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Brain and Language 101 (2007) 246–259

Brain and Language

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Developmental changes in neural activity to familiar words and gestures

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Accepted 30 November 2006
Available online 23 January 2007

Abstract

Infants younger than 20 months of age interpret both words and symbolic gestures as object names. Later in development words and gestures take on divergent communicative functions. Here, we examined patterns of brain activity to words and gestures in typically developing infants at 18 and 26 months of age. Event-related potentials (ERPs) were recorded during a match/mismatch task. At 18 months, an N400 mismatch effect was observed for pictures preceded by both words and gestures. At 26 months the N400 effect was limited to words. The results provide the first neurobiological evidence showing developmental changes in semantic processing of gestures.

Keywords: Event-related potentials; Gestures; Semantic processing; N400

1. Introduction

Infants are highly motivated to interact with those around them. In their communicative attempts, they recruit both verbal symbols and nonverbal symbols, such as gestures, in varying proportion at different points in development. Around 12–13 months of age, infants begin to use words to refer to objects and events in their environment. These words are symbolic in the sense that they are employed in a reliable and intentional manner to refer to a category of referents. Around the time that infants acquire their first words, they also begin to produce symbolic gestures (Acredolo & Goodwyn, 1985; Blake & Dolgoy, 1993; Goodwyn & Acredolo, 1993; Volterra & Iverson, 1995; Zinober & Martlew, 1985).

Acredolo and Goodwyn (1988) reported that infants spontaneously begin to use both gestures and words in the same ways and for the same types of referents. For example, one infant may label a cup using the word "cup" while another infant may acquire a gesture for cup (e.g., the action of drinking) in the same contexts to label or request objects or actions. Early in language development, if an infant has a spoken word for an object that same child usually does not have a gesture for that object and vice versa, suggesting that gestures and words complement each other by serving similar communicative functions (Acredolo & Goodwyn, 1988). Infants also combine two gestures, or a word and a gesture to convey complex propositions in much the same way children combine two words. Acredolo and Goodwyn argue that symbolic gestures increase infants' communicative power and flexibility while reducing pressure on the motor coordination of the vocal tract. As a child's verbal lexicon increases, gestures begin to drop out of use as they are replaced by the corresponding spoken word.

The fact that words and gestures serve similar communicative functions in early language development suggests a common processing of these two symbolic forms as potential types of reference. Namy and Waxman (1998) explored developmental change in children's symbolic use of gestures experimentally by comparing 18- and 26-month-old's interpretation of novel gestures versus novel words as names for object categories. After being introduced to either a novel gesture or a novel word as a label for an object category (e.g., fruit or vehicle), the infant's mapping of the symbol

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doi:10.1016/j.bandl.2006.11.008

to the object category was tested using a forced choice task. Both verbal and gestural symbols were arbitrarily related to their referents. They found that infants at 18 months mapped both novel gestures and novel words to object categories. However, there was also evidence of a change in children's interpretation of gestures over development. The 26-month-olds readily mapped novel *words* to object categories but failed to map *gestures* to object categories. Follow-up analyses confirmed that 26-month-old's failure to map gestures to objects was not a result of inattention to gestures because children at this age frequently spontaneously re-produced the gestures employed, but failed to interpret them as referring to the objects (Namy & Waxman, 2002). Subsequent studies revealed that 26-month-olds can learn symbolic gestures but only do so following explicit encouragement to produce the gesture or when the gesture is iconically related to the referent (Namy & Waxman, 1998; Namy, Campbell, & Tomasello, 2004).

Based on this developmental shift in both observational and experimental studies, Namy and Waxman posited that with experience, infants acquire a priority for words as the predominant form of symbolic reference, reflecting the communicative conventions they observe in the input. Indeed, infants show a gradual change in the use of gestural communication as they gain experience with language, with words replacing symbolic gestures over time (Acredolo & Goodwyn, 1988; Bates & Dick, 2002; Bretherton et al., 1981; Iverson, Capirci, & Caselli, 1994; Namy et al., 2004; Namy & Waxman, 1998, 2002). When referring to an object, infants at older ages show a decrease in the use of representational gestures and an increase in deictic gestures (such as pointing) paired with a word (Iverson et al., 1994). Thus, gestures take on distinct but supplementary roles in communication as children's communication becomes more conventional and adult-like.

A more recent study by Namy et al. (2004) reported that the developmental change in children's interpretation of novel arbitrary gestures actually follows a U-shaped function. Using a similar paradigm as Namy and Waxman (1998), they replicated the finding that 18-month-olds readily mapped novel arbitrary gestures to object names whereas 26-month-olds did not. However, Namy et al. went on to demonstrate that four-year-old children, like 18-month-olds, readily mapped arbitrary gestures to object categories. This U-shaped developmental function in children's receptivity to symbolic gestures suggests that children undergo an intermediate period of relative rigidity in their expectations about how symbolic forms signal reference during the second year, with older children more readily able to apprehend the communicative intent behind non-conventional forms of symbolic reference. Namy and colleagues (Namy & Waxman, 1998, 2002; Namy et al., 2004) have interpreted this developmental trajectory as reflecting a relative ignorance of communicative conventions of words and gesture at 18 months that gives rise to a period of relative inflexibility at 26 months, as children become aware of the distinct communicative functions of words and gestures, followed by a more mature ability to understand communicative conventions while accommodating violations to these conventions in older children.

Thus, experimental and observational evidence suggests shared cognitive processing of words and gestures at the onset of symbolic development, and in older children (and, presumably, adults), with an intermediate developmental period of relative unwillingness to interpret gestures as symbols. That is, the evidence supports a link between verbal and gestural processing both early and later in development, but the U-shaped function suggests that the relation between words and gestures may differ earlier versus later in development. However, behavioral measures alone cannot allow us to make a direct connection between the underlying neural systems mediating gesture and word processing across development. Common performance in word-learning and gesture-learning tasks may imply that there is shared ability to process words and gestures semantically. However, there may also be independent neural systems that serve related communicative functions with distinct underlying cognitive mechanisms.

Bates and Dick (2002) have argued from behavioral and neuropsychological evidence that gestures and spoken language are linked and processed by similar domain-general neural systems. They point to three bodies of literature that illustrate this claim. First, gesture learning and word learning show similar developmental trajectories. Second, deficits in gesture comprehension and production in patients with aphasia tend to be restricted to left hemisphere damage and to correlate with some language deficits, such as naming deficits (e.g., Bates, Bretherton, Shore, & McNew, 1983). Third, comprehension and production of meaningful gestural actions activate language areas, such as Broca's area (e.g., Buccino et al., 2001). In a complementary set of points, Kelly and colleagues (Kelly et al., 2002) argue that gesture played a role in the evolution of formal language (see also Arbib, 2005; Rizzolatti & Arbib, 1998), that nonverbal actions including gestures lay the groundwork for and facilitate the development of language production in children, and that nonverbal actions continue to play an important role in language processing in adults.

