Neuropsychologia ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Ambiguous function words do not prevent 18-month-olds from building accurate syntactic category expectations: An ERP study

Perrine Brusini [a,b,*], Ghislaine Dehaene-Lambertz [c,d,e], Marieke van Heugten [b,f], Alex de Carvalho [b], François Goffinet [g], Anne-Caroline Fiévet [b], Anne Christophe [b,g]

[a] International School for Advanced Studies (SISSA), Language, Cognition and Development Laboratory, Trieste, Italy
[b] Laboratoire de Sciences Cognitives et Psycholinguistique (EHESS-ENS-CNRS), Ecole Normale Supérieure, PSL Research University, Paris, France
[c] INSERM, Cognitive Neuroimaging Unit, F91191 Gif-sur-Yvette, France
[d] CEA, NeuroSpin Center, IFR 49, F91191 Gif-sur-Yvette, France
[e] Université Paris XI, F91405 Orsay, France
[f] Department of Psychology, University at Buffalo, The State University of New York, United States
[g] AP-HP, Université Paris Descartes, Maternité Port-Royal, Paris, France

ARTICLE INFO

Article history:
Received 1 February 2016
Received in revised form
11 August 2016
Accepted 14 August 2016

Keywords:
Noun-verb categorization
Function words
Event related potentials
Early syntactic processing
Brain

ABSTRACT

To comprehend language, listeners need to encode the relationship between words within sentences. This entails categorizing words into their appropriate word classes. Function words, consistently preceding words from specific categories (e.g., *the ball*$_{\text{NOUN}}$, *I speak*$_{\text{VERB}}$), provide invaluable information for this task, and children's sensitivity to such adjacent relationships develops early on in life. However, neighboring words are not the sole source of information regarding an item's word class. Here we examine whether young children also take into account preceding sentence context online during syntactic categorization. To address this question, we use the ambiguous French function word *la* which, depending on sentence context, can either be used as determiner (*the*, preceding nouns) or as object clitic (*it*, preceding verbs). French-learning 18-month-olds' evoked potentials (ERPs) were recorded while they listened to sentences featuring this ambiguous function word followed by either a noun or a verb (thus yielding a locally felicitous co-occurrence of *la* + noun or *la* + verb). Crucially, preceding sentence context rendered the sentence either grammatical or ungrammatical. Ungrammatical sentences elicited a late positivity (resembling a P600) that was not observed for grammatical sentences. Toddlers' analysis of the unfolding sentence was thus not limited to local co-occurrences, but rather took into account non-adjacent sentence context. These findings suggest that by 18 months of age, online word categorization is already surprisingly robust. This could be greatly beneficial for the acquisition of novel words.

1. Introduction

Successful spoken language processing requires listeners to compute complex linguistic analyses. Adults typically experience little difficulty correctly applying the grammatical rules of their native language when they communicate with other people. This stands in sharp contrast with young children, whose early telegraphic speech is abundant with omissions. More specifically, function words, such as determiners, auxiliaries, and pronouns – despite their importance for encoding language structure– appear to be consistently lacking from toddlers' early speech patterns (Gerken et al., 1990). As a result, these words have traditionally been thought to be overlooked and not processed by young children. In more recent years, however, experiments testing the perception of these elements have demonstrated that infants and toddlers are sensitive to these items (Gerken and McIntosh, 1993; Hallé et al., 2008; Shi and Gauthier, 2005; Shi et al., 2006b). These studies suggest that the selective production of content words relative to function words is likely strategic (function words convey less semantic content than content words), and that function words may be omitted due to production rather than comprehension constraints (Demuth and Tremblay, 2008; Gerken and McIntosh, 1993).

If toddlers do not experience difficulty perceiving function words, then these items may be of great use during the process of language acquisition, since they convey rich morpho-syntactic information. Distributional, phonological and acoustic analyses reveal that function words are highly frequent, typically occur at the edges of syntactic phrases, and tend to be short and unstressed

* Corresponding author at: LSCP, Ecole Normale Supérieure, 29, Rue d'Ulm, 75005 Paris, France.
E-mail address: pbrusini@gmail.com (P. Brusini).

http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.015
0028-3932/

(Shi et al., 1998): characteristics that differentiate them from content words and that may allow infants to discriminate between the two types of words. Indeed, children as young as a few days can distinguish lists of function words from lists of content words (Shi and Werker, 2001; Shi et al., 1999) and by 10 months of age, infants have gained sensitivity to frequent function words occurring in their native language (Hallé et al., 2008; Shady, 1996; Shafer et al., 1998; Shi et al., 2006a). Given that most function words tend to consistently co-occur with content words from a specific word class, this early acquisition of function words might also allow infants to rely on these words to anticipate the lexical category of a subsequent content word (Christophe et al., 2008; Gervain et al., 2008; Hochmann, 2013; Hochmann et al., 2010). For instance, if infants learned that determiners (such as *the* or *a*) typically precede nouns whereas pronouns (such as *you* or *he*) generally precede verbs, they could use this knowledge to deduce the syntactic category of words that they have never encountered before. This hypothesis is consistent with a growing body of experimental data showing that children can infer the syntactic category of a novel word after auditory exposure to function word – content word co-occurrences. That is, by 14–16 months of age, infants can work out that a novel content word following one determiner can also follow other determiners, but cannot follow pronouns (Hohle et al., 2004; Shi and Melançon, 2010). Moreover, by 18 months of age, lexical access is speeded and more accurate when known nouns and verbs are preceded by a function word from an appropriate category (i.e. determiners and pronouns, respectively, Cauvet et al., 2014; Kedar et al., 2006; Zangl and Fernald, 2007) and by two years of age, toddlers readily exploit the syntactic context of a novel word to infer whether it refers to an object or an action (Bernal et al., 2007; Oshima-Takane et al., 2011; Waxman et al., 2009). This suggests that early on in life, the presence of a function word can trigger children's expectations regarding the word class of the subsequent item.

Children's early reliance on function words to determine the grammatical category of neighboring content words can be greatly beneficial for language acquisition purposes. However, to become a mature language user, it is important to process not only local co-occurrences of function and content words, but to also learn to take into account the contexts in which these dependencies occur. That is, although function words are generally a good predictor of the word class of the following content word, incorporating the broader syntactic context can sometimes improve or fine-tune categorization. This is particularly profitable in the case of function words that can occupy multiple syntactic roles. Consider, for instance, the French functor *la*, which can surface both as a determiner (e.g., *Très gentiment* ***la*** *girafe me prête sa balle* 'Very kindly **the** giraffe lends me her ball') and as a pronoun clitic (e.g., *Alors moi je* ***la*** *donne au crocodile* 'Then I give **it** to the crocodile'). If toddlers only exploit the local co-occurrence between the two classes to deduce the syntactic category of the content word following the function word, such ambiguities could potentially be devastating. A French-learning child hearing a novel verb in a context such as *Elle* ***la*** *dase* ('She dases **it**'), for example, might erroneously infer that *dase* is a noun, because it is preceded by the functor *la*, which occurs as a determiner much more frequently than as an object clitic (more than 80% of the time, as reported in Shi and Melançon, 2010). If, by contrast, the broader syntactic context could be taken into account, toddlers may be able to infer that, despite the overall likelihood as *la* surfacing as a determiner, the presence of the preceding pronoun *elle* ('she') greatly increases the likelihood of a verb to appear.

Recent work has started to explore whether children's online word categorization is local in nature or whether broader sentence structure is taken into account. In particular, French-learning two-year-olds' brain responses were measured while they listened to sentences featuring the ambiguous function word *la*, either used as a determiner or as an object clitic (Bernal et al., 2010; Brusini et al., 2016). Differences in evoked potentials between grammatical and ungrammatical trials revealed that the classification of content words following the functor *la* depended on the structure of the unfolding sentence. That is, children anticipated a noun when the broader sentence context was indicative of *la* being a determiner (e.g., *hier la* … 'yesterday the …'), but they anticipated a verb when the broader sentence context was indicative of *la* being an object clitic (e.g., *je la* … 'I … it'). This suggests that toddlers use sentence frames to determine the word class of upcoming linguistic material. By their second birthday, children are thus able to compute complex syntactic dependencies during online language processing.

The finding that two-year-olds can take advantage of more than just the immediately adjacent linguistic context during syntactic processing suggests that they possess both the computational abilities and the linguistic experience necessary to accurately compute complex contexts. However, given that children start using function words as a classification method months before their second birthday (e.g. Cauvet et al., 2014, for nouns and verbs in French; Kedar et al., 2006 for nouns in English; Van Heugten and Johnson, 2011, for nouns in Dutch; Zangl and Fernald, 2007, for nouns in English), we may wonder whether learners who are still in the very early stages of exploiting function words as a categorization cue can also incorporate sentence context during online word classification. On the one hand, children may at first rely mainly on local dependencies between word categories, and may not take into account any non-adjacent information. This would align with the finding that the ability to learn adjacent dependencies typically precedes the ability to learn non-adjacent dependencies (Gebhart et al., 2009; Gomez and Gerken, 1999; Udden et al., 2012) and would imply that word classification in the case of ambiguous function words would follow the most frequent adjacent regularity. Only once children can expand their processing window, will they be able to integrate broader sentence context. On the other hand, children may possess more advanced categorization skills, incorporating the wider linguistic context from the beginning. Following this view, children's syntactic categorization would depend not only on the immediately preceding information in the sentence, but also on the more distant information, even during the early acquisition period. To tease apart these two possibilities, it is crucial to test whether 18-month-olds can take into account the non-local syntactic context during the processing of ambiguous function morphemes. To our knowledge, this study is the first one testing whether young infants can use distant contextual information for word categorization in the presence of a consistent adjacent relationship.

