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Successful Word Recognition by 10-Month-Olds Given Continuous Speech Both at Initial Exposure and Test

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Most words that infants hear occur within fluent speech. To compile a vocabulary, infants therefore need to segment words from speech contexts. This study is the first to investigate whether infants (here: 10-month-olds) can recognize words when both initial exposure and test presentation are in continuous speech. Electrophysiological evidence attests that this indeed occurs: An increased extended negativity (word recognition effect) appears for familiarized target words relative to control words. This response proved constant at the individual level: Only infants who showed this negativity at test had shown such a response, within six repetitions after first occurrence, during familiarization.

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Most of the words that infants hear occur within fluent speech (Morgan, 1996; van de Weijer, 1998; Woodward & Aslin, 1990). To build up a vocabulary, infants therefore need to first recognize words by segmenting them from speech. This is a challenging task, given that most interword boundaries in utterances are not reliably marked in any way. Moreover, the sentential context (e.g., co-articulation, stress, intonation) in which words occur modifies acoustic forms (Cole & Jakimik, 1980). Detection of words in running speech relies mainly on listeners' ability to use probabilistic cues learned through experience with the native language (Cutler, 2012); these include, for instance, prosodic cues such as stress that signal likely word onsets for American-English infants (Jusczyk, Houston, & Newsome, 1999), but not for European-French infants (Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006). Segmenting words from speech appears to be crucial for vocabulary construction in infancy: It predicts future vocabulary size (Junge, Kooijman, Hagoort, & Cutler, 2012; Newman, Bernstein Ratner, Jusczyk, Jusczyk, & Dow, 2006; Singh, Reznick, & Xuehua, 2012).

Speech segmentation ability develops gradually between six and 12 months (Jusczyk, 1997; Saffran, Werker, & Werner, 2006). The principal method for testing word recognition in infancy is the behavioral two-stage familiarization-then-test version of the headturn preference procedure (HPP). In a seminal study, Jusczyk and Aslin (1995) showed that infants preferred continuous speech containing words they had heard in isolation and also that they preferred isolated words that they had heard before in continuous speech. Thus, either the familiarization or test phase consisted of isolated words and the other phase consisted of multiple words in utterances.

Recently, researchers have also used this paradigm with electro-encephalography (EEG) to examine whether and how quickly infants could distinguish familiarized from unfamiliar words. In the first adaptation, Kooijman, Hagoort, and Cutler (2005) familiarized 10-month-olds with 10 tokens of an infrequent word in isolation and then recorded event-related potentials (ERPs) to these familiarized words (targets) and to matched unfamiliar words (controls), in utterances. The infants' brain responses showed a clear recognition response: Relative to control words, familiarized target words elicited a negativity around 400 ms after onset of the word. Since then, this word recognition effect (also known as the N200-500; Mills, Conboy, & Paton, 2005) has been reported in other infant studies, although in younger infants, it can occur with a positive polarity instead (Kooijman, Junge, Johnson, Hagoort, & Cutler, 2013; Männel & Friederici, 2013). Table 1 gives an overview of these earlier studies.

As with HPP studies with natural speech, familiarization-and-test ERP studies to date have presented infants with utterances only in one phase, with the other phase consisting of isolated words. However, as noted

TABLE 1
Overview of Previous EEG Studies of Infants' Speech Segmentation Abilities
(N.B. in All Studies, Words were Presented in Isolation Either in the Familiarization or Test Phase)

Study (chronologically)	*language + Age tested*	*Familiarization phase*	*Test phase (familiarized vs. control words)*	*Word recognition effects at test (target relative to control word)*
Kooijman et al. (2005)	Dutch 10-month-olds	10 trochaic words in isolation	8 sentences	Negativity from 350 to 500 ms on left electrodes
Kooijman et al. (2009)	Dutch 10-month-olds	8 iambic words in isolation	4 sentences	Negativity from 370 to 500 ms (time-locked to strong syllable)
Goyet et al. (2010)	French 12-month-olds	10 words in isolation	12 sentences	Negativity from 350 to 500 ms
Junge, Kooijman et al. (2012)	Dutch 10-month-olds	1 sentence	1 word in isolation	Negativity from 200 to 650 ms on left frontal electrodes, for infants with higher vocabularies
Kooijman et al. (2013)	Dutch 7-month-olds	10 trochaic words in isolation	8 sentences	Broad positivity for infants with lower later language scores; left-going negativity for infants with higher scores, from 350 to 450 ms
Männel and Friederici (2013)	German 6-, 9-, & 12-month-olds	8 sentences (with/without accentuation)	8 words in isolation	6-month-olds: Broad positivity for accented words from 500 ms on 9-month-olds: Frontal negativity from 400 ms on, + broad late negativity for accented words 12-month-olds: Broad negativity from 350 ms on

