphones (one attached to the caregiver's clothing and the other to the high-chair) and a Focusrite sound card connected to the stimulation computer. From the audio recordings, a trained coder identified the timings of when parents named the objects in both the test and play phases. Inter-rater reliability analyses of 10% of the interactions revealed strong reliability between coders for the play (kappa=0.86) and test phases (kappa=0.85). We recorded 8.11 (SD = 3.94, range 1-28) labelling events on average during the play phase for each object, trial and dyad, and 2.3 (SD = 0.5, range 1-6) during the test phase. In 12 play phases, mothers named objects in series (e.g., while singing a song: « crab, crab, crab! ») with a very short (< 1 sec) gap between labels. Naming onsets that were separated by less than 1 sec were collapsed in these trials. There was large inter-individual variability in the amount of naming during the play phase, with 5 mothers naming objects less than 5 times on average, and 6 mothers naming objects more than 8 times on average (this included the two mothers who spoke in the languages not understood by the experimenter, who could therefore not count naming events during these sessions). Infant word learning was not significantly associated with the number of naming events overall (Spearman's rho = 0.01, p = 0.9).

Video recording and coding. Sessions were filmed using three Canon LEGRIA HF R806 camcorders recording at 50 fps at different angles (2 cameras filming the infant, 1 the mother) chosen so that both partners' gazes and the two objects could be clearly seen on at least one of the video images. Videos were coded frame-by-frame (50 fps) to identify: 1) where each partner looked at each time (towards an object; the partner; or away (i.e., anywhere else); 2) whether they pointed, reached, touched, or gave/showed one of the objects. Moments where gaze behavior could not be identified were marked as "uncodable". Inter-rater reliability analysis estimated for 10% of the interactions coded with a 20ms precision revealed strong reliability between coders (kappa=0.81). Short interruptions of less than 400ms were interpolated (e.g., if an actor looked at an object, then at their partner for less than 400ms, then back at the object, the short look towards the partner was removed). This threshold was chosen *a* *priori* because we estimated based on pilot data that this should correspond to roughly 10% of look durations, which was confirmed in the main sample. This interpolation mostly smoothed over instances where the parent quickly checked the infant's face, and concerned 3.6% (SD = 0.19) of the data for mothers and 1.8% (SD = 0.14) for infants. For each trial, each object, and each participant of the dyad, we combined these data into a binary vector (with 1 when the participant looked at the object, and 0 otherwise). Similarly, for each trial and participant we extracted a vector reflecting when participants looked towards their partner (with 1 when the participant looked at the partner, and 0 otherwise).

Word learning. For each test trial involving novel objects (NK and NN conditions) we measured learning by comparing the percentage of looks towards the target image after the child hears the target word with the percentage of looks towards the target image during a baseline period. These percentages were computed as follows: number of video frames where the infant was looking towards the target / number of frames during which the infant was looking towards either object during this time window. We pre-registered a fixed time window for the baseline (4 seconds) but the time between the opening of the book and the first word onset was actually much longer, and very variable from trial to trial (M = 7.3, SD = 1.13 seconds). To have a better approximation of infants' baseline preferences, we therefore decided to use a variable – but more realistic – baseline instead. For each test trial, we used as a baseline the time between the actual opening of the book and the actual first word onset, which more accurately reflected what infants looked at before hearing the target word for the first time. According to our pre-registered criteria, the post-naming window started 400ms after the onset of the first naming (to allow for word processing and saccade planning, and following previous research in this age group[43]), and extended until 3 seconds following the onset of the third naming event, with a maximum length of 10 seconds.

Types of looks. Because one of our main purposes was to analyse brain data, we mainly focused on gaze here (rather than babbling or pointing), because gaze shifts towards objects occur very frequently (210.87 times, SD = 58.24, on average per trial for infants, and 236 times, SD = 69.82 for adults), which provided a sufficient number of datapoints to conduct these analyses. A secondary reason is that (unlike pointing) eye-gaze onsets can be precisely identified from video recordings, by identifying the end point of a saccade to an accuracy of +/- 20ms, which allowed us to conduct event-related potential analyses around these specific events. In our pre-registration we planned to identify different types of coordinated attention in 5-second windows using gaze shifts, following previous behavioral research[44]. However, given recent methodological concerns that non-event locked EEG analysis collected during free-flowing interactions are inconclusive because of gaze artefacts[45], we revised this procedure slightly. Instead of identifying attentional coordination bouts as is customary for behavioral research[44], we identified equivalent focal events (i.e., gaze shifts) and analyzed brain data around these events. The advantage of this revised procedure is that it allows us to equate movements (and thus potentially corresponding artefacts) in the actor for each look type: for each event, the behavior is virtually identical across conditions (a gaze onset towards an object), but it is embedded in a different coordination structure.