To address this issue, we exploited the event related potential (ERP) paradigm developed by Bernal et al. (2010) in which two-year-olds were presented with short video clips containing grammatical and ungrammatical sentences. In this procedure, high-density electro-encephalography (EEGs) is recorded without requiring any overt response from toddlers. Thus it is a well-suited paradigm to determine 18-month-olds' spontaneous syntactic abilities by comparing the neuronal response evoked by grammatical and ungrammatical sentences. Although the electrical components induced by syntactic violations described in the toddler literature are more variable than those in the adult literature,[1] a late positivity, which has been related to revision

[1] Variability between studies may depend on the exact nature of the syntactic violation studied, but may also be related to the use of continuous speech in toddler studies (as opposed to serial presentation of written words in many adult studies), which decreases the amplitude and sharpness of the electrical components. The immature syntactic processing of young participants could furthermore lead to

processes in adults (Kuperberg, 2007), is robustly observed across ages for ungrammatical sentences (Bernal et al., 2010; Brusini et al., 2016; Oberecker and Friederici, 2006; Oberecker et al., 2005; Silva-Pereyra et al., 2005a, 2005b). This positivity is sometimes preceded by other components (Brusini et al., 2016; Oberecker et al., 2005; Schipke et al., 2011; Silva-Pereyra et al., 2005b), less consistent across experiments.

Our paradigm relies on the comparison of the same sequences of words embedded in longer sentence contexts. These sentence contexts manipulated the status of the sequences: grammatical sentences either contained an object clitic-critical verb or a determiner-critical noun sequence (e.g., *Alors moi je* ***la*** *donne au crocodile,* 'Then I give **it** to the crocodile' or *Très gentiment* ***la*** *girafe me prête sa balle,* 'Very kindly **the** giraffe lends me his ball', critical words are underlined). Ungrammatical sentences were constructed by placing a noun in a verb context or a verb in a noun context (e.g.,**L'animal et* ***la*** *donne sont heureux*, '*The animal and the give are happy' or **Alors il me* ***la*** *girafe en souriant* '*Then he smilingly giraffes it to me'). We used videos (see Fig. 1 for an example) in which sentences containing the critical content words were first introduced with the support of small toys illustrating the story (introductory part); then when the key grammatical and ungrammatical sentences were presented, only the speaker's face was visible (test part). Thus, the grammaticality of these sentences could not be judged from the visual scene. Crucially, at test, all critical words were preceded by the same ambiguous function word ('la' meaning either *the* or *it*). As a result, the simple adjacent co-occurrence of the functor 'la' and the critical content word does not provide any cue regarding the grammaticality of the sentence. For instance, in the ungrammatical sentence **Alors il me la girafe en souriant* '*Then he smilingly giraffes it to me', the two-word sequences '*il me*', '*me la*' and '*la girafe*' are all legal in French, but '**il me la girafe*' is not. The implementation of this design could lead to three possible patterns of results.

First, if 18-month-olds listening to the test sentences are only able to recover content words provided by the previous visual context (e.g. the presence of a giraffe during the introductory sentences) and/or to compute local statistics between pairs of words, then they should process all sentences similarly, since they contain content words which have been mentioned before, and are always locally correct (all pairs of adjacent words occur frequently together within grammatical sentences). Second, if toddlers are able to make more complex analyses based on the frequency of the categories in natural speech outside the lab, and estimate that "la" should be followed by a noun (since "la" is most often followed by nouns), then they should perceive all sentences containing a 'la + noun' sequence as grammatical and all sentences containing a 'la + verb' sequence as ungrammatical (since in our experimental design 'la' is followed equally often by nouns and verbs, in both grammatical and ungrammatical sentences, this will not lead to an overall distinction between grammatical and ungrammatical sentences). A third possibility would be for toddlers to detect the ungrammaticality regardless of whether nouns and verbs are used. If that were the case, this would indicate that 18-months either build an adult-like syntactic representation of the sentence as it unfolds, or at least pay attention to three- or four-word strings. In line with the ERP literature, we would then expect to record a late positivity for ungrammatical sentences relative to grammatical sentences (Bernal et al., 2010; Brusini et al., 2016; Oberecker and Friederici, 2006; Oberecker et al., 2005; Silva-Pereyra et al., 2005a, 2005b), potentially preceded by an early effect (Brusini et al., 2016; Oberecker et al., 2005; Schipke et al., 2011; Silva-Pereyra et al., 2005b).

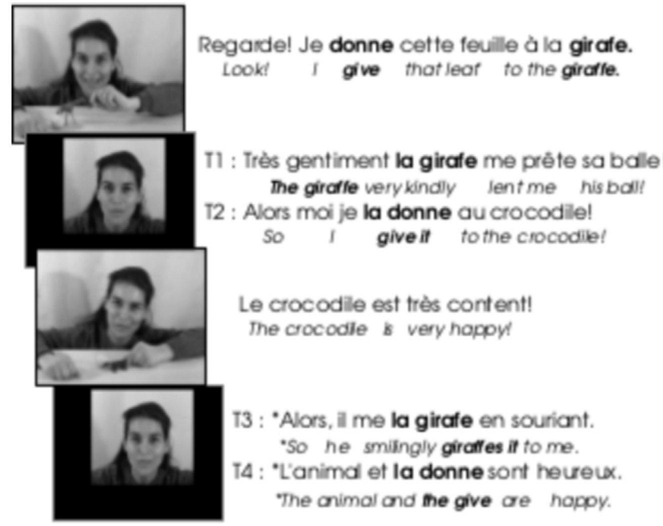

Fig. 1. Example of a video story. Each story had the same structure: during the test trials only the speaker's face was visible, whereas in the remainder of the video the whole scene was presented, to keep toddlers interested.

2. Method

2.1. Participants

A total of 25 monolingual French-learning toddlers (12 boys) were tested (mean age 18.4; range 17.8–19.2). All toddlers were in good health at the time of test, had no detected developmental disorders and no reported hearing deficits. An additional 35 toddlers participated in this experiment but did not provide exploitable data, because they were too agitated, stopped the test prematurely, or the quality of the recorded potentials was not sufficient (only data of toddlers with at least 40 artifact-free trials, and at least 19 in each of the two grammaticality conditions, were analyzed). Another 38 toddlers were recruited for this experiment, but as they refused to wear the EEG net, no data were collected.[2] Families received a diploma as a token of appreciation. This research was approved by the local 'Ile-de-France III' ethics committee.

2.2. Stimuli and design

Four nouns and four verbs that are typically acquired at a young age were selected by Bernal and colleagues (2010) as critical words. None of these critical words were noun/verb homophones (nouns: *une fraise* 'a strawberry', *une balle* 'a ball', *une grenouille* 'a frog', *une girafe* 'giraffe'; verbs: *manger* 'to eat', *donner* 'to give', *regarder* 'to look', *finir* 'to finish'). For each category, two of the words were monosyllabic and two were bisyllabic (for verbs, this

(*footnote continued*)
additional variability in the electrical components: their onsets might be less precisely time-locked, therefore decreasing the amplitude of the averaged evoked responses. Finally, children's EEG response contains more large-amplitude low frequency components compared to that of adults, which has been shown to lead to an increase in background endogenous noise (Chu et al., 2014).

[2] As noted by an anonymous reviewer, the overall rejection rate may seem high (although not unusual for ERP experiments using this age group; e.g. Brusini et al., 2016). Towards the end of the study we reduced the dropout rate by introducing a series of slight modifications to the welcoming procedure of parents and toddlers (playing a cartoon on the screen before the experiment started, and telling the children that the television works only when they have the net on; securing the parents' help by asking them to hold the child's hands while the net was put into place, then asking them to maintain the child firmly on their lap during the experiment, acting as a 'gentle car seat', in order to reduce movement artifacts).

was true for the present-tense form that was used in the experiment). Nouns and verbs were embedded in sentences that were grammatical in half of the test trials (e.g., *Alors moi je **la** donne au crocodile,* 'Then I give **it** to the crocodile' or *Très gentiment **la** girafe me prête sa balle,* 'Very kindly **the** giraffe lends me her ball', critical words are underlined) and ungrammatical in the other half of the test trials (e.g.,**L'animal et **la** donne sont heureux*, '*The animal and **the** give are happy' or *Alors *il me **la** girafe en souriant* '*Then he smilingly giraffes **it** to me' see Table 1 for the full design). All critical words were preceded by the function word 'la', which can either take the role of determiner or that of object clitic. Note that all words were presented in both verb and noun positions across grammatical and ungrammatical sentences. This controls for any possible low-level acoustic differences between the grammatical and ungrammatical conditions. Thus, a main effect of grammaticality cannot be due to acoustic properties of the critical words themselves (they are the same on both sides of the comparison), nor can they be due to acoustic properties of the contexts themselves, as they were carefully matched in number of syllables before the critical words, and in the syntactic structures used (see Supplementary materials for a full list of stories, and a detailed description of the matching procedure).