earlier, infants mainly hear continuous speech, and one characteristic of parents' speech to children is that words are often repeated across different utterances (Aslin, 1993; Phillips, 1973; van de Weijer, 1998). The infant's task is then actually to recognize that a continuous utterance contains a word previously heard in another continuous utterance. The present study examines whether infants are able to build up a memory trace for words repeated across eight different natural utterances and to distinguish them from control words, within new utterances. Using EEG, we compare ERPs time-locked to the first and last two target familiarization tokens (i.e.,. the extremes of an eight-step continuum from unfamiliar to familiar words; collapsing over pairs of tokens delivers more data points without increasing experiment length). The test phase compares whether infants distinguish familiarized target words from control words. As infants were required to segment words from speech in both phases, we expect similar word recognition effects, with negative amplitudes around 400 ms, at familiarization as at test. However, if recognition gradually becomes easier at test than at familiarization, effects may differ in latency and in size of distribution (Kooijman et al., 2005; Mills et al., 2005, respectively).

Finally, we investigate the stability of the word recognition effect across children at each phase of our test. Earlier studies took the size of this effect as an individual marker for language development. For instance, 10-month-olds with larger negative-going recognition effects (over left frontal electrodes) continued to develop larger vocabularies at 12 and 24 months (Junge, Kooijman et al., 2012). Similarly, when another set of infants was retested for language skills at 3 years, those 7-month-olds with a negative recognition effect over left frontal electrodes ("Negative responders") outperformed their peers who had produced positive-going brain responses to the same input ("Positive responders"; Kooijman et al., 2013). Our design allows us to test how reliable word recognition effects are at the individual level. We predicted that infants who display at test negative recognition effects over left frontal electrodes (Negative responders) also display similar effects during familiarization. Moreover, if it is the negative polarity of this effect that marks mature processing, then Negative responders should require fewer tokens to recognize word repetitions, compared to infants with positive recognition effects.

METHODS

Participants

Twenty-eight 10-month-olds participated, all from Dutch monolingual families without history of language impairments (mean age = 307 days, age range = 293–319 days; 16 female). Thirteen further infants were excluded because of too few artifact-free trials (n = 8), fussing (n = 1), refusal to wear the cap (n = 3), or computer problems (n = 1). Infants had not participated in any previous speech segmentation study. Parents signed informed consent forms and received 20 euro and a photograph of their child taken postexperiment, in appreciation of their participation. This study was part of a series examining language processing over the life span, approved by the local Medical Ethical Committee (CMO Region Arnhem-Nijmegen).

Materials

Table 2 shows the 10 pairs of low-frequency trochaic words (henceforth: Target words), selected from the CELEX Dutch lexical database (Baayen, Piepenbrock, & Van Rijn, 1993). We created 12 sentences for each target word. Sentences comprised on average 5.75 words (SD = 0.79; range 4–8), with target words appearing no more than twice with the same preceding words or in the same position in a sentence (measured in syllables). Stimuli were recorded in a sound-attenuating booth by a female speaker in a child-directed manner and sampled to disk at 44.1 kHz mono. Mean sentence duration was 2,665 ms (SD = 318) and mean target duration 697 ms (SD = 112).

Procedure

Infants heard 20 familiarization-and-test blocks, with familiarization comprising eight different sentences containing the same target, followed by test consisting of four randomly presented sentences: Two containing the familiarized word (target condition), two containing the control words

TABLE 2
The 10 Pairs of Dutch Trochaic Target Words (English Glosses in Brackets)

1	*monnik*	(monk)	*bellers*	(callers)
2	*pudding*	(pudding)	*hommels*	(bumblebees)
3	*gieters*	(watering cans)	*drummer*	(drummer)
4	*sultan*	(sultan)	*pelgrims*	(pilgrims)
5	*hinde*	(doe)	*krokus*	(crocus)
6	*otters*	(otters)	*sitar*	(sitar)
7	*fakirs*	(fakirs)	*ronde*	(round)
8	*mosterd*	(mustard)	*krekels*	(crickets)
9	*lener*	(borrower)	*mammoet*	(mammoth)
10	*gondels*	(gondolas)	*zwaluw*	(swallow)

