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Keywords: Language development, verb understanding, ERP, N400, semantic processing, infants

Data Statement

Our stimuli, presentation scripts, data, and analysis scripts are available on the Open Science Framework at https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466

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Highlights

- We used an action-verb pairing paradigm to assess verb knowledge in 10-month-olds.
- We also tested adults who showed a canonical action-speech N400 effect.
- Infants' ERP responses suggest they detected incongruency between actions and verbs.
- We suggest these effects reflect emerging verb understanding.
- Infants' ERP response was not associated with parent-reported vocabulary.

Keywords

Language development, verb understanding, ERP, N400, semantic processing, infants

Abstract

When do infants first begin grasping the meaning of verbs? To learn verbs – words that describe actions and events – theorists suggest that infants must employ word segmentation, event processing, and verb-to-action mapping skills. Prior research suggests that many of these skills emerge by approximately 10 months. In the current study, we examined whether 10-month-old infants understand several early verbs. In a novel action-verb pairing paradigm, infants saw videos of everyday actions while hearing matching or mismatching verbs. We tested adults on the same paradigm to verify that action-verb pairs reliably evoked an N400 mismatch effect. Adults showed an N400-like effect over frontal and centroparietal regions. Infants also showed ERP differences between mismatched and matched action-verb pairs, although the pattern differed from adults, with variation in topography and directionality. Infants' ERP response was not related to their receptive or productive vocabulary size. These findings indicate that infants were sensitive to co-occurrences between actions and verbs, reflecting emerging verb understanding and suggesting nascent semantic knowledge. We further consider alternative explanations, including the possibility that the observed ERP differences reflect early action-verb associations that may serve as building blocks for later semantic verb knowledge. These results expand our understanding of infant language acquisition by demonstrating that, by 10 months, infants are sensitive to mismatches between everyday actions and verbs.

Introduction

Around their first birthday, infants begin saying their first words. For many infants, these words will describe caregivers (e.g., *Mama*), other important familiars (e.g., *Dog*), or prominent objects that feature frequently in their daily lives (e.g., *Banana, Ball*; Fenson et al., 1994). Children's vocabularies continue to feature nouns heavily during early development despite linguistic input from caregivers frequently incorporating other word types such as verbs (Au et al., 1994; Goldfield, 2000; Sandhofer et al., 2000; West et al., 2022). The prevalence of nouns in early vocabulary likely explains why experimental research has often focused on when and how infants begin mapping objects to nouns (Bergelson, 2020; Bergelson & Swingley, 2012, 2015; Golinkoff et al., 1994; Kartushina & Mayor, 2019; Markman, 1990; Markman & Wachtel, 1988; Nelson, 1988; Parise & Csibra, 2012; Samuelson & Smith, 1998; Smith et al., 1996; Tincoff & Jusczyk, 1999, 2012). Looking time and electrophysiological studies have shown that infants know the meanings of several nouns by 6- to 9-months-old, many months before they produce their first words or their parents recognise that they understand them (Bergelson & Aslin, 2017; Parise & Csibra, 2012; Tincoff & Jusczyk, 2012).

Early learnt verbs tend to describe actions and events. Though verbs appear less frequently and later in development than nouns for many languages (Gentner, 1982 but see Choi & Gopnik, 1995; Tardif, 1996; Tardif et al., 1999), some verbs feature in children's earliest word productions and children understand many more verbs before they can say them (Fenson et al., 1994; Goldin-Meadow et al., 1976). The dynamic components of the world described by verbs are thought to be more abstract and ephemeral in nature than early nouns, which often describe concrete, easily individuated objects (Gentner, 1982; McDonough et al., 2011; Snedeker & Gleitman, 2004). Learning the meaning of verbs is a complex task, requiring infants to segment verbs from speech, parse actions from motion, form action categories, and map verbs onto emerging action concepts (Gentner, 1982; Golinkoff et al., 2002). By 10 months, infants exhibit many of these underlying pre-requisite skills. Infants begin segmenting short words from speech from ~8 months (Jusczyk, Hohne, et al., 1999; Jusczyk, Houston, et al., 1999; Jusczyk & Aslin, 1995; Mattys & Jusczyk, 2001; Saffran et al., 1996). For example, Jusczyk, Houston and colleagues (1999) found that 8-month-olds familiarised with strong/weak syllable patterned words (e.g., "DOC-tor", "HAM-let") will later attend longer to passages of words containing these strong/weak words in a head turn preference paradigm. By this age, infants can also individuate distinct actions (Sharon &

Wynn, 1998; Spelke, 1976; Wynn, 1996); for example, Wynn (1996) found that 6-month-olds will look longer to a puppet that jumps more times that they were previously habituated to. Later, by at least 10 months, infants parse actions from within streams of continuous motion (Baldwin et al., 2001) and can predict another person's action goals (e.g., Brandone et al., 2014; Cannon et al., 2012; Gredebäck et al., 2009) which enables them to identify violations of goal-directed action structures (e.g., Monroy, Gerson, et al., 2019; Reid et al., 2009; Reid & Striano, 2008). For instance, Baldwin and colleagues (2001) found that 10-month-olds will dishabituate from a paused video when the goal completion is interrupted (e.g., paused as a person reaches to pick up an object) but not when the video is paused after the goal is completed, indicating sensitivity to action boundaries. This knowledge of actions is thought to arise from learnt statistical regularities through frequent exposures to goal-directed action sequences and from infants' own motor experiences producing related actions (Gerson et al., 2015; Gerson & Woodward, 2014a, 2014b; Gredebäck & Melinder, 2010; Hunnius & Bekkering, 2014). Around this age, infants also become sensitive to the semantic features of actions such as the *manner* (the way in which an action is completed) or *path* (the trajectory of the action in relation to a reference point (Göksun et al., 2011; Pulverman et al., 2013; Talmy, 1985) and later begin forming these components into distinct categories (Pruden et al., 2012, 2013). Between 10 and 13 months, infants have also been reported to understand several high frequency abstract words (Bergelson & Swingley, 2013, but also see Gogate & Maganti, 2017; Nomikou et al., 2019). For example, Bergelson and Swingley (2013) presented 6- to 16-month-olds with pairs of videos depicting abstract referents (e.g., a woman waving "hi" and woman showing an empty container with a shrugging gesture for "all gone") while their parents labelled the target video. Only from 10-13 months did infants look longer to the target video demonstrating that from ~10 months, infants can associate words with abstract concepts, like verbs, that are less perceptually accessible than noun referents. Together, the current evidence reviewed suggests that, by 10 months, infants are equipped with many of the cognitive, conceptual, and linguistic skills proposed to be necessary for early verb learning (Gentner, 1982; Golinkoff et al., 2002).

In the current study, we extend this work by directly investigating whether 10-month-olds understand the meanings of several early emerging verbs. One way to investigate infants' early verb comprehension is by measuring event-related potentials (ERPs) that are sensitive to lexical expectations during early development, such as the N400 component. The N400 component represents lexical-semantic integration and often describes a negative-deflecting waveform that, in adults, peaks around 400ms after word – or other semantic stimulus – onset (Kutas & Federmeier, 2011). The N400 component is typically explored using variations of semantic-priming paradigms, whereby participants are presented with a stimulus that is meaningful in nature (the prime; a stimulus that contains some degree of meaning that is stored in semantic memory, such as an image, word, or sentence) which is followed by another meaningful stimulus (the probe) that either semantically matches or does not (to some degree). The amplitude of the N400 response is modulated by semantic expectations following the prime, with probes less expected resulting in a greater N400 response reflecting greater difficulty integrating the probe with the prior semantic context (Kutas & Federmeier, 2011; Kutas & Hillyard, 1984; Van Petten & Luka, 2006). However, the N400 does not necessarily manifest as a negative voltage, but rather as a relative negativity for less expected (or mismatching) items compared to expected (or matching) items (Kutas & Federmeier, 2011).

In adults, the N400 was initially examined in response to semantically incongruous words embedded within written sentences, which have typically been associated with N400 effects that are maximal over centroparietal regions. For example, in the original Kutas and Hillyard (1980) experiment, the sentence "*he spread the warm bread with SOCKS"* elicited a greater N400 than "*she put on her high heeled SHOES"*. Since its initial description, the N400 in adult participants has also been shown to be sensitive to a rich variety of semantic contexts having been reported in response to various types of meaningful stimuli (see Kutas & Federmeier, 2000, 2011 for reviews) including word pairs (e.g., Bentin et al., 1985), signed languages (e.g., Meade et al., 2018; Zachau et al., 2014), pseudowords (e.g., Coch & Mitra, 2010), auditory words (e.g., Holcomb & Neville, 1990), gestures (e.g., Kelly et al., 2004; Wu & Coulson, 2005), sequential images (McLean et al., 2023), and actions (Amoruso et al., 2013; Sitnikova et al., 2003, 2008). While the negativity of the N400 difference across stimulus types is consistent, there are known key variances in scalp topography and duration associated with differing stimulus input. For example, stimuli that diverge from sentential frames by using visual stimuli (such as pictures) have been associated with N400 responses that are maximal over frontal regions due to increased visual semantic access (Ganis et al., 1996; Holcomb & Mcpherson, 1994; McPherson & Holcomb, 1999; Simons et al., 1992). Similarly, N400 designs using dynamic videos also report frontally distributed N400 effects, attributed to increased activity in the motor cortex and pre-motor cortex when observing actions (e.g., Amoruso et al., 2013; Özyürek et al., 2007; Sitnikova et al., 2003; Sitnikova, Holcomb, Kiyonaga, et al., 2008). Other work has also shown that auditory words, compared to written words, result in longer lasting N400 durations for both adults and children as the stimulus offset is more variable across items compared to written words (Holcomb et al., 1992; Holcomb & Neville, 1990). These differences have been interpreted to suggest that elements of semantic knowledge are stored across a dispersed cortical network which can be accessed through a range of modalities (Kutas & Federmeier, 2000).