We used the same 16 video clips recorded by Bernal et al. (2010). In these clips, a native French speaker narrated a 30-s story in a child-directed fashion. She used toys to illustrate the stories and maintain the toddlers' interest. All stories were scripted in a similar way (see Fig. 1 for an example). They started with an introduction of the characters present in the story (the critical noun and verb of the story were mentioned in these sentences), followed by two test sentences, a filler sentence to keep the toddlers engaged in the task, and ended with two more test sentences. During the introduction and the filler sentences, the whole scene was visible. During the test sentences, by contrast, only the speaker's face was visible (see the screen-shots in Fig. 1). This way, the visual information was highly similar across test sentences and did not provide any cues regarding the plausibility of the items. Because children tend to focus on the speaker's eyes and mouth (Lewkowicz and Hansen-Tift, 2012), this should also help minimize children's eye-movements.

Within each story, two test sentences contained a critical noun and the other two contained a critical verb. The order of the conditions was counterbalanced across the 16 stories. Overall, there were 64 different test sentences, 32 grammatical and 32 ungrammatical. Across stories, test sentences were counterbalanced for the number of syllables before and after the critical word, and for the syntactic structures used in the grammatical and ungrammatical conditions. Toddlers watched these 16 stories several times, in different orders (at least once and no more than 4 times).

Table 1
Construction of the test sentences: the critical words (nouns and verbs) occurred in noun and verb contexts, yielding grammatical sentences (when the context was congruent with the syntactic category of the critical word) and ungrammatical sentences, marked with a star (when context and critical word syntactic category were incongruent).

	Grammatical	Ungrammatical
Nouns	Très gentiment la girafe me prête sa balle	*Alors il me la girafe en souriant.
	Very kindly the giraffe lends me his ball.	**So he smilingly giraffes it to me.*
Verbs	Alors moi je la donne au crocodile !	*L'animal et la donne sont heureux.
	So I give it to the crocodile!	**The animal and the give are happy*

2.3. Procedure

Prior to test, the experimenter positioned a geodesic 128-sensor net (EGI, Eugene, USA) relative to the anatomical markers on the toddler's head. A short play session, featuring the toys that were used in the videos, took place before the experiment and served two purposes: toddlers were reminded of the meaning of the words that would be used in the test session, and they were distracted while the net was put in place. The experiment took place in a sound-attenuated booth. Children were seated on their parent's lap and watched between one and four blocks of 16 video stories, while EEGs were recorded. Parents were asked to remain silent and refrain from distracting their child throughout the experiment. Two computers were used to conduct the experiment; one played the video-clips and the other one selected the clip to be played and sent trial information to the EEG recording system. If necessary, the experimenter paused the session between two stories and restarted it once the toddler appeared to be focusing again.

2.4. ERP recording and data analysis

2.4.1. ERP recording

High-density EEG (128 electrodes, referenced to the vertex) was continuously digitized at 250 Hz during the video presentations (Net amps 200, EGI, Eugene, USA). Recordings were digitally band-pass filtered (0.3–20 Hz) and segmented into 1400 ms-epochs starting 200 ms prior to critical word onset. For each epoch, channels contaminated by eye or motion artifacts (local deviation higher than 80 μV) were automatically excluded, and trials with more than 20% contaminated channels were excluded from the analysis. For each toddler, channels comprising fewer than 50% uncontaminated trials were excluded for the entire session. Excluded channels were interpolated for each trial separately using the linear interpolation method of EEGlab (Delorme and Makeig, 2004). The artifact-free epochs were averaged for each participant in each condition (mean number of artifact-free epochs per toddler: 128.1 in total: 64.5 in the grammatical condition and 63.6 in the ungrammatical condition). Averages were baseline-corrected (−200 to 0 ms) and transformed into reference-independent values using the average of all channels as reference.

2.4.2. Data analysis

Channels at the edge of the scalp, which are generally very noisy in toddlers, were not considered, leaving 91 electrodes for analyses.[3] Given the number of electrodes (here 91) and time samples (here 300), the risk of type I errors (false alarms) is high if each possible comparison (here 91*300) is considered. To avoid this issue and reduce the number of comparisons, three strategies are generally proposed to analyze high-density recordings. The most classic strategy involves constraining the analysis by taking into account the existing literature and computing *t*-tests or ANOVAs on the time windows and scalp regions often reported to be at play in similar experimental conditions. This method has been criticized as being sensitive to biases in the literature and restricting analyses to known effects. Furthermore in less studied populations, the literature may not be sufficiently dense to correctly infer typical time windows and regions. A second strategy consists of first identifying experimental effects in a subset of the

[3] Using the 128-channels Hydrocel Geodesic Sensor Net, the following electrodes, which represent the three outer-most circles of the geodesic net, were removed: 17-126-127-21-14-8-1-125-121-120-119-114-113-107-99-94-88-81-73-68-63-56-49-43-48–128-44–38-32–25-100–95-89–82-74–69-64–57. As a result, 91 electrodes are analyzed.

Please cite this article as: Brusini, P., et al., (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.015

data and then checking whether it replicates it using another subset. However, because this strategy requires the data set to be subdivided, it reduces the number of total trials taken into account to establish an effect, which is problematic with a toddler population where it is challenging to obtain a sufficient number of clean trials. A final strategy, the cluster-based permutation analysis (Maris and Oostenveld, 2007), exploits the fact that neighboring channels and time-points are highly correlated. This approach identifies spatio-temporal clusters that exhibit a significant difference between conditions. The statistical value of these clusters is assessed by comparing them to a null distribution obtained through randomized permutations of the initial data. In practice, a *t*-test is computed on each electrode and time-point, then a threshold is applied and clusters are built as the sum of the t-values above threshold in neighboring points in time and space. The same procedure is applied on the shuffled data and the largest clusters from the original data are compared to the distribution of the clusters obtained in the shuffled data. This general method, which is instantiated in several MATLAB toolboxes (SPM Kiebel and Friston, 2004; TFCE Mensen and Khatami, 2013; Fieldtrip, Oostenveld et al., 2011; LIMO, Pernet et al., 2011), is conservative, but its sensitivity depends on how the clusters are constructed (see Mensen and Khatami, 2013 for a comparison of the different toolboxes and the different choices to construct clusters). In a nutshell, using this method, there is a trade-off between sensitivity to local but intense effects versus effects with smaller amplitude but more sustained in time and diffuse on the scalp. Here, much like in Brusini et al. (2016), we first use the conservative cluster-based permutation analysis to ensure that a main effect of grammaticality was present in our data. Then, to analyze differences between sub-conditions, we use the more sensitive method based on a selection of regions of interest from the existing literature.

The cluster-based permutation analysis was conducted on the main effect of grammaticality (i.e. comparison between grammatical and ungrammatical sentences, pooling across nouns and verbs) using the Fieldtrip toolbox, with 10,000 iterations and a threshold of $p=0.01$. For this analysis, we considered two time-windows: an early one (100–600 ms) to capture the early effects typically described in adults, i.e. either a LAN (Left Anterior Negativity), which typically appears between 100 and 400 ms, or an N400 which surfaces around 300–600 ms. The second time window (500–1000 ms) aims to capture the late P600 response whose typical latency is between 500 and 800 ms, but can also occur later, especially in children (Atchley et al., 2006; Schipke et al., 2012).

In the literature-driven analysis conducted next, we then constrained the time windows and clusters of electrodes to be analyzed based on prior findings. We observed a late posterior positivity resembling a P600, when inspecting the grand-average difference between grammatical and ungrammatical sentences. We selected the time window and clusters of electrodes encompassing this effect and, for each subject in each of the 4 conditions (Grammaticality by Word Category) averaged the voltage over the contributing data points. This allowed us to test for potential differences between our sub-conditions (verbs and nouns). As the grammatical and ungrammatical conditions featured the same set of critical words (and the same visual scenes), any difference between conditions will show that 18-month-old toddlers react differently to ungrammatical sentences relative to grammatical sentences. We also analyzed the grammaticality effect separately for the two halves of the experiment to establish whether toddlers might have changed their behavior over the course of the experiment (e.g., learning that ‘giraffe’ could also be used as a verb, as the experiment proceeds, which would lead to a decrease in the grammaticality effect).