To address the issue of shared vs. distinct neural systems for words and gestures during early vocabulary acquisition, the present study employed event-related potentials (ERPs) to directly compare patterns of brain activity linked to processing meaning for words and gestures in 18- and 26-month-old infants. The ERP technique provides a safe, non-invasive, and practical tool for investigating the organization of neural activity in both infants and adults. ERPs are averages of epochs of neural activity time-locked to a particular event. They are characterized by fluctuations in positive and negative voltage called components. The latency, amplitude, and distribution of ERP components reflect information about the timing, amount, and to some extent physiological source of the associated brain activity (Rugg & Coles, 1995). ERPs that differ in distribution across the scalp are thought to index different cognitive processes mediated by nonidentical neural systems. In the present study, we are particularly interested in whether the distribution of ERPs linked to processing meaning is the same for words and gestures, and the extent to which that pattern changes with development. If children show developmental changes in the way they use words and gestures, as suggested by the behavioral literature, different developmental trajectories should be observed in patterns of brain activity linked to processing words and gestures.

The ERP technique has been successfully used to study changes in language-relevant brain activity during early word learning. ERP studies of vocabulary development have shown marked developmental changes in the lateral distribution of brain activity to known vs. unknown words in typically developing infants between 13 and 20 months of age (Mills, Coffey-Corina, & Neville, 1993, 1997; Mills & Neville, 1997; Mills et al., 2004). Mills and colleagues found that at both age groups, known words elicited more neural activity than unknown words from 200 to 400 ms after word onset. At 13–17 months the distribution of this effect was broadly distributed over anterior and posterior regions of both the left and right hemispheres. In contrast, at 20 months, ERP differences to known vs. unknown words were limited to temporal and parietal regions of the left hemisphere. The results were interpreted as showing changes in cerebral specialization linked to vocabulary size rather than chronological age. Of particular interest here is whether different developmental trajectories will be observed in patterns of brain activity linked to processing words and gestures, as predicted by the behavioral literature showing changes in the way children use words and gestures between 18 and 26 months.

Although no evidence to date has explored gesture processing in children using ERPs, two recent studies investigated semantic processing of gestures by adults (Kelly, Kravitz, & Hopkins, 2004; Wu & Coulson, 2005). Both studies used a match/mismatch paradigm eliciting a negative going component peaking at 400 ms, called the N400. The N400 indexes semantic integration, and the amplitude of the N400 varies as a function of congruency within a semantic context. Typically the N400 is reduced in amplitude when a meaningful stimulus (usually a picture or a word) is congruent with the preceding semantic context, and is larger to a stimulus that is incongruent with the preceding context. The amplitude difference between the N400 to the incongruent stimulus minus the congruent stimulus is called the N400 congruency effect. Recently the N400 congruency effect has been demonstrated using a picture/word match/mismatch paradigm in infants as young as 13 months of age (Friedrich & Friederici, 2005; Mills, Conboy, & Paton, 2005).

The adult gesture studies reported an N400-like effect for gesture processing; however neither study directly compared semantic processing of words and gestures. Of course, a direct comparison of ERPs to words vs. gestures would yield marked differences in ERP distribution due to sensory modality differences in the physical characteristics of the stimuli. To address this issue we designed a priming task in which a symbol (a video clip of a person saying a word or producing a gesture) was followed by a picture that either matched or did not match the preceding video. ERPs to the pictures were then compared across conditions to assess semantic integration with the preceding context. That is, we used ERPs elicited by physically identical stimuli to examine brain activity linked to processing meaning for both gestures and words.

In a preliminary study (Sheehan, Mills, & Namy, 2006), we examined ERPs to words and gestures using this paradigm with adults. In the adult study, participants saw a video clip of an actor either speaking a word or producing an iconic gesture (such as holding a phone to the ear). A matched or mismatched photograph of a real object followed the video clip. The adults showed an N400 effect to mismatched pictures preceded by both words and gestures. This N400 effect was broadly distributed across the scalp and did not reliably differ in distribution across the two symbol types. Based on our adult data, and previous cross-modal studies with infants, we hypothesized that infants may also show an N400 effect to pictures preceded by gestures. Of particular interest was whether the N400 effect in response to gestures and words would show different developmental trajectories between 18 and 26 months reflecting developmental changes in gesture use observed in the behavioral literature.

The present study investigated this change by examining neural processing using ERPs with the intent of answering the following questions:

1. Will infants show an N400 effect for pictures preceded by gestures?
2. Is the latency, amplitude, and distribution of the N400 effect the same for processing meaning conveyed by words and gestures at a given point in development?
3. Does the relation between the N400 congruency effects for gestures and words change over development?

Evidence that symbolic gestures and words are processed by distinct neural systems would be demonstrated by an ERP congruency effect that differs in polarity and/or distribution for pictures preceded by gestures vs. words. Differences in the latencies and amplitudes of ERP effects would indicate differences in the timing and magnitude of the neural response, but not necessarily evidence for distinct brain systems. Based on the behavioral literature showing developmental changes in gesture use, we predicted that 18-month-olds would show an N400 congruency effect for both words and gestures. However, 26-month-olds may be more conservative in their expectations and fail to generate semantic expectancies based on gestures in the same way as 18-month-olds. If so, they may show patterns of brain activity distributed differently across the two symbol types. This would indicate differential processing of the two symbols and lend support to developmental changes documented by prior behavioral research.

2. Method

2.1. Participants

Seventeen 18-month-olds ($M = 18.61$ months, Range = 17.9–19.2 months, 7 males, 10 females) and seventeen 26-month-olds ($M = 26.49$ months, Range = 25.8–27.1 months, 10 males, 7 females) participated in this study. Infants were selected based on having no prior formal training with gestures or exposure to sign language, no history of neurological or language disorders, and exposure to English only according to parental report. Infants trained to use gestures may have presented bias in the sample and misrepresented gesture-use in the typical family; this restriction was set so that only infants with typical exposure to gestures would be included. Parents gave their informed consent. Infants were recruited through a mailing sent out by the Department of Psychology at Emory University and through visits to new mothers at a local hospital. All infants were healthy and full-term. Seventeen additional infants were tested but not included in the final analysis as a result of non-compliance during language assessment or ERP testing (10), or an insufficient sum of artifact-free trials (7). Eleven of these participants were 18-month-olds and six were 26-month-olds. Participants received $6 per hour of participation and a toy worth approximately $5. Prior to beginning, this study was approved by Emory University's Institutional Review Board.

2.2. Stimuli

Twenty-two objects were initially selected because both gestures and words are often associated with these objects. Based on a norming study by Fenson et al. (1994a), the verbal labels for these items are comprehended by an average of 70% of 16-month-olds (Fenson et al., 1994a). No object was included on the stimulus list that had lower than 50% comprehension by 16-month-olds. Comprehension norms are not available for gestures in that study. Of the 22 items, 10 were selected for use in the testing procedure for each child based on familiarity. As a result, the set of 10 stimuli employed differed slightly among infants. Whenever possible a standard list of 10 items was used that included bird, book, brush, car, cat, cup, dog, hat, keys, and phone. The verbal labels for the items on this standard list are comprehended by a mean of 81% of 16-month-olds according to Fenson et al. (1994a) gestural *production* for those items on the standard list for which norming data are available (all except bird, cat, and dog) is at a mean level of 91% of 16-month-olds. Alternative items were substituted for objects that did not reach the inclusion criteria, including alligator, bottle, bunny, duck, elephant, fish, flower, hammer, monkey, spider, spoon, and toothbrush. See the appendix for a list and description of the gestures that parents were asked to rate.

Stringent inclusion criteria were employed to ensure that each child was familiar with both the word and gesture associated with each of the 10 objects selected. First, we administered a preliminary forced-choice assessment of children's comprehension of the word and gesture associated with each object, described below. To be included in the testing procedure for a given infant, the object must have been correctly identified by the child during the picture-pointing task when queried using both the verbal and gestural label. Second, we bolstered this comprehension test with parent ratings of their children's familiarity with the word and gesture associated with each object. Only those objects for which children correctly identified both the word and the gesture and for which parents gave both the word and the gesture a rating of three or four on a four point scale of familiarity (described below) were utilized.