When infants start comprehending words (~9 months), they are also found to evoke an N400 ERP in response to known or recently learned words paired with pictures, representing developing capacity to integrate spoken words with their referents (Junge et al., 2012; Parise & Csibra, 2012). In infants, the N400 is used to measure word comprehension, indexing expectation of a word given a prior image (Junge et al., 2021). For example, after familiarising 9-month-olds with picture-word pairings for several objects, Junge and colleagues (2012) presented infants with novel pictures for each category either paired with a matching label (e.g., a picture of a cat with "cat") or a mismatching label (e.g., a picture of a banana with "cookie"). Across the scalp, infants were found to elicit more negative amplitudes in response to object-noun mismatches than to matches. As with many ERP components, the infant N400 differs from the adult N400 showing longer latencies and durations, greater amplitudes, and more variable scalp topographies due to ongoing neural maturation and greater reliance on visual, compared to linguistic, features (de Haan, 2007; Thierry, 2005).

In contrast to other infant ERPs, there is currently no consensus regarding the temporal window or electrode sites in which N400 effects can be reliably detected. This stems largely from the heterogeneity of N400 effects observed thus far. For many studies, the infant N400 is often detected from 400ms post word onset but varies greatly in offset from 600-1200ms (see Junge et al., 2021 for a review). Scalp topographies have also been inconsistent; many studies report broadly distributed effects, while others observe them only over parietal, central, or frontal regions. These effects have often been reported bilaterally, but in some cases, they are restricted to left and midline electrodes. As with adults, some of these differences can be explained by stimuli choice and design (e.g., visual vs auditory primes, live object vs pre-recorded object labelling) but they have also been explained by age differences of infant participants (with studies conducted from ~6 to 24 months) which impacts both neural maturation and conceptual-linguistic experience. So far, the infant N400 has been almost exclusively reported for concrete referents, in studies presenting either static pictures of objects or live presentations of objects followed by auditory presentation of nouns (Junge et al., 2021).

In the current study, we modified the picture-word N400 paradigm previously used for objects and nouns with infants (e.g., Friedrich & Friederici, 2004, 2005a) to explore verb comprehension in 10-month-olds. So far, infant N400 studies have largely employed paradigms whereby infants see an object on the screen for several seconds and while the object is on screen, they hear a noun that either labels or mislabels the object (e.g., Borgström et al., 2015a; Duta et al., 2012; Friedrich & Friederici, 2004, 2005b, 2005a, 2006, 2008; Junge et al., 2012). These designs allow infants to inspect an object, appraise its category-defining features, and hear the label while attending to it. In contrast, actions are more challenging to process because they unfold and change over time, with the goal of an action and its defining motion elements becoming recognisable at varying points. Moreover, young infants typically encounter infant-directed verbs in the context of ongoing actions, rather than before an action begins or after it has ended (Nomikou et al., 2017; West et al., 2022, 2023). To align with this, the verbs in our study were presented midway through the unfolding action sequence, shortly after the action's goal became identifiable. This timing ensures that, as in noun-labelling paradigms, infants could attend to the referent when the label was produced, mirroring naturalistic verb-labelling events and ensuring the action was still recognisable. If infants understand the meaning of verbs (i.e., existing action-verb mappings), we expected a larger N400 response to incongruent verbs that mislabelled the action compared to congruent verbs.

We focused on testing verbs that parents first report their infants to understand or say, which our analysis revealed to be several verbs describing everyday actions such as "waving" or "walking" (see **Verb Selection**). In designing an action-verb pairing paradigm suitable for capturing 10-month-old infants' knowledge of verbs, there were several considerations. To accurately assess infants' action-verb understanding, we presented infants with dynamic videos of a model completing actions. This is especially important as previous studies capturing abstract word understanding with video stimuli have succeeded (Bergelson & Swingley, 2013; Valleau et al., 2018) where static images have failed (Casey et al., 2023). Although this is the first action-verb pairing paradigm designed to capture verb knowledge in infants, it builds on prior work with adults and children examining semantic integration in naturalistic contexts, where auditory speech occurs alongside unfolding events (e.g., Holle & Gunter, 2007; Molfese et al., 1996; Özyürek et al., 2007; Tan & Molfese, 2009). For example, Özyürek and colleagues (2007) explored whether iconic gestures, which commonly co-occur with speech, are semantically integrated into a sentence context. Adult participants heard a spoken sentence while viewing a video of an iconic gesture as the critical verb was heard (e.g., "He slips on the roof and WALKS to the other side" with a gesture depicting a walking motion), with ERPs time-locked to the verb and gesture onset. Most relevant to measuring the N400 in response to action-verb pairing is Molfese et al. (1996). These authors tested whether the adult N400 differentiates verbs and nouns by presenting videos of common actions, with verbs or nouns heard auditorily partway through. Consistent with N400 studies using dynamic action stimuli (see Amoruso et al., 2013 for a review), these studies observed N400 effects including (or exclusive to) frontal regions, reflecting additional online action processing. To validate our novel action-verb paradigm, we tested adults on the same paradigm to confirm that our design reliably evokes an N400 effect comparable to previous studies. This further enabled us to document how the spatiotemporal characteristics of the N400 in response to action-verb pairs may differ across different stages of development (e.g., Friedrich & Friederici, 2004; Parise & Csibra, 2012).

Finally, some developmental N400 studies have also reported links between the magnitude of the infant N400 effect and vocabulary size (Borgström et al., 2015a; Cantiani et al., 2017; Friedrich & Friederici, 2004, 2006; Helo et al., 2017; Junge et al., 2012; Lozano et al., 2025; Rämä et al., 2013; Sirri & Rämä, 2015), a relationship thought to reflect emerging sensitivity to semantic priming and enhanced semantic integration with increased linguistic experience and knowledge. For this reason, we also explored whether infants' ERP responses were linked with their parent-reported vocabulary.

Methods

Ethical Approval

This study was approved by the Cardiff University School of Psychology Ethics Committee and is associated with ethics approval number EC.19.03.12.5595GRA4.

Participants

Twenty-three 10-month-old infants (14 female, *M* = 301.43 days, *SD* = 11.29 days, *range* = 288-323 days) participated. This sample size was based on previous studies exploring the infant N400 effect (see Junge et al., 2021 for a review). All infants were exposed to at least 70% English, born full-term, and reported as typically developing. Twenty infants were reported as White-British and three as White-Asian ethnicities. All families were recruited from a large city, and its surrounding areas, in the UK. The families were primarily from high SES households with the mean household income, before taxes, at £67,040.91 (*SD*

= £30,944.48, *range* = £21,000 - £160,000), compared to the UK median of £35,100 at the time (Office for National Statistics, 2023). An additional 19 infants were tested and were excluded due to not hearing English as a first language (n = 1), EEG cap refusal (n = 1), or because an insufficient number of trials were contributed to each condition (minimum of 10 artifact free trials; see **EEG Data Acquisition and Processing**) due to inattentiveness, fussiness, or excessive movement (n = 17). Families received a small toy worth approximately £5, an "Infant Scientist" certificate, and a photograph of their infant wearing the EEG cap.

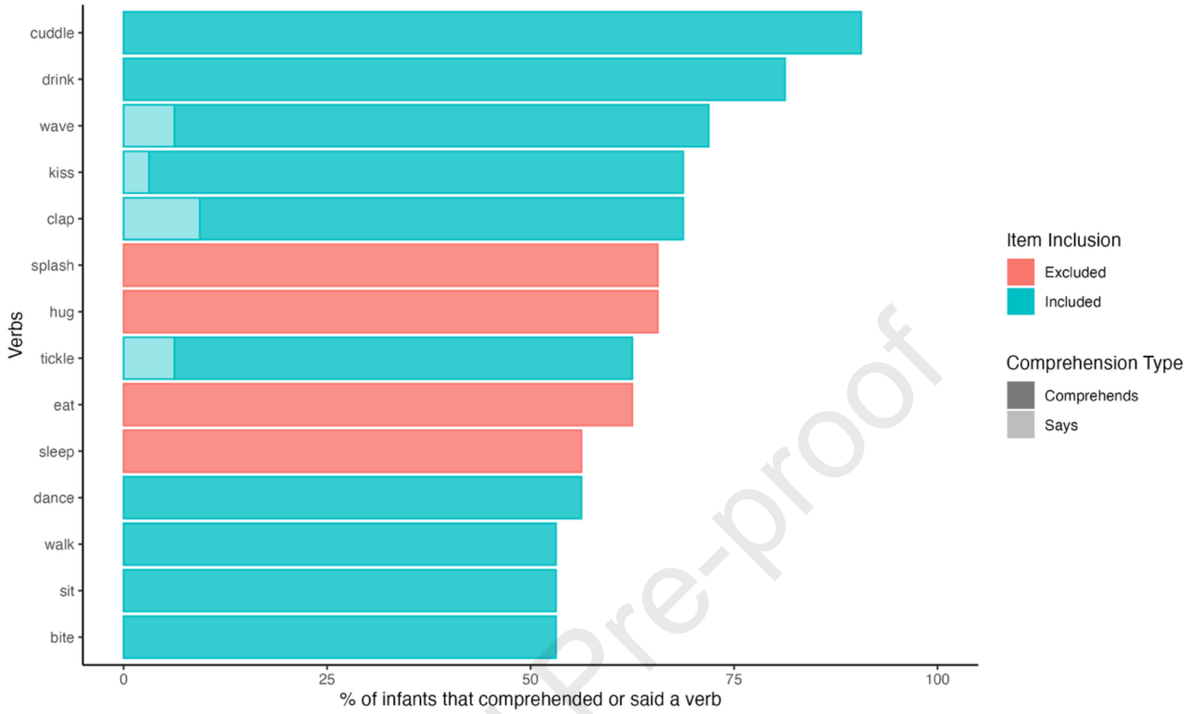
Thirty-one adults (23 female, M = 20.13 years, SD =3.54 years, *range* = 18 – 38 years) participated in the study. Participants were university students recruited from the School of Psychology and participated for course credit. All participants were right-handed and spoke English fluently, but demographics for one adult (e.g., age, gender, handedness) were not provided. An additional 13 participants were tested but were excluded due to being left-handed (N = 3) or because an insufficient number of trials were contributed to each condition (minimum of 30 artifact free trials) due to excessive blinking and/or movement artifacts (n = 10).