TABLE 3
An Example of an Experimental Block (with Literal English Translations Between Brackets). Target Words are underlined

Familiarization phase	
1.	*Een vogel zag de hinde knielen*. (A bird saw the doe kneel.)
2.	*s' Nachts gaat een stoere hinde op jacht*. (At night, a brave doe goes hunting.)
3.	*Het hertje hield van de hinde*. (The little deer loved the doe.)
4.	*Samen vingen zij jouw hinde*. (Together they caught your doe.)
5.	*Daar eet een hinde het gras*. (There a doe is eating the grass.)
6.	*De kleine hinde volgt het spoor*. (The little doe follows the track.)
7.	*Naast een hinde loopt een geit*. (Next to a doe, a goat is walking.)
8.	*Voor de hinde gaat het lastig*. (For the doe, the going is tough.)
Test phase	
9.	*Net naast deze krokus ligt wat* (Just beside this crocus, there is something)
10.	*Een aardige hinde wijst de weg* (A friendly doe shows the way)
11.	*De reus gaf de hinde wat brood* (The giant gave the doe some bread)
12.	*De grotere krokus is mooier* (the larger crocus is prettier)

(control condition; See Table 3 for examples). Intersentence interval was 2,000 ms.

Order of blocks and the subset of sentences forming the testing phase were counterbalanced across subjects, such that test sentences for 14 infants were familiarization sentences for the other 14. Within each set of 14, test sentences in the target condition for seven infants occurred in the control condition for the other seven. Target words were never first or last word of a test sentence.

We further counterbalanced within subjects which member of each word pair appeared in familiarization: The familiarized words in the first half were presented as control words in the second half, and control words in the first half became familiarized in the second half of the experiment. This entailed, of course, that infants received in one condition a "control" word that they had heard at least 116 utterances before (range 116 – 119; average interval time 9.4 min [*SD* 0.09]) as a familiarized target item. Arguably, with this design, we reduced our chance of finding a significant effect due to the consequent attenuation of the familiar/unfamiliar difference,[1] but

[1]We explored learning effects over the course of the experiment by repeating reported ANOVAs for the test phase, with block as additional within-subject factor. We excluded two subjects who only contributed trials to the first 10 blocks. Bear in mind that the number of trials per subject per condition was now lower than commonly accepted (range 2–16, whereas 10 is generally the minimum). There was no main effect of block ($F_{1,25} < 1$), nor any interaction with repetition ($F_{1,25} = 1.1$, $p = .30$), nor with other factors. Hence, this exploratory analysis did not suggest long-lasting learning effects, but more research (with more data points per subject) is needed to warrant this conclusion.

significant word recognition effects have also been observed in studies using the same words as target and as control, with much shorter intervals (Goyet, de Schonen, & Nazzi, 2010; Junge, Kooijman et al., 2012).

At test, infants were awake and seated in a child seat in a sound-attenuating booth. Sentences were presented at 65 dB through two loudspeakers. A parent sat by the child, listening to masking music through closed-ear headphones. The infant could watch screen savers (not synchronized to the auditory input) or play with silent toys. Breaks were taken when necessary. The experiment lasted about 19 min and a whole session about an hour.

EEG recordings and preprocessing

Electro-encephalography was recorded with a sampling rate of 500 Hz, using an infant-size BrainCap with Ag/AgCl electrodes, placed according to the extended 10–20 system (F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8). Vertical eye movements and blinks were monitored via a supra- to suborbital bipolar montage and horizontal eye movements via a right-to-left canthal bipolar montage. Electrodes were referenced online to the left mastoid and re-referenced to linked mastoids offline. Impedances were kept below 5 kΩ for ground and reference electrodes and below 20 kΩ for remaining electrodes. The signal was filtered off-line at 0.1–30 Hz. Individual trials with a baseline of 200 ms were screened for artifacts from 200 ms before to 1,000 ms after target word onset. We rejected trials with amplitudes exceeding $\pm$ 150 μV or with clear correlations with the eye channels or activity in the right mastoid. Whenever there was a break in a familiarization-and-test block (e.g., when the child ate something), we rejected later trials for that block.