A match/mismatch task was used in this experiment with a symbol (word or gesture) followed by a picture of a 3D object. See Fig. 1 for a visual depiction of the trial presentation. On match trials, the symbol was followed by the picture represented by the symbol. For example, the gesture for cup (the action of holding a cup to the mouth and drinking) was followed by a picture of a cup. On mismatched trials, the symbol was followed by an object that was not represented by the symbol. For example, the gesture for cup was followed by a picture of a book. Digital still photographs were taken of prototypical instances of all objects using the same blue background and lighting. The words and gestures were both presented via video. Each video showed the same female model from the waist up against a blue background. For each object, the model was recorded speaking the object's familiar basic level object name (e.g., "key!"). The words were spoken with the hands clasped at the model's waist. For each object, the model was also recorded producing an empty-handed gesture demonstrating a canonical action typically performed by or with the object (e.g., pretending to grasp a key and turn it in a lock). The gestures were produced at chest level, except in the cases of the brush, hat, phone and toothbrush gestures, which were performed at the level of the head. In each gesture clip, the model's hands started in the resting position clasped at her waist, and moved into the gesture space to perform the gesture. The model had a friendly facial expression during the gesture but did not vocalize and only moved her lips for gestures requiring a

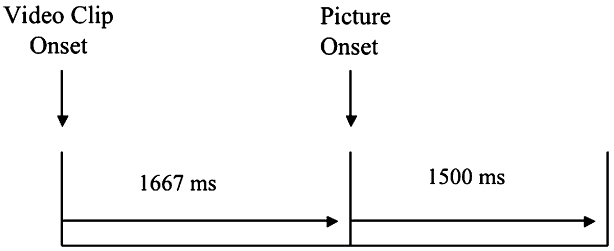

Fig. 1. Time course of trial presentation. A video clip (either a word or gesture) was presented followed by a picture of an object.

facial movement (i.e., fish, monkey, dog, cup). The length of the video clips was equated across all objects and the two modalities to 1667 ms in length. The gesture or word in each clip began immediately after the onset of the video and ranged in length from 734–1500 ms. After producing the word or gesture, the model stood in a neutral position with her hands clasped at her waist. The time between the offset of the word or gesture and the end of the video clip did not differ across the modalities. Additionally the precise duration of the words ($M = 1185.84$, $SD = 167.22$) and gestures ($M = 1201.78$, $SD = 186.27$) did not differ.

2.3. Procedure

2.3.1. Session 1: Infant language and gesture assessment

Within one week prior to participation in the electrophysiological session each infant visited the lab for a language and gesture assessment. This assessment determined which stimuli would be employed during the subsequent ERP session and ascertained the infant's level of language development. Three measures were collected for each infant.

MacArthur-Bates Communicative Development Inventory. Parents were asked to complete the MacArthur-Bates Communicative Development Inventory: Toddler Form (MacArthur-Bates CDI; Fenson et al., 1994b). The MacArthur-Bates CDI is a parental report form designed to assess the verbal production of the infant relative to other infants of the same age. For a summary of the results, see Table 1. This form was only used to assess verbal production and does not include an assessment of gesture production. The picture pointing task and parental rating scale (below) were used to assess gesture comprehension and production. Data from one infant were not included because her form was not returned.

Picture-pointing Task. Each child participated in a forced-choice task. In the task they were presented with two pictures and asked to choose one. Children saw each of the pictures twice, once to test verbal label comprehension and once to test gesture comprehension. The experimenter used wording such as "Point to (fill in gesture or word)" or "Show me (fill in gesture or word)". This visit also acclimated the infant to the lab setting and the people involved in testing on the subsequent visit. The pictures were randomly paired and the same distractor was used in both presentations of each object. Children were positively reinforced with clapping and praise for correct answers. If a child gave an incorrect answer the experimenter moved on to the next set of picture pairs without providing feedback. For an object to be included in the ERP session, the child had to correctly identify the referent of both the verbal label and the gestural label in this picture-pointing task.

Parental rating scale. Caregivers were asked to rate their infant's familiarity with the list of words and gestures from which the stimuli used in the ERP session would be drawn. They rated each on a 1-to-4 scale, with 1 indicating that they were absolutely certain the child did not comprehend or produce the word or gesture and a 4 indicating that they were certain that the child comprehended or produced the word or gesture for a variety of different exemplars in a variety of different contexts. Comprehension and production were rated separately. For the words and gestures used in the task, parental ratings for comprehension and production are listed in Table 1.

Table 1
Summary of language assessment measures

	18 m	26 m
MacArthur-Bates Communicative Development Inventory–Toddler Form		
Word production		
Mean # of words (SD)	52.69 (38.59)	378.18 (148.61)
Range	19–142	118–655
Mean percentile rank	Approx. 30–35	Approx. 40–45
Mean parental rating scale from 1 to 4 (SD)		
Comprehension		
Words	3.66 (.31)	3.92 (.11)
Gestures	3.48 (.41)	3.51 (.33)
Production		
Words	2.57 (.88)	3.78 (.28)
Gestures	2.65 (.73)	2.58 (1.04)

In summary, to insure that both the gestures and words were comprehended, *each child viewed a custom list of ten stimuli for which the child had correctly identified both the gesture and verbal label in the picture-pointing task*, in addition to having parental ratings of 3's or 4's for these gestures and words (Table 1).

2.3.2. Session 2: Event-related potential recording

Electrode placement. The electroencephalogram (EEG) was recorded continuously from tin electrodes at 19 channels affixed to an electrode cap, with two individual electrodes placed on the mastoids, and one electrooculogram (EOG) channel. The channels located on the cap were at 15 of the standard 10/20 locations including FP1/FP2, F3/F4, F7/F8, T5/T6, O1/O2, Fz, Cz, Pz, A1/A2, and non-standard locations including: L22/R22 (1/2 distance between F7/F8 and T3/T4), L41/R41 (2/3 distance from C3/C4 to T3/T4, i.e. closer to T3/T4), WL/WR (1/2 the distance between P3/P4 to T3/T4). See Fig. 2 for a visual display of the electrode site locations on the electrode cap. One electrode was placed to record EOG under the left eye to monitor vertical eye movement and blinks. EEG recordings were taken from the 22 sites and were referenced online to A2. The electrodes were mathematically re-referenced offline to an average of A1 and A2. The EEG was digitized at 250 Hz with a band-pass filter from 0.1 to 100 Hz. All impedances were maintained at or below 10 kΩ. For data analysis, electrode locations were divided into five regions from the front to the back of the head for the lateral sites: frontocentral (F3/F4), frontolateral (F7/F8), anterior-temporal (L22/R22), temporal (L41/R41), and parietal (WL/WR). Measurements were taken