Verb Selection

We used a data-driven approach to select verb items that are reported as earliest emerging by parents on Communicative Development Inventories (CDIs). In a separate study (Frewin et al., 2024), we collected data from parents of 32 infants (20 female, M = 12.1 months, SD = 1.6 months, *range*= 9-14.95 months) using the Oxford-CDI (Hamilton et al., 2000), including additional verb items describing infants' early actions and gestures (e.g., *wave*, *clap*). Based on this, we shortlisted items that at least 50% of the sample were reported to comprehend or say. This resulted in 14 verb items (see **Figure 1**). Three items were removed due to semantic overlap with other items (*hug* was removed for overlapping with *cuddle*) or being challenging to depict in a short video (*splash, sleep*). *Eat* was also removed as parents have previously reported conflating *eat* for both eating food and for nursing/bottle feeding (Nomikou et al., 2019). The final items consisted of 10 verbs; *cuddle, drink, wave, kiss, clap, tickle, dance, walk, sit,* and *bite*. The data and verb selection analysis script are available at https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466.

Figure 1

Shortlisted verb items and percentage of infants reported to understand or say a given verb



Note: X-axis depicts the percentage of infants (aged 9- to 15-months-old) reported to comprehend or say a given verb. Bars in blue show the final items selected for inclusion in the task. Bars in red show items excluded. Dark shaded portions of bars show the percentage of infants reported to say a given verb and light shaded show the percentage reported to say a given verb.

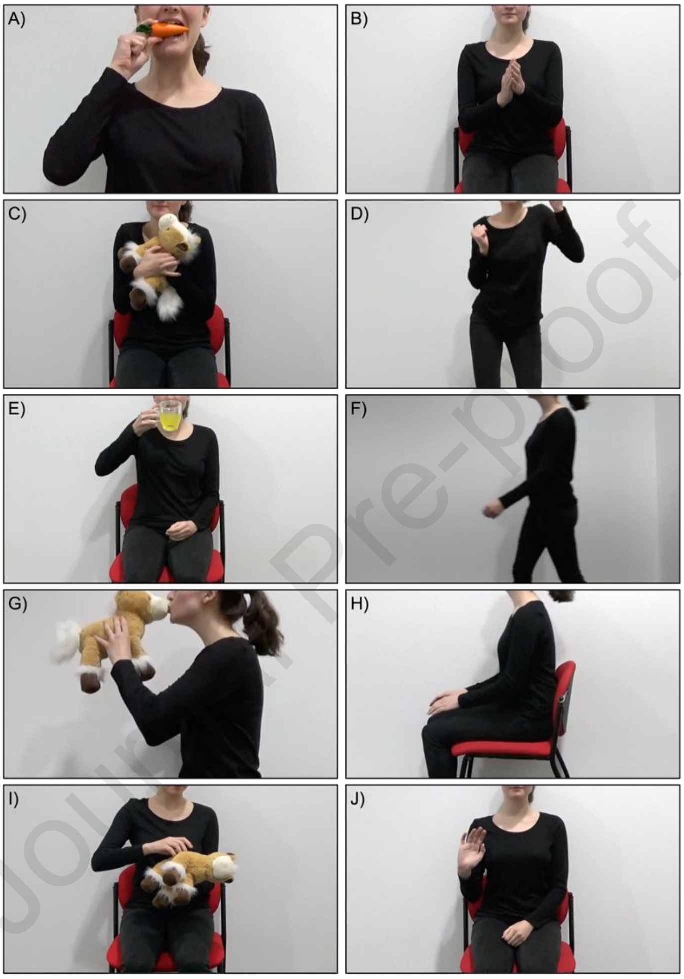
Action Videos and Auditory Verbs

Videos depicted a white female in front of a plain background performing simple actions associated with the verb items. The model's eyes were not visible to reduce infant attentional bias towards the eyes rather than the action (Haith et al., 1977). Videos were 4000ms in length. **Figure 2** shows a still image of each action. Audio were spoken in infant-directed British English by a native female speaker from the local area. Verbs were produced in isolation (e.g., "*wave!*") rather than in a carrier phrase as our stimuli included both transitive and intransitive verbs which require different sentence structures and transitive verbs require the inclusion of the direct object to make sense (e.g., "She is *dancing!*" versus "She is *kicking* the ball"). The audio stimuli were trimmed and noise reduced using Audacity® software (Audacity Team, 2019) and normalised to 70dB using Praat software (Version 6.0.48; Boersma & Weenink, 2019). The spoken verbs ranged from 660ms to

1030ms in length. The stimuli and presentation script are available at https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466.

Figure 2

Still frames of action video stimuli



Note: A still frame from each video stimulus. A) bite, B) clap, C) cuddle, D) dance, E) drink, F) walk, G) kiss, H) sit, I) tickle, and J) wave.

UK-Communicative Development Inventory

The UK-CDI (Alcock et al., 2020) is a parent-report checklist of words that children between 8 and 18 months may understand and say. Parents are asked whether their child understands or produces a word, yielding scores for both overall word production and comprehension. Word comprehension scores are computed by summing the total number of words understood and said, and production scores equal the total number of words said (total possible score of 395 for both comprehension and production). We also added verb items from the action-verb N400 task that did not already feature in the measure.

Procedure

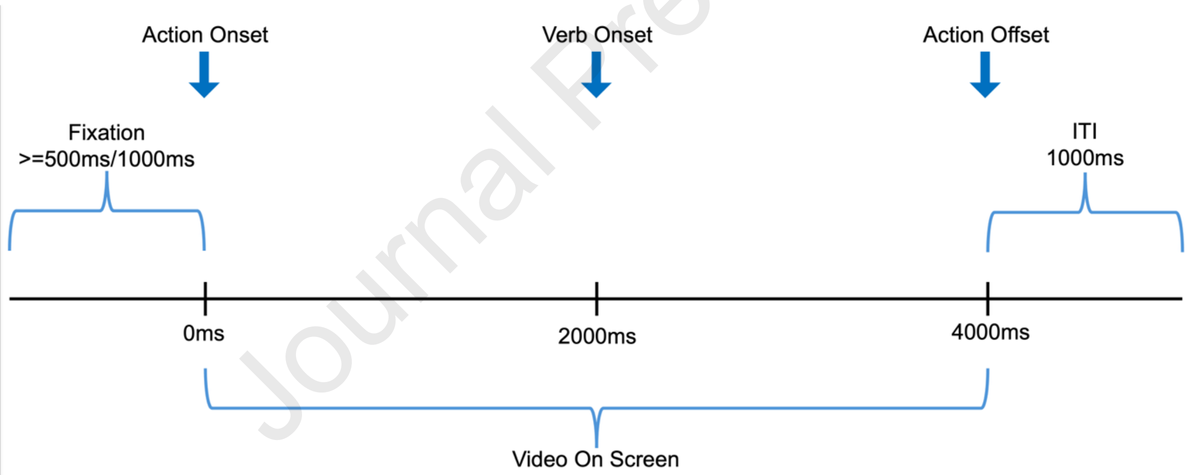
Participants were acclimated to the laboratory while the procedure was explained before providing written informed consent. During the task, infants were sat on their caregiver's lap. A second experimenter sat behind the family, just outside of the testing room, and would enter the room during breaks or periods of fussiness. Parents were asked to refrain from interacting with their child during stimuli presentation aside from reorienting their infant towards the screen. During the EEG task, participants saw videos of actions paired with pre-recorded verbs while their EEG was continuously recorded. Stimuli were presented with E-Prime 3.0 software (Psychology Software Tools, 2016) on a 23" monitor (1920 x 1080 pixels), approximately 60cm distance from the participant. Infant participants were also monitored via a recorded webcam feed on top of the screen. Audio stimuli were played from the monitor speakers. Prior to each trial, infants' saw a fixation cross for a minimum of 500ms. The primary experimenter instigated the trial when the infant oriented to the centre of the screen. If infants did not look at the screen, the experimenter presented a brief attention-grabbing video (e.g., a shaking toy duck accompanied with tinkling bells) until they looked at the centre. Adults saw a fixation cross for 1000ms. Each trial then consisted of a video being presented for 4000ms. See **Figure 3** for trial timeline. The verb stimulus was presented while the video continued playing on screen, 2000ms after video onset. All the actions were recognisable by this time. The inter-trial interval (ITI) included a blank screen and lasted for 1000ms.