Statistical analyses

For both familiarization and test, we compared ERPs time-locked to target words for familiarized targets vs. controls: For the familiarization phase, between the first two tokens (sentences 1 and 2; control) vs. the last two (sentences 7 and 8; target); and for the test phase, between familiarized targets and control words. We examined the word recognition effect separately per phase (as building up a memory trace might be a slower process than subsequent mapping of a novel token to this trace; consequently, the timing of a recognition response could differ). For each infant, we calculated average waveforms per condition, with a minimum of 10 artifact-free trials per condition (mean average of the four examined conditions 15.0 trials, range 10.75–24). Onset of each word recognition effect was determined by examining the difference waveform (target – control words): Using two-tailed *t*-tests, we calculated for each electrode whether and when this difference was significant from 0 on at least five consecutive 50-ms-bins moving in steps of 10 ms (cf. Kooijman et al., 2005).

Time windows were selected by visual inspection of the waveforms, but guided by onset effects. Repeated-measures analyses of variance (ANOVA) were performed on mean amplitudes in selected time windows, with repetition (target vs. control), hemisphere (2: Left and right), frontal/posterior (2; frontal and posterior), and electrode (5 per quadrant of the brain; left frontal: F3, F7, FC1, FC5, C3; right frontal: F4, F8, FC2, FC6, C4; left posterior: T7, CP1, CP5, P3, P7; right posterior: T8, CP2, CP6, P4, P8) as variables. For all ANOVAs, we used the Huynh–Feldt correction and report only main effects of repetition and interactions with repetition.

We used pair-wise comparisons for the mean amplitudes of the selected time window from the familiarization phase to establish how many pairs of repetitions infants needed to hear before the recognition effect differed significantly from the first two tokens (i.e., 1 and 2 vs. 3 and 4, 5 and 6, or 7 and 8; with $\alpha = .0167$ to control for multiple comparisons).

Finally, to examine correspondences between familiarization and test, we used the polarity of mean amplitude difference at test on left frontal electrodes to characterize infants as Positive vs. Negative responders (Junge, Kooijman et al., 2012; Kooijman et al., 2013) and repeated both ANOVAs and pair-wise comparisons from the familiarization phase.

RESULTS

Familiarization phase

Figure 1 shows the mean waveforms for the first two tokens (control) vs. those for the seventh and eighth time (familiarized targets) a target was presented, time-locked to its onset. The more familiarized words elicited, as predicted, a larger negative amplitude. This effect started at 350–380 ms for 10 electrodes (F3, F4, F8, Fz, FC1, FC6, CP1, P3, P4, and Pz). This resembles the finding of Kooijman et al. (2005) for their continuous speech test phase (i.e., 340–370 ms onset). The offset of our effect is unclear, however. For some electrodes (e.g., FC1, CP1, FC6), there is one long effect (350–900 ms), whereas for others (e.g., F3, T8), the differential effect appears in two time windows (350–500 ms, 600–900 ms; i.e., ERPs