Using the binary vectors defined above, we first separated out infant-leader looks (when the infant looks towards an object while the parent was not already looking towards the object) from infant-follower looks (when the infant looks towards an object after the parent already started looking towards the object). Infant looks were then further classified into four categories, both as a function of whether they led a look towards an object or not, and depending on what their caregiver decided to do following this. This led to four categories: infant-leader > mutual (when infants initiated a look towards an object, that was then followed by a gaze shift from their caregiver towards the same object), infant-leader > non-mutual (when infants initiated a look towards the object that was not reciprocated by their caregiver, because they were looking somewhere else for the duration of the infant's object look), infant-leader > partner (when infants initiated a look towards the object that was not reciprocated by their caregiver, because they kept on looking towards their infant's face for the duration of the infant's object look), infant-follower > mutual attention (when infants followed their caregiver in looking towards an object). According to our pre-registered criteria, we then collapsed the infant-leader > non-mutual and infant-leader > partner conditions into a single condition (infant-leader > non-mutual attention), because the infant-leader > mismatch condition corresponded to fewer than 10 looks with clean EEG data per trial on average. Collapsing these two conditions also makes sense because in both cases the look led by the infant actually leads to non-mutual attention. Looks were categorized according to the first gaze shift; one of the partners sometimes shifted their eyes while their partner kept on looking towards the object (e.g., mothers often flicked their eyes back and forth between their infant's face and the object while their infant kept on looking towards the object). When this happened, we categorized the looks according to the first gaze shift produced by partner B following partner A's gaze onset. For each dyad, play phase and object, we then computed the percentage of infant-leader looks towards an object as the number of times the infant initiated a look towards an object / number of times the infant looked towards this object in total during the play. We also computed the same measure for the 4 types of looks that also took into account the caregiver's behavior described above. Finally, based on[46], we also estimated each partner's average latency in following their partners' attention as "the duration of the lags between the initial person's gaze shift and the beginning of simultaneous attention" in seconds.

Types of naming events. We also used gaze data to categorize naming events into the same three categories: infant-leader > mutual attention, infant-leader > non-mutual attention, infant-follower > mutual attention. This was inferred from checking the type of look that that each partner was producing when each naming event occurred. For each dyad, play phase and object, we then computed the percentage of naming events that occurred during each type of look as the number of times labelling occurred during a type of look / number of times that the caregiver named the object in total during the play.

EEG data collection. EEG data were acquired using a 64-chanel BioSemi gel-based ActiveTwo system with a sampling rate of 512Hz with no online filtering. The three cameras were synchronized to the EEG via LED boxes attached to each camera and clearly visible on the footage. Trigger signals were sent from a stimulation computer towards a data acquisition computer running the Actiview Software via a MATLAB script at the beginning and end of each play and test phases, simultaneously with the activation of the LEDs which were controlled via Arduino boards. At the same time, audio recordings were started at the beginning of each trial and stopped at the end of each trial with the same MATLAB script using the audio functions of the *Psychtoolbox* package. This system was extensively checked and found to function with a latency inferior to 20ms. Due to a technical error, data for 10 dyads only included half of the electrodes (the left hemisphere), but visual inspection of the ERPs and TF plots revealed no qualitative differences between results for these participants and the rest of the group.

EEG pre-processing. Our approach here is based on extensive methodological investigations into the best way to pre-process and analyze EEG data collected during free-flowing play[25,45]. First, EEG data were high-pass filtered at 1Hz (FIR filter with a Hamming window applied), and line noise was removed using the EEGLAB function *clean_line.m* before applying a low pass filter with a cutoff frequency of 30Hz. Second, data were referenced to a robust average reference, which excluded noisy channels (selected with the EEGLAB *clean_channels.m* function). Third, noisy channels were rejected from the dataset using the same function (with a 'correlation threshold' of 0.7 and a 'noise threshold' of 3), before being interpolated back from surrounding channels using the EEGLAB function eeg_interp.m. Fourth, sections of the data during which 2/3 of the channels had abnormally (> 5 SD) high power content were removed. Fifth, data for channels that became noisy in restricted time windows were locally interpolated by repeating the above step channel by channel in a running window of 2 seconds. Sixth, ICAs were computed using the EEGLAB function runica.m, and ICA components were automatically rejected using ICLabel[47], which was found to match manual rejection 80% of the time on 25% of the data. This last step was run manually for the 10 dyads for which only the left hemisphere had been recorded.