There were 200 trials in total, 100 congruent and 100 incongruent. Congruent (i.e., the "dance" action paired with the verb "dance") and incongruent (e.g., the "dance" action paired with the verb "bite") trials were equally divided across verb items, similar to previous N400 studies with infants and adults (Parise & Csibra, 2012). For example, the "wave" action video could be seen a total of 20 times; 10 of those trials were followed by a congruent verb (i.e., "wave!") and the other 10 trials were followed by an incongruent verb (e.g., "dance!"). The incongruent action-verb pairings varied across trials using other verbs in the stimuli set and each audio item served as the incongruent verb an equal number of times across the task. Congruent and incongruent trials for each action were equally divided across the first and second half of the experiment. To help maintain (and later assess) attention to the task, adults also completed 20 questions across the task which asked whether the model had been holding an object in the previous trial. Participants also used these questions as breaks for blinking. On average, adults correctly answered the question 96.48% (*SD* = 6.98%, *range* = 65 – 100%) of the time[1]. Two pseudorandom trial orders were constructed, such that no action or verb was repeated in consecutive trials and that each trial type (congruent | incongruent) did not appear more than twice in a row. The task lasted approximately 20 minutes in total, with infant participants completing approximately 10 minutes on average. Testing continued until all trials had been completed or until infants' attention could no longer be maintained.

After testing, parents were sent the UK-CDI vocabulary checklist online to complete at home. Parents were requested to complete the measures within one week of their testing session.

Figure 3

Schematic of the trial sequence



Note: Length of fixation period varied for infant participants (>=500ms) as the trial was triggered when the experimenter deemed the infant to be attending to the centre of the screen. Adults saw a fixation mark for 1000ms.

EEG Data Acquisition and Processing

Continuous EEG was collected (500Hz sampling rate) using a BrainVision actiCHamp Plus amplifier and recorded via BrainVision Recorder (Brain Products GmbH, Gilching, Germany). EEG was recorded from 32 channels using an actiCAP electrode cap

[1] We re-ran our analyses including and excluding the participant who had an accuracy score of 65%; the pattern of results remained the same. This participant is included in all adult analyses described in the Results section.

(Brain Products GmbH, Gilching, Germany) with active electrodes arranged according to the international 10-20 montage (Fp1, Fp2, F7, F3, Fz, F4, F8, FT9, FC5, FC1, FC2, FC6, FT10, T7, C3, Cz, C4, T8, TP9, CP5, CP1, CP2, CP6, TP10, P7, P3, Pz, P4, P8, O1, Oz, O2) and referenced online to Cz with the ground electrode placed over Fpz. To improve conductivity, electro-gel was applied, and impedances were kept below ~50kΩ.

EEG data were pre-processed offline in MATLAB R2023b using the EEGLAB (v2024.0; Delorme & Makeig, 2004) and ERPLAB (v10.1; Lopez-Calderon & Luck, 2014) toolboxes. For infant participants, the data were first video coded for visual attendance based on the video recordings. Trials where infants did not attend to the video and/or likely did not hear the verb (e.g., due to vocalising) were excluded (see **Table 1** for trial loss descriptives). Data were band-pass filtered at 0.1-30Hz using EEGLAB's default FIR filter and bad channels were interpolated using spherical spline interpolation. For adults, bad channels were automatically detected using the Clean Rawdata plug-in and confirmed with visual inspection. As these pipelines have not been optimised for infant EEG, bad channels were identified using visual inspection. Data were re-referenced using an average reference of all channels in the montage. The EEG was segmented into epochs from 200ms before verb onset to 1200ms after verb onset (Paul & Mani, 2022). Automatic artifact identification and rejection was applied with trials containing artifacts -/+200µV. For adults, epochs containing blinks were also detected and rejected using ERPLAB's step-like artifact detection function in channels Fp1 and Fp2. A 200ms moving window (50ms steps) assessed when the difference in mean amplitude between the first and second half of the window exceeded 70µV, which identifies rapid changes in voltage (Lopez-Calderon & Luck, 2014). Remaining epochs were baseline-corrected using the mean voltage from across the 200ms period prior to verb onset.

Mean amplitudes were extracted for each electrode in frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal regions (P3, Pz, P4) as these are most frequently reported in N400 experiments (Šoškić et al., 2021). There is currently no agreed consensus for time windows (or indeed, electrodes) in which to capture N400 differences in infant samples due to the variability of N400 effects reported in the literature so far. For infants, ERPs were scored in a 400–700ms window post verb onset, based on prior infant N400 literature that commonly reports 400ms as the onset and either 600ms or 800ms as the offset, with 700ms chosen as an average between these values and supported by visual inspection of the grand mean plot (Junge et al., 2021). For adults, mean amplitude was calculated within a time window ranging from 300 to 500ms post verb onset based on recent N400 recommendations (Šoškić et al., 2021). The average number of artifact-free epochs contributed to each condition, for both infants and adults, is reported in **Table 1.** This table also provides descriptive statistics for the average number of trials completed and the average number of trials lost to artifact vs. inattention (infants only) for each condition.

Table 1

Final Sample Trial Attrition Descriptives for Infants and Adults, by Condition

		Congruent Trials		Incongruent Trials			
	N	*M*	*SD*	*M*	*SD*	*t*	*p*
			Trials Completed				
Infants	23	41.74	10.82	43.61	10.35	-4.11	<.001
Adults	31	100.13	0.72	100.23	1.26	-1.00	.325
			Artifact-Free Trials				
Infants	23	22.22	8.86	23.78	9.56	-1.97	.061
Adults	31	67.23	21.27	68.77	21.27	-1.26	.218
			Trials Lost to Artifact				
Infants	23	9.83	5.29	11.43	5.46	2.32	.030
Adults	31	32.90	21.50	31.45	20.06	1.20	.240
			Trials Lost to Inattention				
Infants	23	9.70	4.58	8.39	4.82	1.67	.108

Note: Descriptive statistics for trial completion and rejection for infants and adults, split by condition. Number of trials completed, number of artifact free trials included in the final averages, number of trials lost to artifact detection, and number of trials lost to inattention (infants only). The final columns present results from paired t-tests comparing number of congruent and incongruent trials[2].

[2] We noted that the difference in artifact-free trials included in the infant analysis was not significant, but there was a trending difference. We explored this and identified two participants with large differences in artifact-free trial numbers. When removed, the difference between artifact-free trials between the congruent and incongruent conditions no longer trended towards significant. We re-ran our primary analysis with these infants removed and found an equivalent pattern of results and, thus, kept these participants in the analyses reported.

Analysis Plan

The data and analysis scripts are publicly available at https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466. Analyses were conducted in R (Version 4.4.3). To test whether an N400 congruency effect was elicited in response to auditory verbs, the mean ERP amplitudes were entered into a 2 x 3 x 3 repeated-measures ANOVA with congruency (congruent | incongruent), region (frontal | central | parietal), and laterality (left | midline | right) as within-subjects factors. ANOVAs were conducted using *aov_car()* from the *afex* package (Barr et al., 2013; Freeman et al., 2010). The analysis automatically applied the Greenhouse-Geisser correction when non-sphericity was detected.

We planned to follow up any significant interactions or main effects involving congruency; completed with *emmeans()* and *pairs*() from the *emmeans* package (Lenth, 2024) and *p* values were corrected with the Bonferroni-Holm correction. To assess associations between parent-reported vocabulary knowledge and infants' N400 response, correlations were conducted using *cor_test()* from the *rstatix* package (Kassambara, 2021). Vocabulary scores were found to deviate from normality; thus, Spearman's rank correlations were applied, and correlations were one-tailed. See **Table 2** for descriptive statistics associated with infants' vocabulary size. Tests were conducted separately for infant and adult participants and statistical significance was assessed at an α of .05.

Results

Table 2

Infant Vocabulary Descriptives

Score	*N*	*M*	*SD*	*Min*	*Max*
All CDI Words Understood	23	63.91	45.24	0	149
All CDI Words Said	23	2.48	3.91	0	16
All CDI Verbs Understood	23	10.52	8.85	0	26
Task Verbs Understood	23	4.30	3.20	0	10

Note: CDI scores refer to the average number of words reported to be understood and said. Scores have been reported for all items in the measure (total of 395), verb items (total of 59), and task verb items (total of 10). Number of verbs said has not been reported as no infants were reported to say any verbs.

N400-like Effects

Infants

The ERP data in the 400-700ms time window revealed increased negativity in response to incongruent versus congruent verbs in frontal regions, see **Figure 4**. A significant three-way interaction between congruency, region, and laterality was observed, see **Table 3**. Follow-up analyses revealed that the congruency effects observed in the frontal region were localised to the left (F3, *estimate* = 2.12, $t(22) = 2.349$, $p = .028$) and midline (Fz, *estimate* = 3.13, $t(22) = 2.650$, $p = .015$). These analyses also revealed an increased positivity to incongruent versus congruent verbs in the right central electrode (C4, *estimate* = -4.11, $t(22) = -3.518$, $p = .002$).