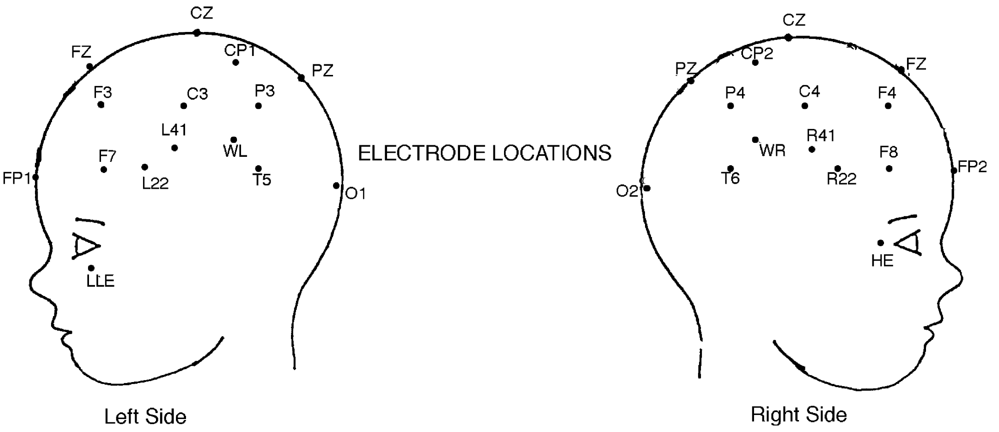

Fig. 2. Placement of electrodes in a modified International 10–20 Array. Results are reported for F3/F4, F7/F8, L22/R22, L41/R41, WL/WR.

for each electrode individually, but were analyzed together when examining distribution over the scalp across laterality. Electrode sites were selected for purposes of data reduction based on prior findings and visual inspection of the ERPs. The central sites (Fz, Cz, Pz) were analyzed separately but are not presented here to conserve space. The N400 congruency effect was observed at the central sites and was consistent with the pattern of results reported for the lateral sites.

Electrophysiological testing. After the electrode cap placement, the participant was tested in a sound attenuated booth. The stimuli were presented on a computer monitor that was located 37 in. directly in front of the participant. To ensure the infant attended to the stimulus, an experimenter sat in the testing booth and pressed a button to start each trial when the infant was oriented to the screen. An orienting stimulus was played between trials to engage the infant's attention. Each of the 10 pictures was shown a total of 12 times:3 times preceded by a video clip of a matching word, 3 times preceded by a mismatching word, 3 times preceded by a matching gesture, and 3 times preceded by a mismatching gesture for a total of 120 trials. The trial presentation was divided into 4 blocks of 30 trials, two of which included exclusively word trials and two of which included exclusively gesture trials. The 4 blocks were presented in alternating order and counterbalanced across participants.

Averaging and artifact rejection. Averaging and artifact rejection were completed offline using Event-related Potential Software System (ERPSS), a custom data analysis tool. Artifact rejection thresholds were determined for each individual after inspection of that individual's trials to reduce artifact that may be due to eye movements, blinking, or other artifact in the data from muscle movements. Individuals were not included in the analysis if they had fewer than 10 trials per condition. The mean number of trials included per condition was 18.69. See Table 2 for the mean number of trials included for each trial type in each age group. The number of artifact-free trials did not differ between matching and mismatching trials within either word or gesture trial types, or between the age groups, nor was there a trial type by age interaction. However, the word trial types ($M = 20.00$, $SD = 4.80$) yielded more artifact-free trials than the gesture trials ($M = 17.43$, $SD = 5.42$): $t(33) = 4.313$, $p<.05$.

Table 2
Average number of artifact-free trials included in the analysis

Trial type	18 months	26 months
Picture preceded by word		
Match	21.41 (4.50)	18.94 (5.51)
Mismatch	19.88 (4.51)	19.59 (5.44)
Picture preceded by gesture		
Match	17.29 (5.96)	17.53 (5.57)
Mismatch	17.29 (6.00)	17.59 (5.41)

Measurement of ERP components. All measurements in the analysis were calculated relative to 100 ms prestimulus onset. Because infant's ERP response to gestures had not been reported before, it was not known when a N400 congruency effect may start for this type of stimulus. Therefore a mean amplitude measure was taken using consecutive 100 ms windows (0–100 ms, 100–200 ms, 200–300 ms, etc.) to ascertain when a significant difference between the match and mismatch trials was observed. Once the onset and offset of the match/mismatch effect was determined, the analysis was conducted on the entire window.

Based on this analysis, the time windows used for analysis were from 200–400 ms and 400–600 ms. Of particular interest was whether both words and gestures would elicit a semantic expectancy and if so, whether the distribution of the congruency effect would be the same for both modalities. Therefore, planned comparisons for the congruency N400 effect to words and gestures were conducted separately for each age group. Each symbol type (pictures preceded by a word and pictures preceded by a gesture) was examined for evidence of a congruency effect. In addition, the amplitude of this effect and the distribution of the effect were analyzed. Repeated measures analysis of variance was conducted using the Huynh–Feldt correction for repeated measures. Effect sizes are reported using partial eta squared (η^2_ρ). Analysis of difference waves, using repeated measures analysis of variance, was conducted to compare the distribution of the congruency effect across the two symbol types.

3. Results

3.1. 18-Month-olds

3.1.1. 200–400 ms

In this early time window, planned comparisons indicated that a significant congruency effect was evident for both pictures preceded by a word, $F(1,16) = 8.950$, $p = .01$, $\eta^2_\rho = 0.36$ and pictures preceded by a gesture, $F(1,16) = 7.732$, $p = .01$, $\eta^2_\rho = 0.33$. See Fig. 3 for a bar graph of the mean amplitude measurements for the matched and mismatched trials for both symbol types.

To examine differences in distribution of the congruency effect, difference waves were analyzed. Difference waves were calculated by subtracting the response to the matched trials from the response to the mismatched trials at each electrode site. This analysis indicated that the magnitude of the congruency effect was larger for pictures preceded by a gesture than pictures preceded by a word in this time window, main effect of Symbol Type: $F(1,16) = 16.197$, $p = .01$, $\eta^2_\rho = 0.50$. Neither symbol type interacted with electrode site or hemisphere indicating that the effect was broadly distributed across the scalp. See Fig. 4 for a visual display of the ERP responses to pictures preceded by a word and pictures preceded by a gesture.

The ERPs for pictures preceded by a gesture (across match and mismatch trials) also tended to be more negative overall than the ERPs for pictures preceded by a word for all electrode sites excluding the parietal sites, Symbol Type x Electrode Site, $F(4,64) = 2.430$, $p = .08$, $\eta^2_\rho = 0.13$. Although the distribution of the effect was variable across individual infants, 14 participants showed the congruency effect for pictures preceded by words in this time window and 16 showed the congruency effect for pictures preceded by gestures.

3.1.2. 400–600 ms

In this later window, the congruency effect was significant for pictures preceded by a word, $F(1,16) = 11.662$, $p = .01$, $\eta^2_\rho = 0.42$, and pictures preceded by a gesture, $F(1,16) = 8.517$, $p = .01$, $\eta^2_\rho = 0.35$. Neither symbol type interacted with electrode site or hemisphere indicating that the effect was broadly distributed across the scalp. See Fig. 5 for a bar graph of the matched and mismatched trials for both symbol types. Analysis of difference waves indicated that the magnitude of the congruency effect was larger for pictures preceded by a word than pictures preceded by a gesture in this time window, main effect of Symbol Type: $F(1,16) = 22.476$, $p = .01$, $\eta^2_\rho = 0.58$. Although the distribution of the effect was variable across individual infants, 16 participants showed the congruency effect for pictures preceded by words in this time window and 15 showed the congruency effect for pictures preceded by gestures.