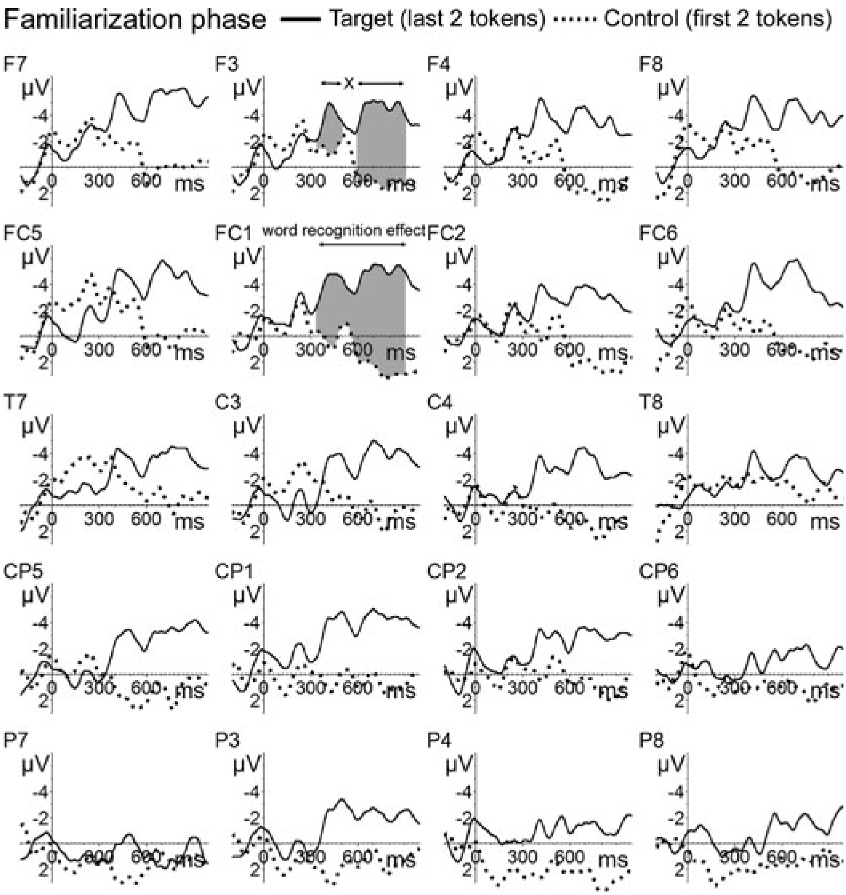

Figure 1 Results of the familiarization phase: Grand average waveforms of the 20 lateral electrodes time-locked to critical word onset. In this figure and in Figure 3, electrodes are arrayed from anterior (top) to posterior (bottom), and from left to right as they were positioned on the scalp; negativity is plotted upwards; an additional 8 Hz low-pass filter has been applied for illustrative purposes. The shaded areas relate to the discussion whether the word recognition effect should be calculated over one large time window (as in FC1) or over two separate time windows (as in F3).

converge between 500 and 600). To evaluate whether word recognition effects should be calculated over one large or two distinct time windows, we correlated difference scores (averaged over the 20 lateral electrodes) between the two shorter time windows: The significant positive correlation (*Pearson's* $r_{28} = +.51$, $p = .006$) suggests that the time windows are related, presumably reflecting the same component. We therefore chose the large time window (350–900 ms) for further inspection. This revealed a main effect of repetition ($F_{1,27} = 10.22$, $p = .004$, $\eta^2 = .28$), widely distributed (i.e., no interactions; $F_{1,27} < 2.37$, $p > .14$).

Figure 2 further shows that the more often a word is presented, the more negative the corresponding ERP becomes during familiarization. Pair-wise comparisons revealed that infants needed to hear seven to eight tokens of a word before the ERPs differed significantly from those to the first two tokens ($t_{27} = 2.83$, $p = .009$; other comparisons, $p > .10$).

Test phase

Figure 3 plots the mean waveforms of words presented in preceding familiarization (target) or not (control). Again, this word recognition effect has the form of an increased negativity for familiarized target words, but its onset appears earlier: It starts around 220–250 ms for four frontal electrodes (F3, F4, Fz, C4). Its offset is similarly ambiguous: It lasts till 900 ms for some electrodes (e.g., F3, F4, FC1), but is divided over two shorter time windows for others (e.g., FC6 and C4 show increased negativities in the time windows 220–500 and 600–900 ms, but not in-between). The larger time window 220–900 ms was selected for further inspection, as the two shorter time windows again correlated (Pearson's $r_{28} = +.52$, $p = .005$). A main effect of repetition appears ($F_{1,27} = 6.24$, $p = .019$, $\eta^2 = .19$), most pronounced over left frontal electrodes, but also significant over right frontal electrodes (interaction of repetition by frontal/posterior: $F_{1,27} = 8.49$, $p = .007$, $\eta^2 = .24$; separate ANOVAs for each quadrant: left frontal electrodes: $F_{1,27} = 10.75$, $p = .003$, $\eta^2 = .29$; right frontal electrodes:

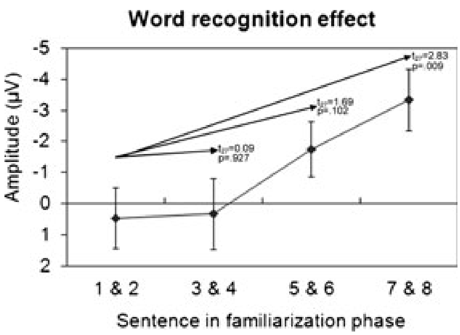

Figure 2 Mean ERP amplitudes for target words during familiarization, from first to last two tokens (averaged over 20 lateral electrodes for the time window 350–900 ms; error bars are 1 *SE* from the mean; negativity is plotted upwards for comparison with Figure 1).