We also examined relations between the size of infants' ERP responses and their parent-reported vocabulary size in three ways. First, we calculated the size of infant ERP response in frontal left and midline electrodes, where the expected direction of effects was detected. To do this, we calculated the average difference in amplitude in these electrodes between incongruent and congruent verbs (incongruent – congruent), with more negative values indicating a more negative response to action-verb mismatches. No significant associations were observed between the size of infants' frontal response and their vocabulary size (number of words understood; $r_s = .06$, $p = .613$; number of words said; $r_s = .03$, $p = .553$; number of verbs understood; $r_s = .20$, $p = .815$) or with the number of task verbs reported to be understood ($r_s = .19$, $p = .802$). Second, we examined associations with the size of infants' ERP response with for electrodes included in the ANOVA (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Again, we calculated the average difference in amplitude in these electrodes between incongruent and congruent verbs (incongruent – congruent). No significant associations were observed between the size of infants' ERP response and their vocabulary size (number of words understood; $r_s = -.23$, $p = .145$; number of words said; $r_s = -.08$, $p = .365$; number of verbs understood; $r_s = -.27$, $p = .109$) or with the number of task verbs reported to be understood ($r_s = -.21$, $p = .170$). Finally, we also reconducted the repeated measures ANOVA described above with vocabulary scores (median split; low vs high) included as an additional between-subjects factor. No significant main effect or interactions between vocabulary score and congruency were observed and the pattern of results remained the same across predictors (see **Supplemental Materials**).

Table 3

Repeated measures ANOVA output exploring N400-effect in infants

Effect	*df*	*MSE*	*F*	η_p^2	*p*
Congruency	1, 22	22.57	0.15	.007	.706
Region	1.71, 37.58	103.64	53.24	.708	<.001 ***
Laterality	1.55, 34.07	103.55	1.59	.067	.220
Congruency:Region	1.72, 37.80	40.39	4.25	.162	.027 *
Congruency:Laterality	1.77, 38.87	18.14	1.11	.048	.333
Region:Laterality	2.85, 62.67	31.71	4.55	.171	.007 **
Congruency:Region:Laterality	3.42, 75.30	14.97	3.06	.122	.027 *

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Adults

The ERP data in the 300-500ms time window revealed increased negativity in response to incongruent versus congruent verbs with a broad scalp distribution, see **Figure 5**. A significant main effect of congruency was observed, see **Table 4**. Follow-up analyses revealed that amplitudes in the incongruent verb condition were significantly more negative than in the congruent verb condition, across the scalp (*estimate* = 0.51).

Table 4

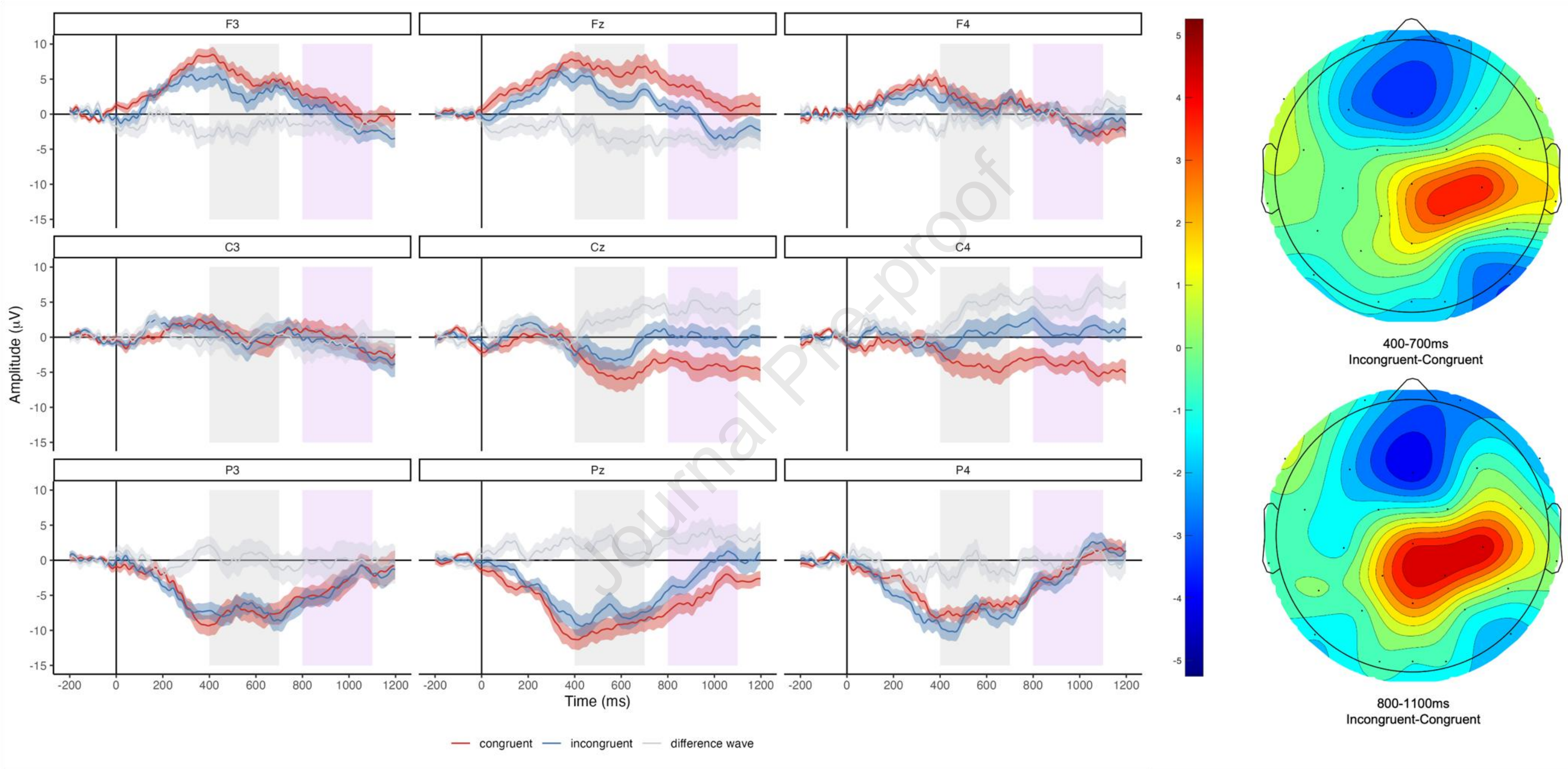
Repeated measures ANOVA output exploring N400 effect in adults

Effect	*df*	*MSE*	*F*	η_p^2	*p*
Congruency	1, 30	1.89	19.54	.394	<.001 ***
Region	1.24, 37.34	16.63	6.30	.173	.012 *
Laterality	1.75, 52.59	1.64	3.04	.092	.063
Congruency:Region	1.16, 34.73	3.05	0.56	.018	.484
Congruency:Laterality	1.30, 39.03	1.57	1.06	.034	.329
Region:Laterality	3.54, 106.29	0.56	1.04	.034	.383
Congruency:Region:Laterality	3.16, 94.89	0.37	2.28	.071	.081