3.1.3. Summary

For 18-month-olds, the congruency effect was apparent from 200–400 and 400–600 ms for both pictures preceded by words and pictures preceded by gestures. This effect was larger for pictures preceded by gestures at 200–

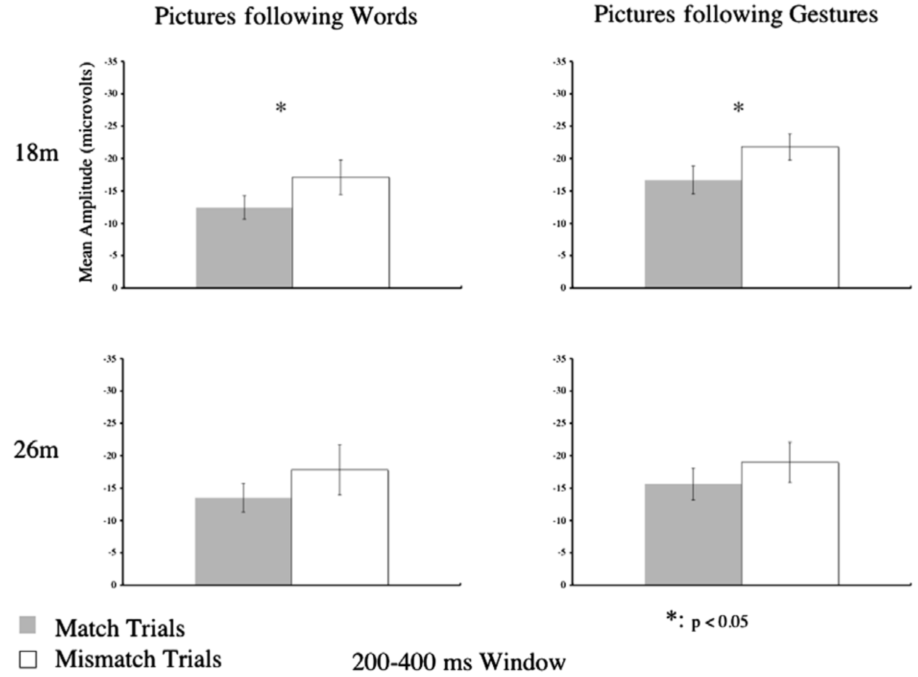

Fig. 3. N200–400 mean amplitudes to pictures preceded by words and pictures preceded by gestures for both age groups.

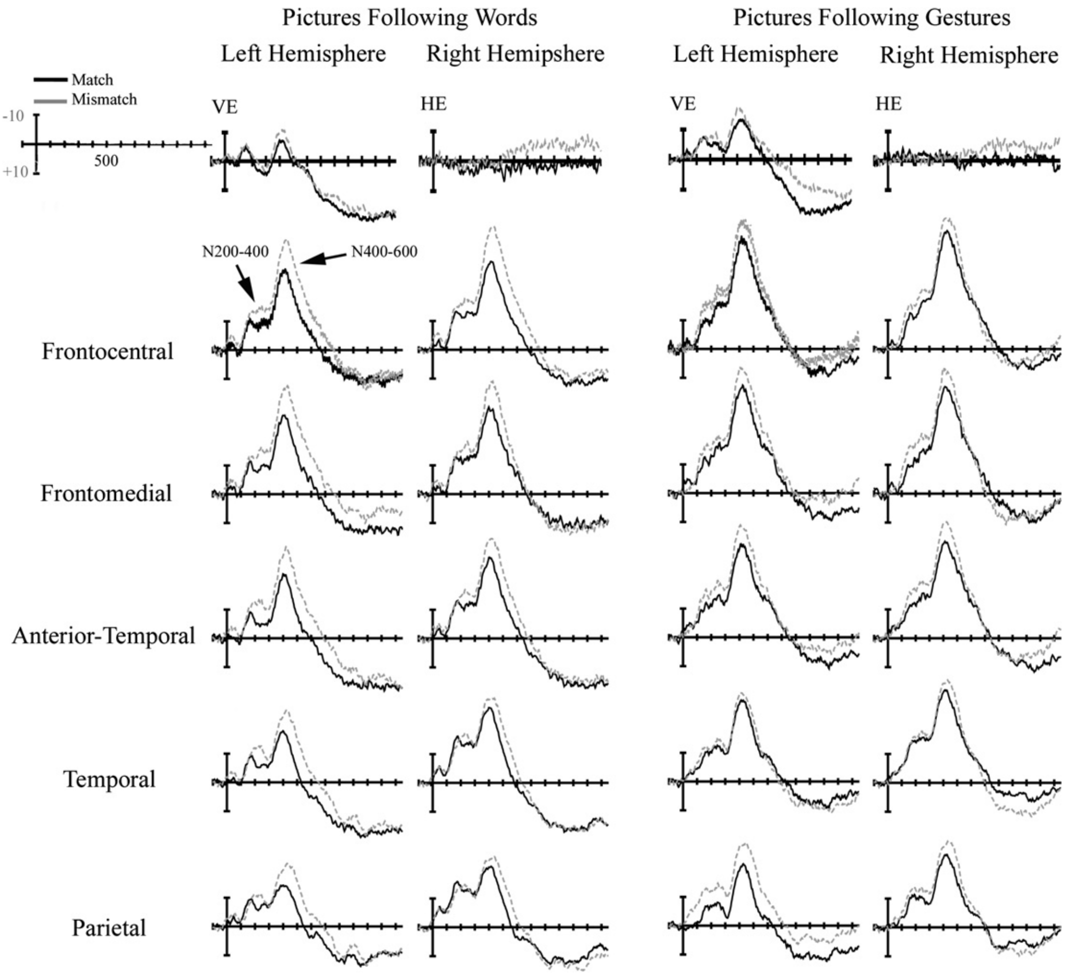

Fig. 4. Eighteen-month-old's ERPs to pictures preceded by words and pictures preceded by gestures for match and mismatch trials. Note that for this and all subsequent figures negative voltage is plotted up.

400 ms but larger for pictures preceded by words at 400–600 ms. The congruency effect was broadly distributed across the scalp for both symbol types. The majority of individual infants displayed the congruency effect for both symbol types during both time windows.

3.2. 26-Month-olds

3.2.1. 200–400 ms

Planned comparisons showed that for words but not gestures the N200–400 tended to be larger to the mismatch trials than the match trials over anterior temporal and temporal sites, Condition × Electrode Site, $F(4,64) = 2.544$, $p = .06$, $\eta_\rho^2 = 0.14$. Eleven participants showed the congruency effect for pictures preceded by words in this time window and only five showed the congruency effect for pictures preceded by gestures; however the distribution of the effect was variable. See Fig. 3 for a bar graph of the matched and mismatched trials for both symbol types.

3.2.2. 400–600 ms

Planned comparison analyses revealed that the N400–600 congruency effect was not significant for pictures preceded by a gesture, $F(1,16) = 1.25$, $p = .28$, $\eta_\rho^2 = 0.07$. For pictures preceded by a word, the congruency effect was significant over specific sites, Condition × Electrode Site, $F(4,64) = 3.251$, $p = .02$, $\eta_\rho^2 = 0.17$. These included anterior temporal, temporal, and parietal sites. See Fig. 5 for a bar graph of the matched and mismatched trials for both symbol types. The difference waves analysis indicated that the magnitude of the congruency effect was larger for pictures preceded by a word than pictures preceded by a gesture, main effect of Symbol Type, $F(1,16) = 5.082$, $p = .04$, $\eta_\rho^2 = 0.24$. See Fig. 6 for a visual display of the ERP responses to pictures preceded by a word and pictures preceded by a gesture. Although the distribution of the effect was variable across individual infants, 15 participants showed the congruency effect for pictures preceded by words in this time window whereas only six showed the congruency effect for pictures preceded by gestures.