3. Results

3.1. Cluster-based permutation analysis

During the early time-window (100–600 ms), the cluster-based permutation analysis did not reveal any significant effect. In contrast, the analysis of the late time-window revealed a near-significant positive centro-posterior cluster ($p=0.051$) spreading between 875 and 925 ms and consisting of up to four electrodes around P8 and P4 at its peak, together with a negative cluster that was its counterpart and was significant between 900 and 925 ms, containing 7 electrodes at its peak, around F3 ($p=0.02$). This effect exhibits the timing and topography typical of a P600, which is almost systematically present in adults when grammatical and ungrammatical sentences are compared. These first analyses reveal that toddlers are able to distinguish between our grammatical and ungrammatical sentences, even in the strictly controlled contexts used here.

3.2. Literature-driven analysis

consistent with the cluster-based permutation analysis reported above, the inspection of the two-dimensional reconstruction of the Ungrammatical-Grammatical difference revealed a late posterior positivity starting 800 ms after the beginning of the ungrammatical words, for a duration of 150 ms. This positivity was located over the parietal area and right-lateralized (Fig. 2). An ANOVA conducted on the average voltage of the 800–950 ms period and over the selected electrodes revealed a significant effect of Grammaticality ($F(1,24)=20.0$, $p=0.0002$). This effect remained significant when we considered each half of the experiment separately (first half, $t(24)=2.97$, $p=0.007$; second half: $t(24)=3.21$, $p=0.004$). The main effect of Word Category was not significant ($F(1,24)<1$), nor was the interaction between Word Category and Grammaticality ($F(1,24)<1$). Restricted analyses showed that the Grammaticality effect was present for both Word Categories (for Nouns: $t(24)=2.0$, $p=0.057$; for Verbs: $t(24)=3.52$, $p<0.002$, see graphs in Fig. S1, Supplementary materials). This suggests that both for nouns and for verbs, 18-month-olds detect the misuse of the critical words in the ungrammatical conditions.

4. Discussion

4.1. On-line identification of noun and verb contexts

In this experiment, we examined 18-month-olds' ability to identify the syntactic contexts in which nouns and verbs occur. More specifically, we observed that toddlers distinguish between contexts that require a noun and contexts that require a verb, even when the function word preceding the critical word was phonemically identical in both cases (i.e., *la* , meaning ‘the’ or ‘it’ depending on the context). Phrases such as *Hier* ***la*** X_N ‘Yesterday **the** X_N’ and *Elle* ***la*** X_V ‘She X_V **it**’ require different word classes for the critical word X, and toddlers exhibit different evoked potentials for critical content words when they are unexpected (nouns in verb contexts, or verbs in noun contexts) than when they are consistent with their preceding contexts (nouns in noun contexts, and verbs in verb contexts). Thus, by 18 months of age, toddlers' analysis of the unfolding sentence is not limited to tracking two-word co-occurrence patterns of function and content words: if that were the case, they should have based their expectations on the most frequent associations, anticipating a noun after hearing *la*, since this function word occurs more frequently as a determiner (therefore preceding nouns) than as an object clitic (therefore preceding verbs). Instead, their processing is more sophisticated,

Please cite this article as: Brusini, P., et al., (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.015

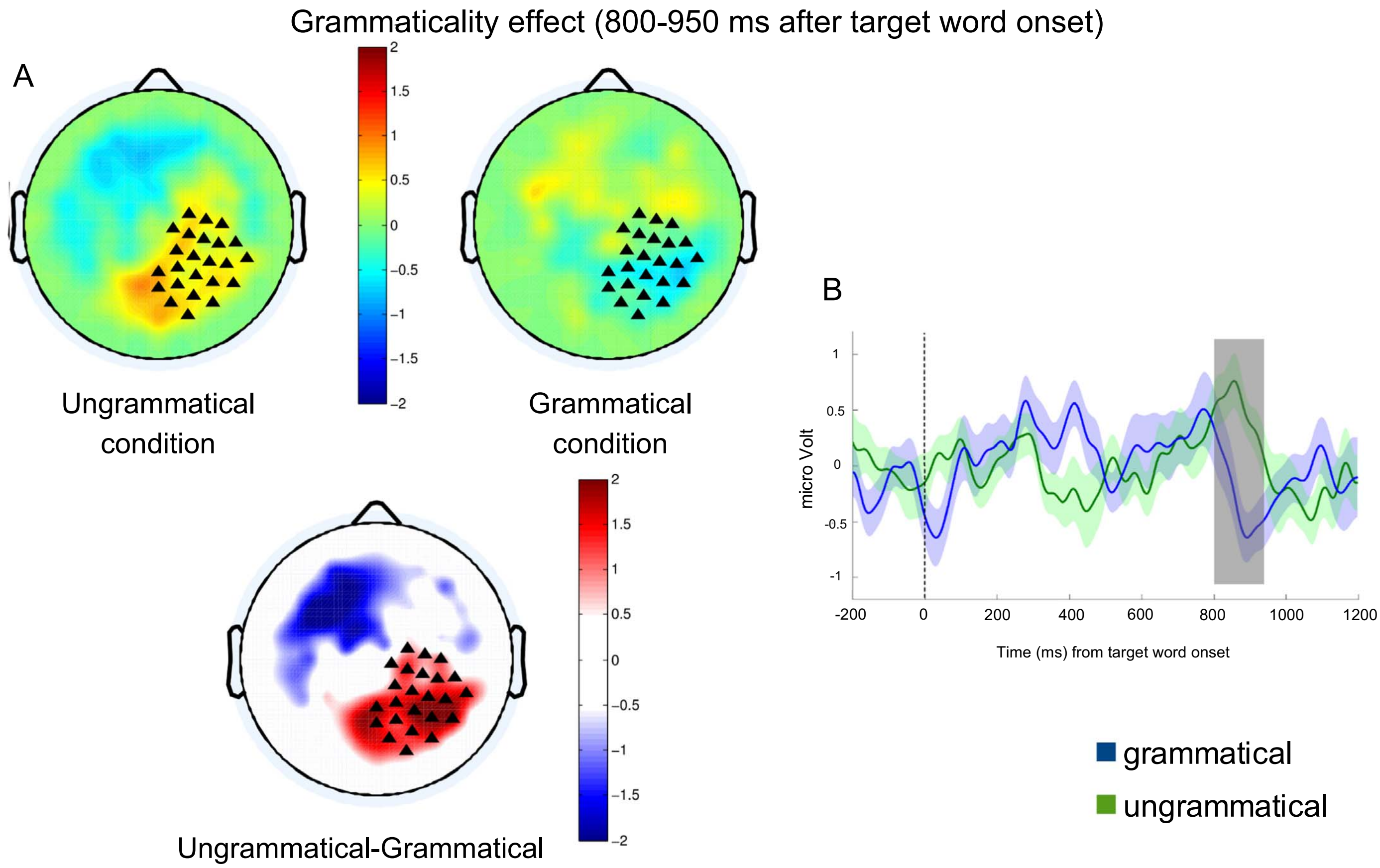

Fig. 2. *Grammaticality effect*: A late positive potential was observed in response to ungrammatical sentences 800 ms after the misplaced noun or verb. (A) Voltage recorded for the ungrammatical and grammatical sentences (on top) together with the map of statistical significance (*z*-score) of the difference Ungrammatical – Grammatical (triangles represent the electrodes used in the ANOVAs). (B) Time course of the activation for the selected cluster of electrodes, over the entire trial (blue curve: grammatical sentences; green curve: ungrammatical sentences); the selected time window is shaded (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

based on the on-line integration of nouns and verbs within their syntactic contexts. This experiment thus reveals that 18-months know not only the meaning of the verbs and nouns we used, but also the broader syntactic frames in which they occur.

Toddlers may have reacted to inconsistencies between the preceding context and the syntactic category of the critical word in two different ways. First, they may have accessed the lexical entry for the critical word (e.g. *mange* 'eat') and noticed that it occurred in a context that was inconsistent with its syntactic category. Under this interpretation, the ungrammaticality response would reflect a difficulty in integrating a known lexical item within the syntactic-semantic structure of the sentence. On the other hand, toddlers might have attempted to construct a novel lexical entry, with a different syntactic category (and different meaning) for a known phonological form. Under that assumption, upon hearing *mange* 'eat' in a noun context, they would search for a possible meaning for this word, much like they would if they had encountered a novel word form (such as *blicket*). This interpretation is not implausible, since we know i) that there are myriad noun/verb homophones in natural languages; ii) that children under two years of age have already acquired many such homophones (de Carvalho et al., 2014, 2016a; Veneziano and Parisse, 2011); and iii) that toddlers readily learn homophones of well-known words, especially when the two interpretations belong to two different syntactic categories (Dautriche et al., 2015a; Dautriche et al., 2015b). However, in these homophone-learning studies, children were provided with a plausible referent for the second member of the homophone pair. In the present experiment, by contrast, the 'new' homophone (*girafer* 'to giraffe' or *une donne* 'a give') appeared in the absence of any supportive context (as only the face of the speaker was visible in the test sentences), while the 'known' homophone (e.g. *la girafe* 'the giraffe' or *elle donne* 'she gives') appeared in a supportive visual context in which the known meaning was reinforced (during introductory sentences) about half the time. An alternative possibility is thus that this may have encouraged children to access the known lexical item rather than attempt to build a novel lexical entry. The present results do not allow us to disentangle these two interpretations. At any rate, both interpretations lead to the conclusion that 18-month-olds are able to distinguish between noun and verb contexts, and experience difficulty when known nouns and verbs are placed in incorrect contexts.