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Figure 4

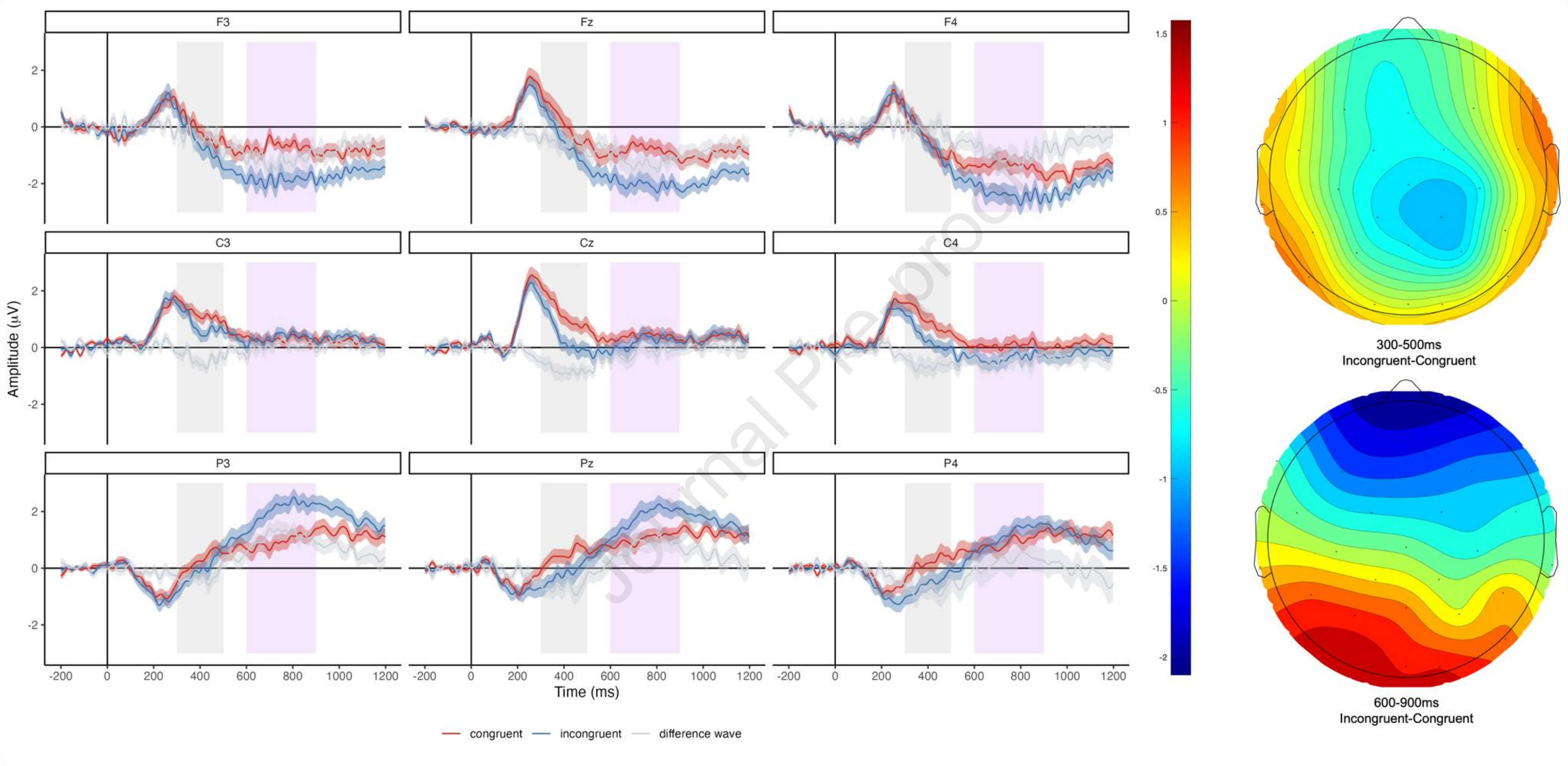
Infant ERP waveforms and scalp maps



Note: On the left, the grand average ERP waveforms for infants. Red lines are congruent verbs, blue lines are incongruent verbs, grey line is difference wave (incongruent-congruent). Negative is plotted down. Grey box: 400-700ms. Lilac box: 800-1100ms. Ribbons represent 1SE. On the right, scalp maps depicting the spatial distribution of the difference in activity between the incongruent and congruent verb conditions (incongruent-congruent).

Figure 5

Adult ERP waveforms and scalp maps



Note: On the left, the grand average ERP waveforms for adults. Red lines are congruent verbs, blue lines are incongruent verbs, grey line is difference wave (incongruent-congruent). Negative is plotted down. Grey box: 300-500ms. Lilac box: 600-900ms. Ribbons represent 1SE. On the right, scalp maps depicting the spatial distribution of the difference in activity between the incongruent and congruent verb conditions (incongruent-congruent).

Exploratory Analyses: Late Windows

Based on visual inspection of the waveforms (see **Figures 4 & 5**) we identified two late effects warranting further investigation; a late sustained negativity in frontal regions to incongruent verbs and a late posterior increase in positivity also to incongruent verbs (adults: parietal electrodes; infants: centroparietal electrodes). Comparable effects have previously been reported in adult and infant N400 studies. For example, N400 studies contrasting auditory and visual probes have reported longer durations for auditory items, thought to be explained by variation in spoken word length (Holcomb et al., 1992; Holcomb & Neville, 1990). Most infant N400 studies rely on auditory words, with several also reporting long N400 durations (e.g., Cantiani et al., 2017; Friedrich & Friederici, 2005a, 2005b, 2008), but it remains unclear whether this is driven by the auditory modality, age-related delays associated with infant ERPs, or a combination of these factors. Similarly, studies using dynamic visual stimuli, such as actions or gestures, also tend to report longer frontal durations (up to ~900ms post probe onset). These sustained effects may reflect the variable time point in which an action or gesture can be identified or continued processing as the scene unfolds (Sitnikova et al., 2003; Sitnikova, Holcomb, Kiyonaga, et al., 2008, see Amoruso et al., 2013 for a review). Such effects have also been reported in infant action N400 paradigms (Reid et al., 2009).

Adult N400 studies have also reported late positive waves maximal over parietal regions that follow on from N400 effects, often referred to as the Late Positive Component (LPC), with greater amplitudes to incongruent than congruent probes (see Van Petten & Luka, 2012 for a review). These effects are typically detected between ~600-900ms post probe onset and reflect prolonged analysis or re-analysis of the prior semantic violation (Kuperberg, 2007). The LPC is considered functionally distinct from other late positive waves, such as the P600, which reflect syntactic rather than semantic processing. LPC waveforms are rarely reported or examined in infant samples but in recent years, two studies have reported LPC-like effects following on from the N400 in older infants. Cantiani and colleagues (2017, 2021) reported LPC-like effects in 19- to 20-month-old children starting approximately ~700-1000ms after hearing a word mislabel an object (occurring ~100ms after the N400 effect).

Based on this prior work, we aimed to examine the late waveforms in both adults and infants. For adults, we focused on 600-900ms post word onset, as this is where the LPC is typically observed and where sustained frontal effects with dynamic stimuli have also been reported. For infants, like Cantiani et al.'s (2017, 2021) examination of LPC-like responses, we used a window 100ms after the initial N400 window from 800-1100ms.

Infants

We ran an exploratory analysis on mean amplitude across the same electrodes in a late window (800-1100ms) using the same 2 x 3 x 3 repeated measures ANOVA design, following up interactions or main effects involving congruency (see **Figure 4**). A significant three-way interaction between congruency, region, and laterality was observed ($F(3.24, 71.29) = 2.79$, $p = .043$, $\eta_p^2 = .113$). Follow-up analyses revealed more negative amplitudes to incongruent than congruent verbs in the frontal midline (Fz, *estimate* = 3.95, $t(22) = 3.905$, $p < .001$) and greater positive amplitudes in response to incongruent than congruent verbs in the central and parietal midline (Cz and Pz, *estimate* = -3.99, $t(22) = -2.311$, $p = .031$; *estimate* = -3.28, $t(22) = -2.146$, $p = .043$, respectively) and central right (C4, *estimate* = -4.89, $t(22) = -3.369$, $p = .003$).

We also examined relations between the size of infants' ERP responses and their parent-reported vocabulary size using a similar approach as the earlier analysis window; we calculated the average difference in amplitude between incongruent and congruent verbs (incongruent – congruent). First, we examined the relation between the size of frontal response in Fz with infants' parent-reported vocabulary size; no significant associations were observed (number of words understood; $r_s = .32$, $p = .930$; number of words said; $r_s = .14$, $p = .731$; number of verbs understood; $r_s = .40$, $p = .970$; number of task verbs understood; $r_s = .39$, $p = .968$). Second, we examined the relation between the size of late positive waveform (Cz, Pz, C4) with infants' parent-reported vocabulary size; no significant associations were observed (number of words understood; $r_s = -.02$, $p = .818$; number of words said; $r_s = .04$, $p = .422$; number of verbs understood; $r_s = -.32$, $p = .930$; number of task verbs understood; $r_s = -.24$, $p = .866$). Third, we examined associations with the size of infants' ERP response across all electrodes included in the ANOVA (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4); no significant associations were observed (number of words understood; $r_s = -.09$, $p = .348$; number of words said; $r_s = .07$, $p = .624$; number of verbs understood; $r_s = -.18$, $p = .209$; number of task verbs understood; $r_s = -.12$, $p = .287$). Finally, as with the early window, we also reconducted the repeated measures ANOVA described above with vocabulary scores (median split; low vs high) included as an additional between-subjects factor. No significant main effect or interactions between vocabulary score and congruency were observed and the pattern of results remained the same across predictors (see **Supplemental Materials**).

Table 5

Repeated measures ANOVA output exploring the late window in infants

Effect	*df*	*MSE*	*F*	η_p^2	*p*
Congruency	1, 22	17.86	2.09	.087	.162
Region	1.99, 43.71	56.61	3.95	.152	.027 *
Laterality	1.62, 35.59	75.90	0.06	.003	.912
Congruency:Region	1.80, 39.63	57.23	3.66	.143	.039 *
Congruency:Laterality	1.84, 40.54	25.20	2.67	.108	.085
Region:Laterality	3.00, 66.04	28.27	3.20	.127	.029 *
Congruency:Region:Laterality	3.24, 71.29	29.26	2.79	.113	.043 *

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Adults

We ran an explanatory analysis on mean amplitude across the same electrodes in a late window (600-900ms) using the same 2 x 3 x 3 repeated measures ANOVA design, following up interactions or main effects involving congruency (see **Figure 5**).

The analysis revealed a significant two-way interaction between congruency and region ($F(1.19, 35.8) = 12.25$, $p < .001$, $\eta_p^2 = .290$). Follow up analyses revealed significant differences in amplitude in frontal and parietal regions. In frontal regions, amplitudes in response to incongruent versus congruent verbs were significantly more negative (*estimate* = 1.13, $t(30) = 4.110$, $p < .001$) whereas amplitudes in parietal regions were significantly more positive in the incongruent verb condition than in the congruent verb condition (*estimate* = -0.71, $t(30) =-2.369$, $p = .024$).