3.2.3. Summary

For 26-month-olds, the congruency effect was limited to pictures preceded by words over anterior temporal, temporal, and parietal sites from 200–400 and 400–600 ms. There was no evidence of a congruency effect for pictures preced-

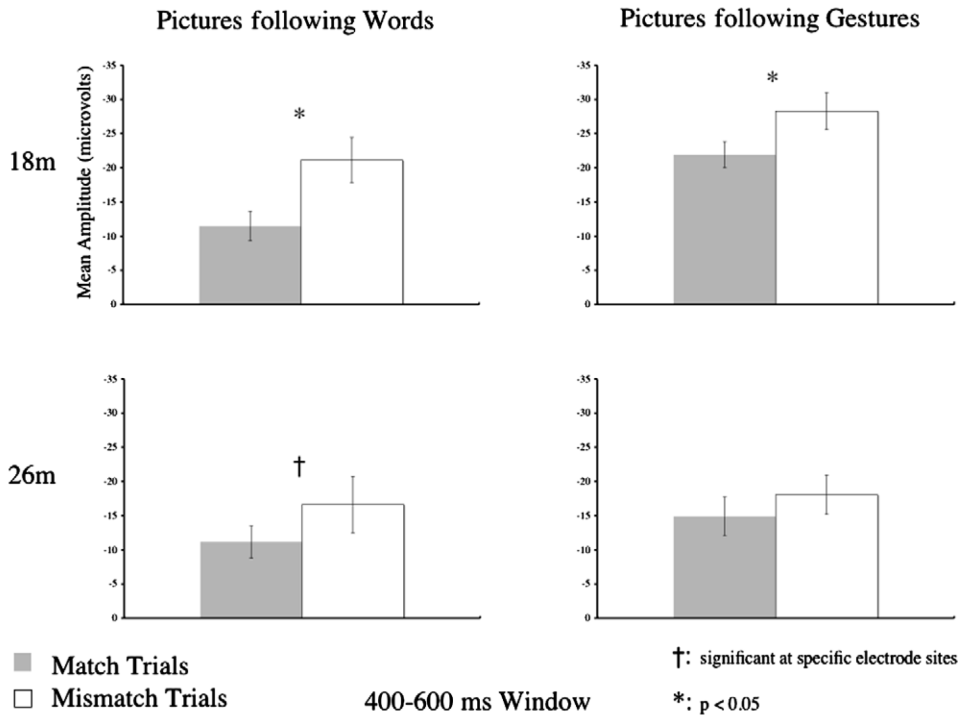

Fig. 5. N400–600 mean amplitudes to pictures preceded by words and pictures preceded by gestures for both age groups.

ed by gestures at this age in either time window. The majority of individual infants displayed the congruency effect for words in both time windows, however few did so for gestures in either time window.

4. Discussion

The present study investigated developmental changes in patterns of brain activity linked to meaning conveyed by gestures and words from 18 to 26 months. To this end, we examined the N400 congruency effect to pictures that matched or did not match a preceding word or gesture. In both adults and children, the amplitude of the N400 appears to reflect the amount of processing required to integrate the target stimulus with the preceding context. That is, a larger N400 effect reflects more effortful processing. In this study, we used this measure of semantic integration to gauge whether words and gestures elicit different patterns of semantic activation. Based on prior research, we expected words to elicit a semantic expectancy that could be violated by a picture that did not match, thereby eliciting an N400 effect. Of interest was whether gestures would elicit a similar pattern. Alternatively, if words have a special status to convey meaning, gestures may not convey a similar semantic expectancy, but perhaps a simple association. If so, we expected that gestures would not elicit a similar N400 effect or could show a different pattern of brain activity such as a P300, which indexes stimulus discrimination and memory updating.

In the present study, 18-month-olds showed an N400 congruency effect from 200–400 and 400–600 ms after the onset of the pictures preceded by both gestures and words. The distribution of the effect at both time windows for both symbol types was broadly distributed over the scalp. This replicates the diffuse pattern of activation observed in previous studies of the N400 observed for words at this age (Mills et al., 2004), and extends these findings to gestures. The amplitude of the N400 reflects the amount of processing required to integrate the target stimulus with the preceding context. This suggests that at 18 months, words and gestures may elicit similar semantic expectancies leading to similar patterns of brain activity for pictures preceded by a word and pictures preceded by a gesture.

In contrast, 26-month-olds showed the N400 congruency effect only for words and only at specific electrode sites over temporal, anterior temporal and parietal areas. This pattern replicates previous findings showing increased localization of semantic processing over development (Mills et al., 2004; Mills et al., 1993, Mills, Coffey-Corina, & Neville, 1997). These results indicate that for the older age group only *words* provided a strong enough semantic context to elicit different amounts of neural activity to the matched vs. mismatched pictures. The ERP results are consistent with behavioral findings showing developmental changes in the way children process gestures in this age range. Namy and colleagues (Namy et al., 2004; Namy & Waxman, 1998) suggest that the reason children readily accept a gesture to name a novel object at 18 but not 26 months is due to children's developing appreciation of the conventional roles of words and gestures in communication. This position is supported by the ERP findings indicating that 26-month-olds show an N400 congruency effect for pictures preceded by words but not gestures.