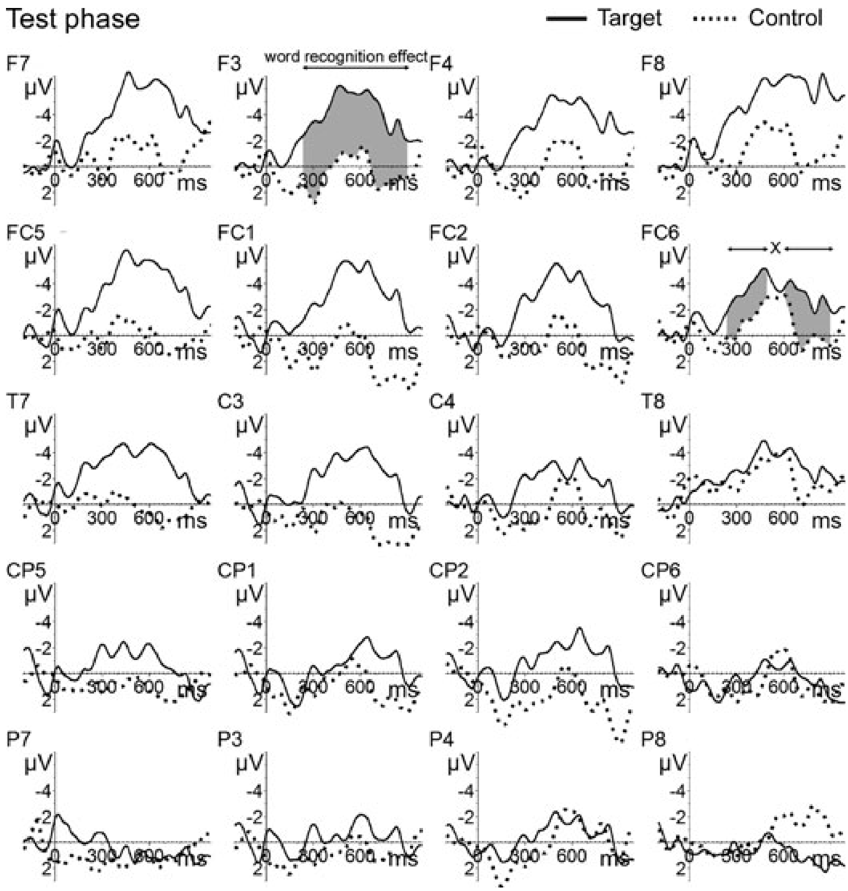

Figure 3 Results of the test phase: Grand average waveforms time-locked to critical word onset. Again, the shaded areas relate to the discussion whether the word recognition effect should be calculated over one large time window (as in F3) or over two separate time windows (as in FC6).

$F_{1,27} = 5.95$, $p = .022$, $\eta^2 = .18$; left posterior electrodes: $F_{1,27} = 3.01$, $p = .09$, $\eta^2 = .10$; and right posterior electrodes: $F_{1,27} < 1$, $p = .52$, $\eta^2 = .02$).

Linking familiarization to test

Overall, infants display a word recognition effect with negative amplitude both at familiarization and at test. At test, 19 infants showed a negative effect ("Negative responders", 11 girls; mean −7.7 μV, *SD* 5.8; Repetition: $F_{1,18} = 19.42$, $p < .001$, $\eta^2 = .49$; Repetition by frontal/posterior: $F_{1,18} = 17.15$, $p = .001$, $\eta^2 = .52$), while nine other infants displayed a positivity instead ("Positive responders," five girls; mean +2.7 μV, *SD* 2.9; Repetition: $F_{1,8} = 4.91$, $p = .06$, $\eta^2 = .38$; no interactions with distribution factors). To test whether infants' effects pattern similarly across phases, we repeated the familiarization phase analyses with group as a between-subjects factor. Although the repetition main effect is no longer significant ($F_{1,26} = 2.95$, $p = .10$, $\eta^2 = .10$), repetition interacts significantly with group ($F_{1,26} = 12.01$, $p = .002$, $\eta^2 = .32$). Separate analyses reveal that Negative responders display a significant effect ($F_{1,18} = 19.3$, $p < .001$, $\eta^2 = .52$), but Positive responders do not ($F_{1,8} = 1.37$, $p = .28$, $\eta^2 = .15$). Pair-wise comparisons further indicate that Negative responders' recognition starts within six repetitions ($t_{18} = 3.79$ and 4.01, $p < .001$, for 1 and 2 vs. 5 and 6, and vs. 7 and 8, respectively), while Positive responders show no differences between the first token pair and later pairs ($p > .08$).