The finding that 18-month-olds differentiate between grammatical and ungrammatical sentences, even when the function word immediately preceding the critical word is ambiguous, is consistent with earlier results from 24-month-old children on similar stimuli (Bernal et al., 2010; Brusini et al., 2016). In these two other studies, 24-month-olds exhibited different responses for critical nouns and verbs in correct vs. incorrect contexts. In Bernal et al. (2010), a long-lasting left-temporal positivity was observed starting around 300 ms and extending until 1000 ms after target word onset. In Brusini et al. (2016), by contrast, a late posterior positivity was observed (700–900 ms), preceded by an early left anterior negativity (100–400 ms), a pattern which closely mirrored the results obtained with adult participants tested in the same experiment, who exhibited a LAN-P600 complex typically observed in the processing of ungrammatical sentences in adults (Brusini et al., 2016). The results from the present experiment are very similar to the late response observed in Brusini et al. (2016), only slightly delayed in time (800–950 ms).

This late positivity response is also consistent with prior work from other laboratories examining young children's processing of ungrammatical sentences (Oberecker et al., 2005; Schipke et al., 2011; Silva-Pereyra et al., 2005b). Although the timing of this response is delayed in young children relatively to the typical adult P600 (here by approximately 250 ms), its topography is consistent with the description in adults. Delayed latencies have typically been attributed to greater task difficulty for younger participants (Atchley et al., 2006; Holcomb et al., 1992) and slower higher-level responses due to the weak myelination of long-range tracts and immature cortical areas (Kouider et al., 2013). Following proposals from the adult and child literature, this P600-like effect probably reflects the highest level of sentence integration, unifying the semantic and syntactic levels of analysis (Friederici, 2011; Hagoort, 2005).

Contrary to several studies conducted with older children, the present study did not evoke an early response (Brusini et al., 2016; Oberecker and Friederici, 2006; Schipke et al., 2011; Silva-Pereyra et al., 2005a). The presence of an early response in these other studies was interpreted as an automatic mismatch between the expected and the actual word, thus reflecting children's ability to build on-line expectations regarding the syntactic category of an upcoming word. It may be the case that sentence processing in 18-month-olds is not yet fast enough to allow them to rely on such rapid predictive processing. Alternatively, the onset of this response in children this young may be too variable from one trial to the next, thus hindering the observation of an early effect when trials are averaged.

4.2. Syntactic analysis or multi-word contexts?

The finding that toddlers processed our grammatical and ungrammatical sentences differently is indicative of surprisingly sophisticated categorization skills early on in life. Given that all pairwise combinations of adjacent function and content words in our sentences (even in the ungrammatical ones) are legal in French, the present experiment demonstrates that 18-month-old toddlers are able to take into account non-adjacent lexical items when computing syntactic structure. What may have underlied this processing of broad sentence context in order to identify noun and verb contexts? One possibility, suggested by a reviewer, is that toddlers may have treated the ambiguous functor *la* as an optional item, thus considering *Alors moi je* ***la*** X… ('Then I X **it**…') or *Très gentiment* ***la*** X… ('Very kindly **the** X…') to be functionally similar to *Alors moi je X* or *Très gentiment X*, respectively. According to this proposal, toddlers' analysis of the preceding material alone might lead them to anticipate whether the next item is a verb (in the case of *Alors moi je X*) or a noun (in the case of *Très gentiment X*[4]) and *la* may simply be left unanalyzed. While our design indeed leaves open the possibility that the ambiguous function word does not contribute to the prediction of the category of the following word, we believe that this account is unlikely given the vast amount of evidence that 18-month-olds have long gained sensitivity to the co-occurrence between determiners and nouns (Hohle et al., 2004; Kedar et al., 2006; Shi and Melançon, 2010; Zangl and Fernald, 2007). Nonetheless, future EEG work directly targeted at the processing of the ambiguous function word could potentially further clarify this.

[4] Note that common nouns are obligatorily preceded by an article in French, which would make 'très gentiment girafe…' (*Very kindly giraffe*…) ungrammatical. But proper names are bare, and it may happen in children stories that an animal is named after its kind (e.g. '*very kindly, Giraffe*…'); under that reading the sentence would then be grammatical.

This leaves us with two remaining explanations. First, it is possible that 18-month-old toddlers have started to compute the syntactic structure of sentences in an adult-like manner. According to this view, children would know that *giraffe* is a noun and that nouns can follow determiners or adjectives, but not object clitics. In addition, children would assign the correct category to the preceding ambiguous function word –determiner or clitic– depending on the grammatical structure of the sentence. In essence, this would thus involve taking into account the syntactic category of the item preceding the ambiguous function word to build expectations about the syntactic category of the word following this ambiguous function word.

A second possibility is that toddlers relied on the two- or three-word contexts that preceded the critical nouns and verbs. According to this view, the specific brain responses evoked by ungrammatical sentences are due to the fact that the sequence of words *elle+la* has never been heard directly before a noun. Computing two-word contexts has been shown to be an effective way of categorizing nouns and verbs. For instance, a computational model tested on child-directed speech achieved very high precision in noun/verb categorization, simply by using two-word contexts that were extracted during a training phase on the basis of just a handful of nouns and verbs (under the assumption that these words are known by toddlers) to classify unfamiliar content words at test (Brusini et al., 2011; see also Redington et al., 1998). Thus, toddlers may very well have succeeded in the present experiment because they know which two-word contexts are indicative of subsequent nouns and which are indicative of subsequent verbs. Both of these mechanisms, the computation of a full-fledged hierarchical syntactic structure and the computation of two-word contexts, can greatly facilitate language processing. In fact, they are both part of mature behavior, as adult listeners have been shown to use both strategies during language processing (e.g. Ferreira and Patson, 2007).

Although the present experiment does not allow us to distinguish between these latter two interpretations, an indication that 18-month-olds might already be able to compute a rough syntactic structure, rather than solely relying on two-word contexts, comes from very recent behavioral work showing that French 18-month-olds are able to use phrasal prosody to assign two different syntactic structures to the same string of words (de Carvalho et al., 2015). For example, a sentence like 'Do you see the baby blicks' can be produced either as '[Do you see the baby blicks]? ', where the novel word 'blicks' is a noun, or as '[Do you see]? [the baby] [blicks]! ', where 'blicks' is a verb (as in 'Do you see? the baby sleeps! '; brackets indicate prosodic boundaries, reflecting the different syntactic structures). Toddlers correctly attributed a noun or a verb meaning to the critical word 'blicks', depending on its position within the prosodic-syntactic structure that they heard (consistent with earlier work with adults and preschoolers, de Carvalho et al., 2016a, 2016b; Kjelgaard and Speer, 1999; Millotte et al., 2008, 2007). Note that to succeed in this task, processing two-word contexts is not sufficient, since the words themselves are identical: 'Do-you-see-the-baby-blicks'. Thus, only phrasal prosody, reflecting the different syntactic structures, gives an indication as to how the words might be organized into syntactic constituents. This suggests that 18-month-olds pay attention to more than strings of words and take into account the hierarchical syntactic structure of sentences during language comprehension.

To conclude, this study shows that 18-month-old toddlers have gained a thorough understanding regarding the contexts dedicated to nouns and verbs. This knowledge is sufficiently detailed to allow them to compute the syntactic category of the content word following an ambiguous function word. Despite the overwhelming evidence for the local co-occurrence of 'la' and nouns in their input, children – at least by 18 months of age – do not solely rely on

Please cite this article as: Brusini, P., et al., (2016), http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.015

the computation of these simple distributional patterns, but also take into account the broader sentence context to deduce the syntactic category of the upcoming word. Toddlers might eventually use this ability to infer the syntactic category of novel words, and constrain their possible meanings. Thus, even at an age when children only produce extremely short utterances, their processing of syntactic structure is surprisingly robust.

Acknowledgements

This work was supported by the French Ministry of Research, the French Agence Nationale de la Recherche (grants n° ANR-2010-BLAN-1901, ANR-13-APPR-0012, ANR-11-0001-02 PSL* and ANR-10-LABX-0087), the Fondation de France (grant n° 2012-00033704), as well as by the Région Ile-de-France (grant n° 2009 IF-09-2095/R), a postdoctoral grant from the Fondation Fyssen to M.vH., and the European Research Council 269502, which supported P.B. while writing this manuscript. We thank L. Legros for help with data collection and V. Ul and M. Dutat for technical help, as well as all children and their families for their participation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2016.08.015.

References

Atchley, R.A., Rice, M.L., Betz, S.K., Kwasny, K.M., Sereno, J.A., Jongman, A., 2006. A comparison of semantic and syntactic event related potentials generated by children and adults. Brain Lang. 99 (3), 236–246. http://dx.doi.org/10.1016/j.bandl.2005.08.005.