Table 6

Repeated measures ANOVA output exploring the late window in adults

Effect	*df*	*MSE*	*F*	η_p^2	*p*
Congruency	1, 30	2.30	2.57	.079	.120
Region	1.38, 41.41	10.33	53.33	.640	<.001 ***
Laterality	1.42, 42.49	3.26	5.94	.165	.011 *
Congruency:Region	1.19, 35.83	5.39	12.25	.290	<.001 ***
Congruency:Laterality	1.23, 36.94	1.92	1.68	.053	.205
Region:Laterality	3.13, 93.81	0.67	0.19	.006	.909
Congruency:Region:Laterality	3.28, 98.38	0.50	2.60	.080	.051

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

Discussion

Infants' understanding of early nouns during the first year of life is well documented in both looking time (Bergelson & Swingley, 2012; Kartushina & Mayor, 2019) and neurophysiological studies (Parise & Csibra, 2012), but when they begin understanding verbs is less clear. We created a paradigm where infants saw videos of everyday actions paired with verbs that either matched or mismatched the action to measure whether 10-month-olds understand several early verbs. Using parent-report vocabulary data, we used a data-driven approach to select verb items that parents first report their infant to understand around ~10 months. We also tested adult participants on the same paradigm to validate our procedure and to explore how the N400 response to overlapping action-verb pairs manifests in adults. Adults showed a clear N400 response to action-verb mismatches, with a frontocentral distribution in a window 300-500ms after verb onset, confirming that our paradigm elicits semantic integration effects. In infants, during the 400-700ms window, we observed differences in ERPs between congruent and incongruent verbs; a negatively deflected waveform in frontal regions and a positively deflected waveform in central, both of which were greater in response to incongruent verbs. These differences in ERPs to congruent and incongruent verbs indicate that infants, by the age of 10 months, can detect mismatches between verbs heard in the context of observing everyday actions. This detection is a remarkable feat given that infants needed to generalise from their prior experiences with actions and verbs – born from their day-to-day interactions at home – to novel variations of these actions produced by an unfamiliar person and words spoken by an unfamiliar speaker.

This may indicate emergence of some of the cognitive, conceptual, and linguistic skills necessary to begin forming rudimentary links between verbs and actions (Baldwin et al., 2001; Bergelson & Swingley, 2013; Jusczyk, Houston, et al., 1999; Jusczyk & Aslin, 1995; Pruden et al., 2012, 2013; Pulverman et al., 2013). However, we note that qualitative differences between the infant and adult effects may cast some doubt on whether the infant response we observed can unambiguously be interpreted as an index of semantic processing. We consider several interpretations. Firstly, we describe how these effects reflect infants' difficulty integrating a mismatching verb with the on-going action, suggesting emerging semantic understanding of the tested verbs. We also consider that differences between the infant ERP effects seen here and effects reported in prior infant N400 studies could be explained by either key differences in design between the current and previous studies, or by the possibility that infants' detection of action-verb mismatches was supported by earlier, precursor action-verb associations rather than mature semantic knowledge. In the following sections, we discuss these explanations in greater detail, contrasting the infant response with the adult effects and prior infant literature.

One potential interpretation of the infant ERP effect is that the observed response is an N400-like semantic processing response, but the topography and polarity have been shaped by our methodological approach. Most prior infant semantic priming paradigms have shown static pictures of objects for ~2-3 seconds before presenting an auditory noun that correctly or incorrectly labels the image while it is still on screen (though some of these studies reverse image-word order; e.g., Asano et al., 2015; Borgström et al., 2015a, 2015b; Duta et al., 2012; Friedrich & Friederici, 2004, 2005b, 2005a, 2005c, 2008, 2010, 2011; Helo et al., 2017; Junge et al., 2012; Mani et al., 2012; Parise & Csibra, 2012; Torkildsen et al., 2008, 2009). These designs enable infants to attend and recognise the visual image before hearing it labelled. The delay before language stimuli also results in attenuation of much of the earlier activity associated with visual processing, ensuring temporal separation between neural processes. In our design, infants watched a video of an everyday action and during the on-going action heard a verb that matched or mismatched. This was designed to support infants' verb-to-action mapping as much of their infant-directed verb input is synchronised with action production (Nomikou et al., 2017; West et al., 2022, 2023). This design also builds on several prior adult N400 studies overlapping dynamic videos and auditory speech (e.g., Amoruso et al., 2013; Cornejo et al., 2009; Ibáñez et al., 2011; Molfese et al., 1996; Özyürek et al., 2007). Most similar is the paradigm developed by Molfese et al. (1996), later used with children (Tan & Molfese, 2009), where videos of actions were observed while hearing verbs or nouns that varied in congruency with the scene, with the aim of observing how the N400 is modulated by word type in naturalistic contexts. Across these studies, an N400 mismatch effect is observed but the effect is often more frontally distributed and delayed in offset than studies using written text. This is attributed to increased activity in motor and pre-motor cortices in response to action perception during semantic integration (Amoruso et al., 2013; Manthey et al., 2003; van Elk, van Schie, & Bekkering, 2010; van Elk, van Schie, Zwaan, et al., 2010). Indeed, infants like adults have increased motor activity during action observation (Cuevas et al., 2014; Vanderwert et al., 2013). Likely, as participants heard the verb while continuously processing the action unfolding, neural activity associated with motor activation, action prediction, and continued attentional allocation may have overlapped with semantic integration signals. In this task, both infants and adults had N400-like responses over frontal regions (namely, Fz and F3). For infants, this effect was more localised than the adults, whose effect was also detected in centroparietal regions. Given these differences, it is possible that the infant ERP pattern observed reflects a similar – but less mature – interaction between action perception and semantic processing which alters the N400 presentation. It is also not unsurprising that infants and adults' neural activity may differ in response to such overlap. For example, whereas adults have extensive experience with many of the actions depicted, 10-month-olds have relatively little, and motor experience is known to modulate motor resonance activity during action observation for both infants (e.g., Gerson et al., 2015; Paulus et al., 2012) and adults (e.g., Cannon et al., 2014). Infants also tend to have N400 responses that are more frontal than adults, thought to reflect visually dominant – rather than linguistic – semantic representations in infancy (Friedrich & Friederici, 2004, 2005a) or increased attentional responses to novelty (Torkildsen et al., 2006). Conceivably, this overlap of action and semantic processes may have altered the topography and polarity of N400-like response; this may be particularly pronounced in infants, whose less developed motor, language, and semantic systems may interact differently with overlaps in action and verb processing.

While this explanation may account for some aspects of the infant ERP pattern, directly comparing against the adult response provides an alternative perspective. Adults showed a canonical N400 response; maximal over centroparietal regions in a 300-500ms window, with additional sustained frontal effects typical of auditory and dynamic visual stimuli (Amoruso et al., 2013; Ganis et al., 1996; Holcomb et al., 1992; Holcomb & Neville, 1990; Kutas & Federmeier, 2000, 2011; Sitnikova et al., 2003, 2008). In contrast, the infant response qualitatively differed in several ways. Though infants had significant effects in a typical infant N400 window (400-700ms; which is often slower than adults) and exhibited a somewhat similar frontal response to the adults (with more negative amplitudes to incongruent versus congruent verbs), they lacked the anticipated response in centroparietal regions. In central regions, a reversal of directionality was observed with more negative amplitudes to congruent (rather than incongruent) verbs and no differences observed in parietal regions in contrast to the adult response and prior infant N400 studies (e.g., Friedrich & Friederici, 2004, 2005a, 2005b; Junge et al., 2012). While developmental differences may be a contributor, it could be argued that the trial structure alone may not explain the reversal of centroparietal effects in infants. That is, if the differences in the infant ERP pattern were largely due to the overlap in action-verb stimuli and developmental differences in processing such overlaps, we might still expect a descriptively similar altered N400 response in adults. Although infant N400s are often slower and sometimes more frontal than adults (Friedrich & Friederici, 2004, 2005b; Parise & Csibra, 2012), much of the topographical distribution, polarity, and directionality should be comparable if the current design was the driver of the infant ERP effect. The adult pattern seemingly reflects semantic integration processes, with greater difficulty integrating verbs that are semantically incongruent the viewed actions.

What alternative explanations might explain infants' detection of mismatches between actions and labels, if not existing semantic verb knowledge? Given that the same actions and verbs appeared in both conditions where only the pairing differed, the observed ERP differences cannot solely be attributed to infants' sensitivity to lower-level perceptual properties of the stimuli. Moreover, as this study involved no training – and interleaving between items prevent online word-to-referent mapping at this age (Pomiechowska & Gliga, 2019) – this suggests that the sensitivity seen here is derived from infants' experiences in day-to-day life. One plausible interpretation, therefore, is that the ERP findings here provide evidence that 10-month-olds are sensitive to hearing verbs that are unlikely in the context of an on-going everyday action. This may be evidence of emerging action-verb associations that form the initial building blocks of later semantic verb knowledge. These emerging associations likely reflect infants' cross-situational statistical learning of action-verb co-occurrences (Monaghan et al., 2015; Smith & Yu, 2008), where infants learn that certain verbs are more likely to occur with some actions versus others. Under this view, the neural activity observed here may partially be a function of processing driven by perceptual and attentional systems, whereby infants' attention is differentially allocated between conditions when unexpected auditory input aligned with familiar actions. That is, infants' attention may have been engaged by the violation between their expectations about the observed action and a verb that rarely co-occurs with that action. Support for this attentional account comes from prior studies showing that infants are typically sensitive to statistical regularities associated with action events (Kaduk et al., 2016; Langeloh et al., 2020; Monroy et al., 2019; Reid et al., 2009). We suggest that spoken verbs are also one such regularity, given that infants frequently experience co-occurrences between actions and associated verbs in everyday life (Nomikou et al., 2017; Tomasello & Kruger, 1992; West et al., 2022, 2023). This interpretation aligns with the idea that infants' sensitivity to action-verb co-occurrences is supported by their developing action knowledge which helps them understand how common actions are likely to unfold; violations of this knowledge have been reflected in various ERP components (e.g., Nc, P400, N400) across the first year of life (e.g., Maffongelli et al., 2018; Monroy et al., 2019; Ní Choisdealbha et al., 2025). Action knowledge emerges through repeated goal-directed action exposure and from infants own motor action experience (Gerson & Woodward, 2014a, 2014b; Gredebäck & Melinder, 2010; Hunnius & Bekkering, 2014), with common action consequences and other frequent co-occurrences (such as spoken verbs) thought to form part of infants' early action concepts (Sootsman Buresh et al., 2006).