DISCUSSION AND CONCLUSION

Ten-month-olds' brain responses differentiate familiarized from unfamiliar words when the words are heard within utterances both at initial exposure and at test. First, a long-lasting negative-going word recognition effect at test establishes that 10-month-olds accomplish such recognition. Second, familiarization phase responses revealed a similar recognition effect, with a gradual increase in negativity. Third, the infants who show the effect at test are the same infants who show the effect at familiarization.

In comparison with earlier studies, the latency of the word recognition effect observed here is rather long (up to 900 ms, cf. up to 500 ms: Kooijman et al., 2005; Kooijman, Hagoort, & Cutler, 2009). However, others have observed recognition effects in later time windows, either single elongated effects (to 800 ms; Friedrich & Friederici, 2011; to 650 ms; Junge, Kooijman et al., 2012) or two separate effects (Conboy & Mills, 2006; Mills, Coffey-Corina, & Neville, 1997; Mills et al., 2005; Torkildsen et al., 2009; Zangl & Mills, 2007). The correlated negativities over time suggest a single elongated effect in the present case, which could indicate either that infants continue to show recognition as words unfold or that word recognition proper precedes a later stage, for example, of attention increase, or memory trace update (Junge, Kooijman et al., 2012).

During familiarization, the recognition effect increases in negativity. Such a gradual increase has also been reported in other word recognition studies (Junge, Cutler & Hagoort, 2012; Kooijman et al., 2005; Männel & Friederici, 2013).

Although the word recognition effects across familiarization and test are alike in makeup, they differ slightly in distribution and in timing. Recognition effects with smaller distributions (i.e., based on less neuronal resources) have been linked to infants with better processing skills (Mills et al., 2005). Similarly, an earlier onset is associated with an easier situation in which word recognition is achieved (Kooijman et al., 2005). Because our word recognition effect observed at test has both a smaller distribution and an earlier onset, we speculate that word recognition is easier at test than in familiarization. This could indicate that constructing a new memory trace for a novel word (surrounded by other words) is harder than subsequently mapping input to this existing trace. Yet although recognition takes a little longer at familiarization, even here infants only need to partially hear a familiarized word (average word duration 697 ms) to initiate a recognition response (from 350 ms onwards). This underlines the efficiency of infants' responses to continuous speech input at this age. Finally, our design required infants to segment words from speech both in familiarization and at test. We already know that speech segmentation ability, as indexed by word recognition effects, effectively predicts future language development of individuals (Junge, Kooijman et al., 2012; Kooijman et al., 2013), with polarity, size, and shape of the EEG effects indicating more mature recognition responses and being associated with higher language skills. A second goal of the present study was therefore to examine the stability of the word recognition effect within our test population. Indeed, we observed response constancy: Infants who showed a negativity at test had also produced a similar recognition response within six repetitions during familiarization, while infants who did not show such a negativity at test had not shown any recognition during familiarization. Even at test, the positive familiarity effect proved insignificant (although power was low). Given that word recognition effects in infancy transitions from (an immature) positive- to (more mature) negative-going polarities (for a discussion, see Kooijman et al., 2013; Männel & Friederici, 2013), it is unclear whether Positive responders in our study fail to recognize words or whether they are in the middle of this transition phase (sometimes showing positive responses; but occasionally also showing negative responses). ERP tasks do not allow examination of word recognition for each trial, because the word recognition effect is calculated as the averaged EEG difference between trials with familiarized vs. unfamiliar words.

Most 10-month-olds in our study repeatedly displayed a negative familiarity effect. This demonstrates that at least in infants in the normal range, ability to detect word repetitions relates to subsequent successful word recognition, even when in both cases, words are surrounded by other words. As infants mainly encounter words in continuous speech, this observed link further underscores the importance of speech segmentation skill for successful vocabulary construction.

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