Bernal, S., Dehaene-Lambertz, G., Millotte, S., Christophe, A., 2010. Two-year-olds compute syntactic structure on-line. Dev. Sci. 12, 69–76. http://dx.doi.org/10.1111/j.1467-7687.2009.00865.x.

Brusini, P., Amsili, P., Chemla, E., Christophe, A., 2011. Learning to categorize nouns and verbs on the basis of a few known examples: a computational model relying on 2-word contexts. Paper presented at the Society for Research on Child Development Biennial Meeting, Montreal (Canada).

Brusini, P., Dehaene-Lambertz, G., Dutat, M., Goffinet, F., Christophe, A., 2016. ERP evidence for on-line syntactic computations in 2-year-olds. Dev. Cogn. Neurosci. 19, 164–173. http://dx.doi.org/10.1016/j.dcn.2016.02.009.

Cauvet, E., Limissuri, R., Millotte, S., Skoruppa, K., Cabrol, D., Christophe, A., 2014. Function words constrain on-line recognition of verbs and nouns in French 18-month-olds. Lang. Learn. Dev. 10, 1–18. http://dx.doi.org/10.1080/15475441.2012.757970.

Christophe, A., Millotte, S., Bernal, S., Lidz, J., 2008. Bootstrapping lexical and syntactic acquisition. Lang. Speech 51, 61–75. http://dx.doi.org/10.1177/00238309080510010501.

Chu, C.J., Leahy, J., Pathmanathan, J., Kramer, M.A., Cash, S.S., 2014. The maturation of cortical sleep rhythms and networks over early development. Clin. Neurophysiol. 125 (7), 1360–1370. http://dx.doi.org/10.1016/j.clinph.2013.11.028.

Dautriche, I., Fibla, L., Christophe, A., 2015a. Learning homophones: syntactic and semantic context matters. Paper presented at the Boston University Conference on Language Acquisition, Boston (USA).

Dautriche, I., Swingley, D., Christophe, A., 2015b. Learning novel phonological neighbors: syntactic category matters. Cognition 143, 77–86. http://dx.doi.org/10.1016/j.cognition.2015.06.003.

de Carvalho, A., Dautriche, I., Christophe, A., 2014. Phrasal prosody constrains online syntactic analysis in two-year-old children. Paper presented at the Boston University Conference on Language Acquisition, Boston (USA).

de Carvalho, A., Dautriche, I., Christophe, A., 2016a. Preschoolers use phrasal prosody online to constrain syntactic analysis. Dev. Sci. 19, 235–250. http://dx.doi.org/10.1111/desc.12300.

de Carvalho, A., He, A.X., Lidz, J., Christophe, A., 2015. 18-month-olds use phrasal prosody as a cue to constrain the acquisition of novel word meanings. Paper presented at the Boston University Conference on Language Acquisition, Boston (USA).

de Carvalho, A., Lidz, J., Tieu, L., Bleam, T., Christophe, A., 2016b. English-speaking preschoolers can use phrasal prosody for syntactic parsing. J. Acoust. Soc. Am. 139 (6), EL216–EL222. http://dx.doi.org/10.1121/1.4954385.

Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J. Neurosci. Methods 134 (1), 9–21. http://dx.doi.org/10.1016/j.jneumeth.2003.10.009.

Demuth, K., Tremblay, A., 2008. Prosodically-conditioned variability in children's production of French determiners. J. Child Lang. 35 (1), 99–127. http://dx.doi.org/10.1017/s0305000907008276.

Ferreira, F., Patson, N.D., 2007. The "Good Enough" approach to language comprehension. Lang. Linguist. Compass 1 (1–2), 71–83. http://dx.doi.org/10.1111/j.1749-818X.2007.00007.x.

Friederici, A.D., 2011. The brain basis of language processing: from structure to function. Physiol. Rev. 91 (4), 1357–1392. http://dx.doi.org/10.1152/physrev.00006.2011.

Gebhart, A.L., Newport, E.L., Aslin, R.N., 2009. Statistical learning of adjacent and nonadjacent dependencies among nonlinguistic sounds. Psychon. Bull. Rev. 16 (3), 486–490. http://dx.doi.org/10.3758/pbr.16.3.486.

Gerken, L., Landau, B., Remez, R.E., 1990. Function morphemes in young children's speech perception and production. Dev. Psychol. 26, 204–216. http://dx.doi.org/10.1037/0012-1649.26.2.204.

Gerken, L., McIntosh, B., 1993. Interplay of function morphemes and prosody in early language. Dev. Psychol. 29, 448–457. http://dx.doi.org/10.1037/0012-1649.29.3.448.

Gervain, J., Nespor, M., Mazuka, R., Horie, R., Mehler, J., 2008. Bootstrapping word order in prelexical infants: a Japanese-Italian cross-linguistic study. Cogn. Psychol. 57 (1), 56–74. http://dx.doi.org/10.1016/j.cogpsych.2007.12.001.

Gomez, R.L., Gerken, L., 1999. Artificial grammar learning by 1-year-olds leads to specific and abstract knowledge. Cognition 70 (2), 109–135. http://dx.doi.org/10.1016/s0010-0277(99)00003-7.

Hagoort, P., 2005. On Broca, brain, and binding: a new framework. Trends Cognit. Sci. 9 (9), 416–423. http://dx.doi.org/10.1016/j.tics.2006.07.004.

Hallé, P., Durand, C., de Boysson-Bardies, B., 2008. Do 11-month-old French infants process articles? Lang. Speech 51, 45–66. http://dx.doi.org/10.1177/00238309080510010301.

Hochmann, J.-R., 2013. Word frequency, function words and the second gavagai problem. Cognition 128 (1), 13–25. http://dx.doi.org/10.1016/j.cognition.2013.02.014.

Hochmann, J.-R., Endress, A.D., Mehler, J., 2010. Word frequency as a cue for identifying function words in infancy. Cognition 115, 444–457. http://dx.doi.org/10.1016/j.cognition.2010.03.006.

Hohle, B., Weissenborn, E., Kiefer, D., Schulz, A., Schmitz, M., 2004. Functional elements in infants' speech processing: the role of determiners in the syntactic categorization of lexical elements. Infancy 5 (3), 341–353. http://dx.doi.org/10.1207/s15327078in0503_5.

Holcomb, P.J., Coffey, S.A., Neville, H.J., 1992. Visual and auditory sentence processing - a developmental analysis using event-related brain potentials. Dev. Neuropsychol. 8 (2–3), 203–241. http://dx.doi.org/10.1080/87565649209540525.

Kedar, Y., Casasola, M., Lust, B., 2006. Getting there faster: 18-and 24-month-old infants' use of function words to determine reference. Child Dev. 77 (2), 325–338. http://dx.doi.org/10.1111/j.1467-8624.2006.00873.x.

Kiebel, S.J., Friston, K.J., 2004. Statistical parametric mapping for event-related potentials (II): a hierarchical temporal model. Neuroimage 22 (2), 503–520. http://dx.doi.org/10.1016/j.neuroimage.2004.02.013.

Kjelgaard, M.M., Speer, S.R., 1999. Prosodic facilitation and interference in the resolution of temporary syntactic closure ambiguity. J. Mem. Lang. 40, 153–194. http://dx.doi.org/10.1006/jmla.1998.2620.

Kouider, S., Stahlhut, C., Gelskov, S.V., Barbosa, L.S., Dutat, M., de Gardelle, V., Dehaene-Lambertz, G., 2013. A neural marker of perceptual consciousness in infants. Science 340 (6130), 376–380. http://dx.doi.org/10.1126/science.1232509.

Kuperberg, G.R., 2007. Neural mechanisms of language comprehension: Challenges to syntax. Brain Res. 1146 (23–49). http://dx.doi.org/10.1016/j.brainres.2006.12.063.

Lewkowicz, D.J., Hansen-Tift, A.M., 2012. Infants deploy selective attention to the mouth of a talking face when learning speech. Proc. Natl. Acad. Sci. USA 109 (5), 1431–1436. http://dx.doi.org/10.1073/pnas.1114783109.

Maris, E., Oostenveld, R., 2007. Nonparametric statistical testing of EEG- and MEG-data. J. Neurosci. Methods 164 (1), 177–190. http://dx.doi.org/10.1016/j.jneumeth.2007.03.024.

Mensen, A., Khatami, R., 2013. Advanced EEG analysis using threshold-free cluster-enhancement and non-parametric statistics. Neuroimage 67, 111–118. http://dx.doi.org/10.1016/j.neuroimage.2012.10.027.

Millotte, S., René, A., Wales, R., Christophe, A., 2008. Phonological phrase boundaries constrain on-line syntactic analysis. J. Exp. Psychol.: Learn. Mem. Cogn. 34, 874–885. http://dx.doi.org/10.1037/0278-7393.34.4.874.

Millotte, S., Wales, R., Christophe, A., 2007. Phrasal prosody disambiguates syntax. Lang. Cogn. Process. 22, 898–909. http://dx.doi.org/10.1080/01690960701205286.

Oberecker, R., Friederici, A.D., 2006. Syntactic event-related potential components in 24-month-olds' sentence comprehension. Neuroreport 17 (10), 1017–1021. http://dx.doi.org/10.1097/01.wnr.0000223397.12694.9a.