ERP analyses. EEG data were epoched around gaze shifts in a -500 to 1500ms time window, and classified as a function of the type of looks described above. Data were removed when the actor moved their eyes before the end of the time window to avoid contamination by gaze artefacts (e.g., if the actor looked towards an object for less than 1.5 seconds, the data was removed from the moment they moved their eyes away from the object). We extracted visual ERPs (-500 to 1500ms) by averaging infant and parent EEG data locked to look onsets. We used a ROI approach based on the literature to identify the P1/P400/Nc components[20]. Data were averaged in a fronto-central (AF3, AFz, AF4, F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2 for the Nc) and an occipito-temporal (O2, O1, Iz, Oz, POz, PO4, PO8, PO3, PO7, for the P1/P400) clusters of electrodes. We then averaged the amplitudes of each component in a 100ms window around the peaks, identified based on the grand average. ERPs were not baseline corrected because it is not obvious what the optimal time window should be here, and as a consequence we prefer to show raw ERPs for more transparency. Though, note that baseline correcting the data did not change the findings. For instance, brain activity during a baseline window ranging between -500ms to -100 prior to look onset was not significantly different between conditions (fronto-central cluster: $t(37) = 0.23$, $p > 0.8$; occipito-temporal cluster: $t(37) = 1.32$, $p = 0.2$). As a consequence, baseline correcting ERPs using activity averaged in this time window leads to the same findings concerning the Nc and P400 (i.e., stronger Nc/P400 complex for infant-leader as compared to infant-follower looks).

Time-frequency analyses. EEG data were epoched around gaze shifts in a -2000 to 2000ms time window, averaged in the fronto-central cluster of electrodes described above, and classified as a function of the same type of looks. As described above, data were removed when the actor performed a subsequent gaze shift before the end of the time window to avoid contamination by gaze artefacts. Power was then computed around each look in all frequency bands between 1 and 16 Hz in 1 Hz bins by running a time-frequency decomposition via continuous Morlet wavelet analysis; the EEG signal was convoluted with 7-cycles wavelets ranging from 1-16Hz, and power was extracted from the absolute squared of the complex signal, before being averaged for each participant and condition. Power following look-onset was then normalized with respect to a baseline (-1 to -0.6 sec) by converting it to dB (activity = 10*log10(activity)/baseline activity)[48]. Epochs were shortened to a -1 to 1.5 seconds time window centered around naming onsets.

A 2-D cluster-based permutation was then used to identify significant changes in power as a function of condition while correcting for multiple comparisons over both frequency bands and time. Power was then averaged within time-frequency clusters, or in restricted frequency bands, to further test for statistical differences within the restricted time-windows identified by the permutation procedure for separate frequency bands. Frequency bands of interest were identified based on previous studies focusing on neural markers of attentional engagement[12,25,49], and included the theta band [3 to 6 Hz] and the alpha band [6 to 9 Hz]. The exact same procedure was then repeated in a window centered around the onset of target words.

Rejection criteria. In our pre-registration, we planned to exclude dyads with fewer than 20 naming instances where the parent names an object during a time at which we could code both the infant and the parent's gaze as being directed either to one of the objects, or to their partner, but none of the 38 dyads who provided usable data fit this criterion; we also planned to exclude trials if dyads had fewer than 10 naming instances associated with object or partner directed looks after artefact rejection, but again no data had to be excluded based on this criterion. For the analyses on learning, we planned to exclude dyads in which infants provided fewer than 2 valid test trials, at least 1 with a correct performance and 1 with an incorrect performance, which led to excluding 1 dyad from these analyses. During the test phase, trials were excluded if infants looked at the book for less than 20% of the time during the 10-second time window following the first labeling event. We also planned to exclude trials if the parent named one of the objects fewer than 4 times during the play phase. This criterion was not applied because it turned out not to be justified given the fact that infants' performances were above chance in the test phase even in the 27 trials where the object was named only once ($t(26) = 2.33$, $p = 0.03$). Therefore, instead, we only excluded trials were the caregiver never named a target object, which led to excluding 8 trials in total.

Statistical analysis. Aside from classical statistics (e.g., t-tests), we used hierarchical model comparisons comparing nested linear mixed regressions including dyad as a random factor. For these analyses, we first report main effects and interaction effects by specifying the output of the nested model comparisons (X2 and p-values), before reporting the output of the significant best fitting models to compare specific conditions (beta, standard errors, t-values and p-values).

Competing interests.

The authors declare no competing interests.

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