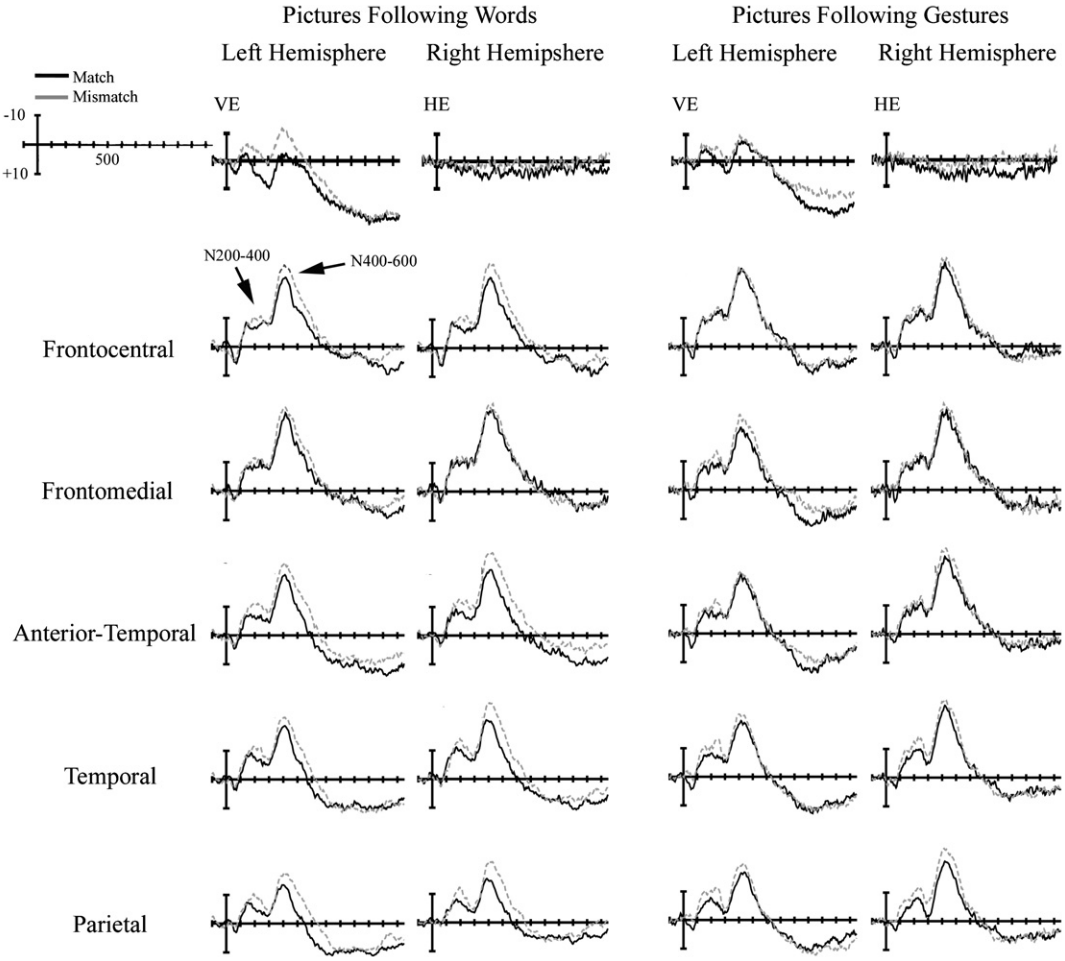

Fig. 6. Twenty-six-month-old's ERPs to pictures preceded by words and pictures preceded by gestures for match and mismatch trials.

Our data are consistent with the hypothesis that children's use of gestures takes on less of a symbolic and more of a deictic function over the course of early development (Iverson, Capirci, Longobardi, & Caselli, 1999; Masur, 1982). Altogether, these findings highlight that by two years of age, children have begun to appreciate that words and gestures serve different but complementary communicative functions. However, these results support the argument that words and non-verbal symbols such as gestures have similar symbolic and communicative status at 18 months, challenging the perspective that words play a privileged role in the communicative repertoire from the onset of word learning (cf. Balaban & Waxman, 1997; Xu, 2002).

Although we predicted that N400 effects would be less robust for gestures at 26 months than at 18 months, the lack of evidence of an N400 effect at the older age is actually somewhat surprising given that the stimuli were gestures with which children were highly familiar, as evidenced by both parental report and their performance in the forced-choice picture pointing task. Namy et al. (2004) also found that 26-month-olds readily mapped iconic (but not arbitrary) gestures to object categories. Thus, behavioral measures imply that 26-month-olds were processing these iconic, familiar gestures as object names. Why, then, did they fail to show an N400 congruency effect for the gesture-picture pairings?

One possible explanation, and one of the authors believe is the most likely, is that at 26 months the association between the gesture and the object is not as strong as the association between the word and the object. If so, we would expect that gestures would be less predictive of the matching picture, resulting in greater neural activity in the match trials. A higher amplitude N400 on the match trials could diminish the magnitude of the N400 congruency effect for gestures relative to words, if the N400 on match trials was greater for gestures than for words. A larger N400 to the matching pictures for gestures than words was, in fact, evident at both 26 and 18 months, suggesting that words provide a stronger semantic context than gestures, even in the younger group. However, only at 26 months did the N400 fail to differ in magnitude on match relative to mismatch trials. This outcome suggests that children did not have strong expectations about how gestures relate to referents at this age. Prior research has shown that nonverbal stimuli can result in greater amplitude of the N400 on matching trials. Because stimuli such as pictures provide a less specific semantic constraint than words, multiple possible interpretations are accessed (Federmeier & Kutas, 2001; Federmeier, McLennan, De Ochoa, & Kutas, 2002). Perhaps for 26-month-olds gestures, like pictures, (because they are both visual representations) elicit activation of a broader set of possible congruent alternatives, eliciting comparable attempts to integrate pictures and gestures for both match and mismatch trials. However, this account does not appear to apply at 18 months. The finding that 18-month-olds use gestures and words in the same manner suggests that gestures are creating the same specificity of semantic constraints as words at this younger age.

Alternatively, perhaps the lack of congruency effect for gestures at 26 months is a product of the relative lack of familiarity children had with the gestures. Although less familiarity with gestural symbols would certainly explain the lack of congruency effect at this age, we may rule out this interpretation on several counts. First, all children were able to match the gesture with its correct referent during the forced-choice comprehension task with 100% accuracy during the preliminary language and gesture assessment. Second, although parents rated the gestures employed as slightly less familiar than the words employed, the gestures still averaged a familiarity score of 3.51 on a 4-point scale. Finally, the familiarity ratings provided by the parents of the 26-month-olds did not differ from those provided by the parents of the 18-month-olds who did display a congruency effect for gestures. Thus there is no evidence that familiarity of the gestures was sufficiently low at 26 months to obviate the possibility of a congruency effect, if children were processing them semantically.

Another consideration is that repetition effects on N400 amplitudes may have differed for words vs. gestures. The fact that the stimulus pictures were each repeated 12 times might have led to greater semantic expectancies over time, resulting in an attenuation of the N400 for both words and gestures over time. However, the robust evidence for an N400 congruency effect for words at both ages and for both words and gestures at 18 months despite repetition suggests that repetition did not play a significant role. Because similar repetition effects are observed for both visual and auditory stimuli (Besson et al., 1992; Domalski et al., 1991; Mills, Plunkett, Prat, & Schafer, 2005), there is no reason to expect that repetition would interact with symbol modality. Additionally, the ERPs presented here are time-locked to the picture, which was presented exactly the same number of times for gesture and word stimuli. Thus, although differential effects of repetition on semantic expectancies elicited by words and gestures is possible, it is unlikely that repetition effects alone account for the age-related differences in the N400 effect for gestures at 18 and 26 months.

A fourth possible explanation of the lack of congruency effect for gestures at 26 months is a difference in motivation to generate a symbolic mapping of gesture to picture for the two age groups, resulting in the observed differences in ERP effects. We believe that we can rule out this possibility on methodological grounds. One of the greatest strengths of ERP as a tool for studying developmental populations is that it requires no overt response or motivation. Provided that the child is attending to the task, a congruency effect should be observed if children are processing gestures as semantic primes. Because (1) every trial in this experiment was preceded by an orienting stimulus, (2) the trials were initiated manually by an experimenter only after the child was oriented, and (3) trials on which children blinked or looked away were excluded, we have no reason to believe that relative lack of attention or motivation can account for these findings.

In sum, the lack of congruency effect for gestures at 26 months, taken by itself, might be accounted for by a range of interpretations. However, when taken together with the findings from 18-month-olds, the case for developmental change in the symbolic status of gestures becomes much more compelling. Neither lack of familiarity nor lack of motivation can explain why children who associated gestures with their referents during the forced-choice comprehension task with 100% accuracy would fail to display evidence of semantic priming during the ERP task. We argue that the gesture-object pairings children have learned at this age have taken on a different status from words, perhaps as conventionalized associations that are not semantic or symbolic in nature. In future research, it will be important to explore further how symbolic gestures are being processed neurally at 26 months, perhaps by comparing children's processing of symbolic gestures with their processing of other, non-symbolic gesticulation (e.g., pointing or other gestures of emphasis), for example. Additionally it will be important to identify the mechanism for recovery of gesture use after 26 months as shown by Namy and colleagues. Our ERP studies of adults (Sheehan et al., 2006), showing an N400 congruency effect for both words and gestures, suggests that older children might also show an N400 effect across both modalities. To address questions regarding the developmental trajectory of the changes in neural activity reported here, testing with additional age groups needs to be done. At four years of age, children were shown to map both arbitrary and iconic gestures like their 18-month-old counterparts (Namy et al., 2004). Based on behavioral measures, we would predict that this age group would show patterns of brain activity more similar to those we observe with adults than those we see in 26-month-olds. It would also be of interest to explore differences in ERP patterns for 26-month-olds with versus without sign training in the home. Of particular interest is whether children for whom the gestural modality continues to be a highly supported form of symbolic reference display ERP patterns more like 18-month-olds in the present study.