Oberecker, R., Friedrich, M., Friederici, A.D., 2005. Neural correlates of syntactic processing in two-year-olds. J. Cogn. Neurosci. 17, 1667–1678. http://dx.doi.org/10.1162/089892905774597236.

Oostenveld, R., Fries, P., Maris, E., Schoffelen, J.-M., 2011. FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. Comput. Intell. Neurosci. 2011. http://dx.doi.org/10.1155/2011/156869.

Oshima-Takane, Y., Ariyama, J., Kobayashi, T., Katerelos, M., Poulin-Dubois, D., 2011. Early verb learning in 20-month-old Japanese-speaking children. J. Child Lang.

38 (3), 455–484. http://dx.doi.org/10.1017/S0305000910000127.

Pernet, C.R., Chauveau, N., Gaspar, C., Rousselet, G.A., 2011. LIMO EEG: a toolbox for hierarchical LInear MOdeling of ElectroEncephaloGraphic data. Comput. Intell. Neurosci. 2011. http://dx.doi.org/10.1155/2011/831409.

Redington, M., Chater, N., Finch, S., 1998. Distributional information: a powerful cue for acquiring syntactic categories. Cogn. Sci. 22 (4), 425–469. http://dx.doi.org/10.1207/s15516709cog2204_2.

Schipke, C.S., Friederici, A.D., Oberecker, R., 2011. Brain responses to case-marking violations in German preschool children. Neuroreport 22, 850–854. http://dx.doi.org/10.1097/WNR.0b013e32834c1578.

Schipke, C.S., Knoll, L.J., Friederici, A.D., Oberecker, R., 2012. Preschool children's interpretation of object-initial sentences: neural correlates of their behavioral performance. Dev. Sci. 15 (6), 762–774. http://dx.doi.org/10.1111/j.1467-7687.2012.01167.x.

Shady, M., 1996. Infant's Sensitivity to Function Morphemes (Ph.D Thesis). State University of New York, Buffalo.

Shafer, V.L., Shucard, D.W., Shucard, J.L., Gerken, L., 1998. An electrophysiological study of infants' sensitivity to the sound patterns of English speech. J. Speech Lang. Hear. Res. 41, 874–886.

Shi, R., Cutler, A., Werker, J., Cruickshank, M., 2006a. Frequency and form as determinants of functor sensitivity in English-acquiring infants. J. Acoust. Soc. Am. 119, EL61–EL66. http://dx.doi.org/10.1121/1.2198947.

Shi, R., Gauthier, B., 2005. Recognition of function words in 8-month-old French-learning infants. J. Acoust. Soc. Am. 117, 2426–2427. http://dx.doi.org/10.1121/1.4786583.

Shi, R., Melançon, A., 2010. Syntactic categorization in French-learning infants. Infancy 15, 517–533. http://dx.doi.org/10.1111/j.1532-7078.2009.00022.x.

Shi, R., Morgan, J.L., Allopenna, P., 1998. Phonological and acoustic bases for earliest grammatical category assignment: a cross-linguistic perspective. J. Child Lang. 25 (1), 169–201. http://dx.doi.org/10.1017/s0305000997003395.

Shi, R., Werker, J., 2001. Six-months old infants' preference for lexical words. Psychol. Sci. 12, 71–76. http://dx.doi.org/10.1111/1467-9280.00312.

Shi, R., Werker, J., Cutler, A., 2006b. Recognition and representation of function words in English-learning infants. Infancy 10, 187–198. http://dx.doi.org/10.1207/s15327078in1002_5.

Shi, R., Werker, J., Morgan, J., 1999. Newborn infants' sensitivity to perceptual cues to lexical and grammatical words. Cognition 72, B11–B21. http://dx.doi.org/10.1016/S0010-0277(99)00047-5.

Silva-Pereyra, J., Klarman, L., Lin, L.J.F., Kuhl, P., 2005a. Sentence processing in 30-month-old children: an event-related potential study. Neuroreport 16 (6), 645–648.

Silva-Pereyra, J., Rivera-Gaxiola, M., Kuhl, P.K., 2005b. An event-related brain potential study of sentence comprehension in preschoolers: semantic and morphosyntactic processing. Cogn. Brain Res. 23, 247–258. http://dx.doi.org/10.1016/j.cogbrainres.2004.10.015.

Udden, J., Ingvar, M., Hagoort, P., Petersson, K.M., 2012. Implicit acquisition of grammars with crossed and nested non-adjacent dependencies: investigating the push-down stack model. Cogn. Sci. 36 (6), 1078–1101. http://dx.doi.org/10.1111/j.1551–6709.2012.01235.x.

Van Heugten, M., Johnson, E.K., 2011. Gender-marked determiners help Dutch learners' word recognition when gender information itself does not. J. Child Lang. 38 (1), 87–100. http://dx.doi.org/10.1017/s0305000909990146.

Veneziano, E., Parisse, C., 2011. Retrieving the meaning of words from syntactic cues: a comprehension study. Paper presented at the International Conference on the Study of Child Language, (Montreal, Canada).

Waxman, S.R., Lidz, J.L., Braun, I.E., Lavin, T., 2009. Twenty four-month-old infants' interpretations of novel verbs and nouns in dynamic scenes. Cogn. Psychol. 59 (1), 67–95. http://dx.doi.org/10.1016/j.cogpsych.2009.02.001.

Zangl, R., Fernald, A., 2007. Increasing flexibility in children's online processing of grammatical and nonce determiners in fluent speech. Lang. Learn. Dev. 3, 199–231. http://dx.doi.org/10.1080/15475440701360564.

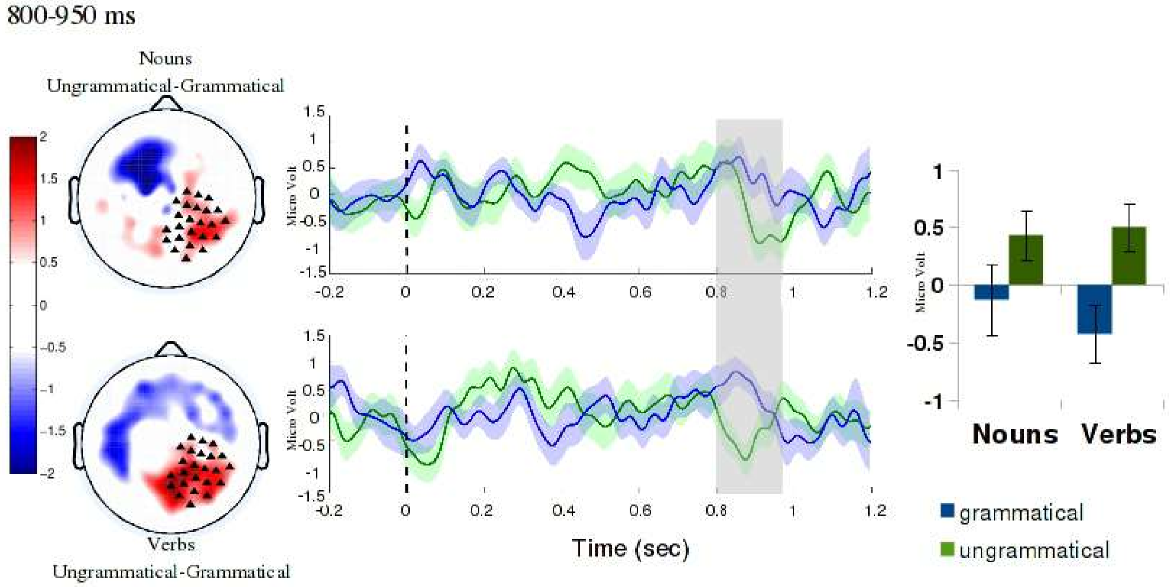

Figure S1: Grammaticality effect restricted to nouns (top half) and verbs (bottom half of the figure). Right: topographies of statistical significance (Z-score) of the difference Ungrammatical – Grammatical (triangles represent the electrodes used in the ANOVAs). Middle: Time course of the activation for the selected cluster of electrodes, over the entire trial (blue curve: grammatical sentences; green curve: ungrammatical sentences); the selected time window is shaded. Left: interaction between the Grammaticality and Word Category factors, over the selected time-windows and electrodes (this interaction is not significant, see text).

Appendix 1: Scripts for the 16 stories.
Each story contained 4 test sentences, during which there was a close-up on the speaker's face. Within each story, two of these sentences featured a verb as the critical word, and two featured a noun; two of the sentences were ungrammatical, and two grammatical. Each story started with one or two introductory sentences presenting a larger view of the speaker playing with toys, with which she illustrated what she was saying. The two critical words (one noun, one verb) that would be used in that story, were always mentioned in the introductory sentence(s). It was followed by two test sentences, then one or several liaison sentences with again the larger view (to keep toddlers interested in the story), then the last 2 test sentences. There were either 3 or 4 syllables before the 'la+critical word' sequence, and these numbers were matched between categories (with an average of 3.31 syllables for each of the 4 subcategories created by crossing the factors Gram/Ungram and Noun/verb).
The syntactic structures preceding the critical sequence were also matched between grammatical and ungrammatical sentences. For instance, for noun contexts, there were 6 sentences with a full NP subject followed by a verb, before the article 'la', as in 'la poupée voit la…' *the doll sees the…* or 'la fille prend la…' *the girls takes the…*; out of these 6 sentences, 3 were in the Grammatical Noun condition and 3 in the Ungrammatical Verb condition (and so on for all the structures that were used, they were matched one-to-one, each ungrammatical sentence sharing its context with a grammatical sentence).