In an exploratory analysis, we also observed a late positive waveform that was more positive for incongruous verbs than congruous verbs in posterior regions for both infants and adults, though this also included central electrodes for infants (infants, 800-1100ms; adults, 600-900ms). In adult studies, the N400 is often followed by a later positive-going component between approximately 600 to 900ms in posterior regions that is greatest for incongruent trials, referred to as the LPC. This late positivity has been interpreted as a downstream marker of semantic integration, representing enduring effort to integrate the word with the prior context (Van Petten & Luka, 2012). Like the N400, the LPC is sensitive to both implausible words as well as unexpected action outcomes (Amoruso et al., 2013; Sitnikova et al., 2003). The LPC is rarely reported in infant studies, but it is currently unclear whether this is due to infants not eliciting LPC responses associated with deeper semantic integration or whether researchers have not yet explored such effects in infancy. However, two recent studies with older infants aged 19- to 20-months-old have reported LPC-like effects in posterior electrodes (Cantiani et al., 2017, 2021). In our adult participants, the late positive waveform aligned with previous spatiotemporal distributions of the LPC, highlighting that adults continued to analyse the mismatches between actions and verbs. In infants, we also found a significant difference in a later time window in Cz, C4, and Pz, with greater amplitudes to incongruent than congruent verbs. However, we refrain from referring to these differences an LPC given that activity in these electrodes seems to have begun diverging early in the time window (thus, unlikely to reflect re-analysis) and due to the lack of similar effects reported in other studies with a similar age range. Likely, these differences reflect continuation of infants' sensitivity to action-verb co-occurrences as actions unfolded across the trial. Future studies or re-analysis of other existing infant N400 data will be necessary to understand whether infants aged ~10 months regularly evidence LPC-like semantic integration effects to mislabelled referents.

Some previous studies have reported links between the size of infants' N400 effect and their parent-reported vocabulary. Here, we also examined links between the size of infants' ERP responses and their vocabulary. However, we found no relations with all CDI items, CDI verb items, or for verb items from the task. Though one previous infant N400 study with younger infants, aged 9 months, found links between the N400 and receptive vocabulary (Junge et al., 2012) many of these studies were with much older infants between 18 and 24 months and mostly found effects when examining productive vocabulary (Borgström et al., 2015a; Cantiani et al., 2017; Friedrich & Friederici, 2004, 2006; Helo et al., 2017; Lozano et al., 2025; Rämä et al., 2013; Sirri & Rämä, 2015). One potential explanation for our failure to detect associations is the young age of our participants. At 10 months, infants in our study had small vocabularies, understanding, on average, two words with most infants in the sample reported to say fewer than five words (typical for this age range). This limited variability in vocabulary size, in combination with a modest sample size, may have reduced statistical power to detect these effects. Additionally, because productive vocabulary sizes were small, parents may have struggled to estimate receptive vocabulary without word production as a cue. For example, López Pérez and colleagues (2025) found that parents' estimates of individual word comprehension on CDIs primarily correlated with performance on word comprehension tasks when based on productive vocabulary and found that accuracy was highest for older children. Indeed, one other study has also recently found that parents' estimation of word knowledge on CDIs is best predictive of performance in empirical language tasks when they are highly confident in their estimation (Weaver & Saffran, 2026). Given that 10-month-olds in this study were saying few or no words, it's conceivably that parents would have lower confidence in estimating vocabulary without word production to rely on. Alternatively, if infant ERP responses represent earlier action-verb associations – rather than semantic verb knowledge – any associations with vocabulary may be smaller or less reliable compared to previous infant studies. As such, the ability to detect effects between ERP magnitudes and vocabulary may have been weakened.

Future Directions and Limitations

This study is the first to test infants' verb knowledge using an action-verb pairing task to measure ERPs. However, there are aspects of our design that may have constrained concrete identification of an N400 response in infants. Primarily, our task differs from prior infant N400 studies in that activity in our analysis window captured both processing of the probe (the verb) and on-going processing of the prime (the action). Previous infant N400 studies have separated activity between prime and probe by introducing an occluder between the two (Parise & Csibra, 2012) or including long interstimulus intervals such that probe processing is likely to have faded prior to word onset (e.g., Friedrich & Friederici, 2004, 2005b). Our task was designed to help infants map verbs onto the actions while they were still recognisable, and we ensured that the degree of action-verb overlap was matched across conditions. However, due to on-going action processing, it is challenging to definitively determine whether the differences in ERP amplitudes seen in infants indeed reflect an N400 response (modified by stimulus overlap and developmental differences in semantic processing) or attentional processing that would reflect a precursor stage of verb semantic knowledge. The observed N400 effect in adults using this paradigm provides some confidence that the task is effective at producing mismatched semantic processing, however, to concretely confirm an N400-like response to action-verb mismatches in infants, future studies will need to incorporate a design in which the action and linguistic stimuli are temporally separated. For example, future work could use videos of actions that freeze at a critical moment (e.g., someone lifting a cup to drink and freezing when the cup is tipped into their mouth) for a brief period, before a verb is heard. Such a design would ensure neural activity from processing the action would dissipate before verb onset, enabling a clearer presentation of an N400-like response if it is present (e.g., Friedrich & Friederici, 2004, 2005b).

Whilst the current data provides insight into emerging verb comprehension, it cannot speak to the mechanisms that may support their acquisition. Several word learning accounts suggest that children rely on skills that begin emerging during the first year of life to start learning about verbs. For example, from 6 months, infants demonstrate sensitivity to social cues (e.g., gaze following; Senju & Csibra, 2008) to attend to the correct action or event necessary to infer the meaning of abstract words (Akhtar & Tomasello, 2000; Tomasello & Kruger, 1992). Children may also use their existing object-noun knowledge to reduce event processing demands and the number of referent hypotheses (Golinkoff & Hirsh-Pasek, 2008; Hollich et al., 2000). Such noun knowledge is thought to also aid infants' recognition of statistical regularities in sentence structure over time, that supports verb segmentation, especially for transitive verbs (Fisher et al., 2020; Naigles, 1990). Infants likely rely on domain-general associative learning mechanisms to start track verb-action co-regularities across exposures (McMurray et al., 2012; Monaghan et al., 2015; Scott & Fisher, 2012) but further research will be necessary to understand if infants employ these skills as they begin mapping verbs to actions they are exposed to during their daily life or whether additional mechanisms may be at play.

Conclusion

In the current study, we showed that at 10 months, infants are sensitive to hearing verbs that incorrectly label on-going actions, evidenced by diverging ERP responses after verb onset. We tested this using a novel action-verb pairing paradigm where infants and adults saw videos of a person completing actions which were paired with matching or mismatching verbs. In adults, we observed an N400-like response over frontal and centroparietal regions in responses to action-verb mismatches. Infants' ERP responses differentiated matching and mismatching verbs; however, this effect differed from adults in topography and directionality. Though more negative-going waveforms to mismatches were detected in frontal regions – overlapping with the adult frontal response – a reversal of effects was detected in central channels with no differences observed parietally. Though our design differed from typical picture-word priming paradigms, due to overlaps in action and verb processing, the adult N400 response demonstrates that this paradigm evokes semantic processing. We suggest that the infant findings can be interpreted as evidence of emerging verb understanding that enable infants to detect incongruity between actions and verbs, but that infants' neural response may differ from adults due to less mature action and semantic processing systems. We also consider an alternative explanation; that these findings represent emerging sensitivity to co-occurrences between actions and verbs, which may serve as a precursor to later verb understanding. Future research will be necessary to concretely confirm an infant N400 response to action-verb mismatches, and we anticipate that future adaptations of the current paradigm will directly test whether the effects observed represent semantic verb knowledge or emergent action-verb associations. Our findings suggest that 10-month-olds can detect action-verb mismatches, but the mechanisms that support their emerging verb understanding warrant further investigation.

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Scientific transparency statement

DATA: All raw and processed data supporting this research are publicly available (all personally identifying information about infants has been removed from questionnaire data): https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466, https://osf.io/sz2wm/overview?view_only=b92fcfc87fa5442ab54a981758f9a466

CODE: All analysis code supporting this research is publicly available: https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466

MATERIALS: All study materials supporting this research are publicly available: https://osf.io/sz2wm/?view_only=b92fcfc87fa5442ab54a981758f9a466

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

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