Future research should also include the use of arbitrary gestures to compare the relative semantic status of arbitrary versus iconic symbols within a given modality in both infants and adults. For example, participants could be trained on novel arbitrary gestures and novel words as object names prior to being tested on congruency effects using ERP. Although we would predict a less robust congruency effect overall due to the relative novelty of the symbols in both modalities, we may find a more robust effect for words than gestures in this case. This would suggest that the apparent semantic processing of gestures at 18 months in the current study may be due to familiarity with a gesture or frequency of exposure to the pairing of a gesture with a particular object as opposed to a symbolic interpretation of the gesture. This manipulation would also allow us to investigate the impact of experience with a symbolic modality in general as opposed to experience with specific instances of gestures and words. Previous research on developmental change in the distribution of brain activity related to semantic processing indicates that greater localization of neural activity is linked to vocabulary size rather than age *per se*. Future studies examining 18- to 20-month-old children who vary in vocabulary size to a greater extent than the sample tested here would address the issue of similar developmental shifts in lateral organization linked to vocabulary size for gesture and word processing.

The fact that the same effects were observed in both the 200–400 and 400–600 ms time windows for pictures preceded by both words and gestures at 18 months also has important implications for our understanding of the timing and interpretation of N400 effects. In the adult literature, although the typical time window to measure the N400 is between 300–500 ms, the onset of ERP differences to the matched vs. mismatched conditions is frequently observed as early as 200 ms. The interpretation of the functional significance of the congruency effect from 200–400 ms is not without controversy. Picture–picture priming studies suggested that the congruency effect in the early time window is specific to picture processing and has a more anterior distribution than the later window (McPherson & Holcomb, 1999). However, a study comparing picture–word vs. word–picture priming found a similar onset latency for the mismatch effect in both conditions, (Pratarelli, 1994). Time course analyses of phonological and semantic processing places word recognition during comprehension within this time window (Rodriguez-Fornells, Schmitt, Kutas, & Munte, 2002). Mills and colleagues argue that the amplitude of the N200–400 is modulated by comprehension of individual word meanings in children as young as 13 months of age (Conboy & Mills, 2006; Mills et al., 1997, 2004). In contrast, Connolly and colleagues (Connolly & Phillips, 1994; D'Arcy, Connolly, Service, Hawco, & Houlihan, 2004) argue that the negative component preceding the N400, peaking around 270 ms, is sensitive to phonological expectancies independent of word meaning. The phonological mismatch negativity, PMN, has been elicited in both auditory sentence and cross-modal picture–word paradigms. The PMN displays a different distribution from the N400 and has been localized to different brain regions (D'Arcy et al., 2004). Although the amplitude of the N200–400 can be modulated by phonological expectancies in specific paradigms, the presence of this component for both verbal and non-verbal primes (for which there can be no phonological explanation) provides further support to Mills and colleague's position that the N200-400 in infants may also be modulated by word meaning rather than phonology (see Mills et al., 2004).

Alternatively, this early component of the congruency effect may be an N300. The N300 has been related to semantic processing of visual stimuli such as pictures, and peaks around 300 ms (Barrett & Rugg, 1990; Hamm, Johnson, & Kirk, 2002; Holcomb & McPherson, 1994; McPherson & Holcomb, 1999; West & Holcomb, 2002). To date however, this component has not been studied developmentally and has only been reported for adults. Although also sensitive to congruency, this component is more frontally distributed in contrast to the broadly distributed N400. The broad distribution observed in our data in both the 200–400 and 400–600 ms time windows is more consistent with the N400. This component has been elicited in paradigms using auditory words leading us to believe that it is not in the N300 family. However, it is important to consider ERP components developmentally and it is possible that the component we consider the N400 may develop into two separate components (the N300 and the N400) as infants and children become more specialized in semantic processing.

5. Conclusions

The current ERP findings substantiate and expand upon earlier behavioral findings showing that words and gestures are equipotential forms of symbolic reference early in development but diverge with development. The observed N400 congruency effect for pictures preceded by both words and gestures at 18 months provides the first neurobiological evidence that at the point in development when infants use words and gestures in the same way, processing of words and gestures activate shared neural systems. That is, the similar congruency effects for pictures preceded by both words and gestures supports the argument that common mechanisms underlie the mapping process for these two symbolic media early on but shift over the course of the second year. When children no longer use gestures primarily as referential labels, patterns of brain activity to words and gestures also diverge. By 26 months of age, children show an N400 congruency effect only to words despite their ability to comprehend the gestures employed in the task. We interpret these results as reflecting the changing roles gestures serve in communication as children become more familiar with the conventions of their language. More generally, the use of ERPs provides a unique window into the organization of brain activity that informs the relations between language and gesture. These findings suggest an important neural link between words and gestures and highlight the importance of mapping how this link shifts over the course of development.

Appendix

Description of gestures

Hat: Motion of putting a hat on your head

Cat: Motion of petting a cat with your right hand while holding it in your left arm

Car: While holding a toy car in your hand, run it across the table

Telephone: Using your hand as a phone and holding it to your ear

Dog: Hold two hands at chest level like paws and make a face that looks like panting (tongue out)

Brush: Motion of brushing hair

Bird: Arms flapping like wings

Cup: Form your hand as you would when you hold a cup and lift to your mouth like taking a drink

Book: Open and close your hands like a book while looking down at them like you are reading

Key: Motion like unlocking the door

Alligator: Hold arms straight out and clap them together like the mouth of an alligator

Bottle: Form hand in fist with thumb out, and drink from it like a bottle with your thumb as the top

Duck: Open and close one hand like the beak of a duck

Bunny: Hold up two fingers on your hand (with the rest forming a fist) like bunny ears and make a hopping motion

Flower: Put your hand in front of you like you are holding a flower, then make a sniffing motion

Spoon: Make a motion like you are eating from a spoon

Hammer: Make a fist like you are holding a hammer, then motion as if you are hammering a nail in

Spider: From the "Itsy Bitsy Spider" song; hold your hands in front of you with your finger forming an "L" shape, then put them together so that your right pointer finger touches your left thumb and your left pointer finger touches your right thumb – forming a diamond. Keep the top of the diamond the same and rotate the bottom fingers around to join at the top, and repeat.

Monkey: Make a face like a monkey (with your lips in a "O" shape) and bend your arms while opening and closing your hands just beneath your shoulders

Elephant: Use one arm as a "trunk" and lift it as an elephant would

Fish: Purse your lips and make an opening and closing motion, with or without using your hands as fins by your face

Keyboard: Motion as if typing on a keyboard

Toothbrush: Brush your teeth using your finger as a toothbrush.

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