Each video lasted 28 seconds, therefore each block of 16 videos lasted about 10mn. Any given toddler watched at least one block of 16 videos (10mn), and no more than 4 blocks, for those who were willing to sit through the task longer (so 40mn at most).

Story 1 : *(translation is provided for the first story only)*
Introduction : Sur ma table, je vois une **girafe** qui va à l'école. Elle **regarde** la poule.
On my table, I see a giraffe who goes to school. She's looking at the hen

T1. Donc la poule **la regarde** aussi. (3syll) Gram Verb
So the hen looks at her too.
T2. Pourtant, elle **la girafe** très vite. (3syll) Ungram Noun
However she giraffes it very quickly.

Liaison : Elles jouent ensemble. La poule danse devant la girafe!
They play together. The hen dances in front of the giraffe !

T3. C'est drôle, elle **la regarde** en riant. (3syll) Gram Verb
It's funny, she looks at her laughing
T4. Alors l'autre **la girafe** aussi. (4syll) Ungram Noun
So the other one giraffes her too.

Story 2 :
Regarde! J'ai trouvé une pomme et une **balle** ! Je **donne** la pomme au chat.

T1. Le chat me **la donne**, elle est à moi! (3syll) Gram Verb
T2. Alors je **la balle** plus loin. (3syll) Ungram Noun

Le chat court là-bas. Je donne la balle au crocodile.

T3. Il tape sur **la donne** avec son nez. (3syll) Ungram Verb
T4. Puis il lance **la balle** vers moi. (3syll) Gram Noun

Story 3 :
Le chien **mange** des fruits. Cette **fraise** a l'air très bonne!

T1. Mais si je **la mange**, le chien n'en aura plus! (3syll) Gram Verb
T2. Il croit que je **la fraise** avant lui! (4syll) Ungram Noun

Je lui rends cette fraise, tu as vu comme je suis gentille!

T3. Il prend donc **la fraise** avec plaisir! (3syll) Gram Noun

T4. Tu crois que **la mange** est bonne ? (3syll) Ungram Verb

Story 4 :

La **grenouille finit** son repas. La petite fille boit encore de la soupe**.**

T1. Elle a vu **la grenouille** qui mange. (3 syll) Gram Noun

T2. Gentiment, **la finit** lui donne de la soupe (3 syll) Ungram Verb

Il reste une pomme. La grenouille l'a vue.

T3. La fille prend **la finit** avant elle. (3 syll) Ungram Verb

T4. La fille et **la grenouille** n'ont plus faim. (3 syll) Gram Noun

Story 5 :

Tu as vu cette **grenouille**? Elle **regarde** la poupée.

T1. Donc, celle-ci **la regarde** aussi, amusée. (3 syll) Gram Verb

T2. Mais elle tape **la regarde**, ce n'est pas très gentil. (3 syll) Ungram Verb

La grenouille s'est cachée, elle a eu peur.

T3. La poupée voit **la grenouille**, et la caresse. (4 syll) Gram Noun

T4. Ensuite, elle **la grenouille** en souriant. (3 syll) Ungram Noun

Story 6 :

Le chat a vu une poire. Il donne sa **fraise** à la **poule**.

T1. Il aime bien **la donne**, miam ! (3 syll) Ungram Verb

T2. La poule prend **la fraise** et la regarde. (3 syll) Gram Noun

Mais ça ne lui plaît pas, elle aimait bien la poire !

T3. Alors, elle rend **la fraise** au chat. (4 syll) Gram Noun

T4. Après ça, **la donne** est tranquille. (3 syll) Ungram Verb

Story 7 :

Quel drôle de chat ! On dirait qu'il **mange** de la viande près de **sa balle**...

T1. Oh! Le chat **la balle** par là ! (3 syll) Ungram Noun

T2. Finalement, il **la mange** avec plaisir. (4syll) Gram Verb

Il cherche quelque chose… Oh ! il y a aussi de la soupe.

T3. Il aime ça, il **la balle** comme la viande. (4syll) Ungram Noun

T4. Mmmh, le chat **la mange** , c'est bon ! (3syll) Gram Verb

Story 8 :

Oh! Quelle jolie **girafe**. Elle **finit** de manger une feuille avec le chien.

T1. C'est drôle, elle **la girafe** longtemps ! (3 syll) Ungram Noun

T2. Mais le chien **la finit** le premier. (3 syll) Gram Verb

Il reste une feuille. Peut-être que la girafe a encore faim ?

T3. Elle veut manger **la finit**, je crois. (4syll) Ungram Verb

T4. Tu crois que **la girafe** aime les feuilles ? (3syll) Gram Noun

Story 9 :

Le chien **regarde** ce qu'il y a sur la table. Tiens! Une **balle**.

T1. Il observe **la balle** avec attention. (3syll) Gram Noun

T2. Il joue avec **la balle** un moment. (4syll) Gram Noun
J'aimerais bien jouer aussi. Le chien est d'accord.
T3. Mais il lance **la regarde** trop bien pour moi! (3syll) Ungram Verb
T4. Donc je jette **la regarde**, je ne suis pas contente! (3syll) Ungram Verb

Story 10 :
La **grenouille** a trouvé une fleur. Le chat dit **'Donne**-la moi!'.
T1. Alors elle **la donne** au chat. (3syll) Gram Verb
T2. Mais le chat **la grenouille** par terre. (3syll) Ungram Noun
La grenouille est en colère. Elle reprend la fleur
T3. Après ça, elle **la grenouille** un moment. (3syll) Ungram Noun
T4. Enfin elle **la donne** à la poule, c'est aussi bien! (3syll) Gram Verb

Story 11 :
Oh, tu as vu! **La girafe** et le coq **mangent** de la purée.
T1. Je crois que **la mange** n'aime pas trop ça! (3syll) Ungram Verb
T2. Le coq regarde **la mange** avec un drôle d'air! (4 syll) Ungram Verb
Maintenant ils ont envie d'une pomme. En voilà une !
T3. Ca alors, **la girafe** a vite terminé! (3syll) Gram Noun
T4. Après ça, **la girafe** n'a vraiment plus faim. (3syll) Gram Noun

Story 12 :
Miam! J'ai **fini** une **fraise**. Mais il en reste une autre!
T1. Alors, je **la fraise** avant qu'un autre ne la prenne! (3syll) Ungram Noun
T2. Pendant que je **la finis**, un petit chien arrive. (4syll) Gram Verb
Le chien a apporté une poire! Elle est jolie.
T3. Maintenant il **la fraise** pour rire. (4syll) Ungram Noun
T4. Et puis on **la finit** ensemble. (3syll) Gram Verb

Story 13 :
La poule **regarde** par terre. Elle voit une **fraise**!
T1. Alors elle **la fraise** sans y faire attention! (3syll) Ungram Noun
T2. Maintenant, elle **la regarde** avec envie! (4syll) Gram Verb
Qu'est-ce qu'elle va faire La manger ?
T3. Elle veut manger **la fraise**! (4syll) Gram Noun
T4. Alors elle pousse **la regarde** pour mieux l'attraper. (4syll) Ungram Verb

Story 14 :
Regarde! Je **donne** cette feuille à **la girafe.**
T1. Très gentiment **la girafe** me prête sa balle! (4syll) Gram Noun
T2. Alors moi je **la donne** au crocodile! (4syll) Gram Verb
Le crocodile est très content! C'est une jolie balle.
T3. Alors, il me **la girafe** en souriant. (4syll) Ungram Noun
T4. L'animal et **la donne** sont heureux. (4syll) Ungram Verb

Story 15 :
La **grenouille mange** bien. Il ne reste qu'une feuille.
T1. Pourtant, elle **la grenouille** avec envie. (3syll) Ungram Noun
T2. Enfin elle **la mange**, c'est bon. (3syll) Gram Verb

Et toi, tu aimerais manger cette nouvelle feuille?

T3. Je crois que **la grenouille** aimerait bien, elle! (3syll) Gram Noun

T4. Elle prendra **la mange** qui reste, sûrement. (3syll) Ungram Verb

Story 16 :

Le chien **finit** sa poire. Puis il fait rouler sa **balle**.

T1. Il s'assied sur **la finit**, c'est drôle! (4syll) Ungram Verb

T2. Oh! Comme il **la balle** bien! (3syll) Ungram Noun

Je lui ai encore donné de la soupe. Elle est chaude !

T3. Il aime ça, il **la finit** très vite! (4syll) Gram Verb

T4. Il joue à **la balle** avec moi, ensuite. (3syll) Gram Noun