**When dogs meow: an electrophysiological study of lexical-semantic processing in
toddlers**

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Abstract

The goal of this study was to investigate lexical–semantic processing at an early phase of language development. Adults often communicate with children using *infant-directed speech* that typically involves lexical and syntactic modifications such as *onomatopoeias* (Soderstrom, 2007). Here we asked how and when children start to show an advantage for processing conventional linguistic forms, such as common nouns, and consequently decreasing sensitivity to onomatopoeias. We recorded event-related brain potentials in children of two age groups (16 to 20 months and 24 to 30 months) and in an adult control group during the presentation of the four conditions in which either common nouns or onomatopoeias were presented auditorily followed by either a congruent or incongruent image. The younger children showed a N400 effect only for onomatopoeic words, while the older children showed a N400 effect only for common nouns. The adults show N400 for onomatopoeia and nouns. These different N400 effects suggest that these categories are differently organized in children’s semantic memory and that the acquisition of linguistic abilities affects and modifies semantic processing of different lexical information.

Keywords: Event-related potentials; N400; Onomatopoeic words; Sound symbolism; Early semantic processing; Toddlers

1. Introduction

During the first year of life, infants start to map speech sounds onto meaning and to establish lexical–semantic representations (Imai & Kita, 2014; Delle Luche et al., 2014; Friedrich & Friederici, 2004, 2005, 2010). An important unanswered question is when children start to build the semantic lexicon that relies more on arbitrary conventional linguistic signs (i.e. common nouns) and less on the sound symbolic properties of the words (i.e. onomatopoeic words).

Recently, researchers have started to investigate the process of language acquisition by focusing on *iconicity* (Perniss & Vigliocco, 2014). Iconicity is defined as the resemblance between properties of a linguistic form and the sensorimotor and/or affective properties of referents (Perniss & Vigliocco, 2014). For example, during everyday conversations, the gestures that accompany speech are often iconic (i.e. imaginistic) of the content of the speech (e.g. a heart gestured with index fingers and thumbs creating a symbolic heart). Recent findings suggested that iconicity eases language learning processing in children (Laing, 2017; Asano et al., 2015; Imai et al., 2008). One particular form of iconicity is the so-called *sound symbolism*. Sound symbolism is a non-arbitrary relationship between speech sounds and meaning (Imai & Kita, 2014a; Laing, 2017c). A popular case is the takete-maluma effect (Köhler, 1947; Ramachandran & Hubbard, 2001), in which voiceless stop consonants (e.g., /p/, /t/ and /k/), and high-front unrounded vowels (e.g., /i/ as in heed) tend to be associated with sharp shapes, and sonorant consonants (/m/, /n/ and /l/) and back rounded vowels (e.g., /u/ /ou/) show an association with round shapes (Sidhu et al., 2019). Therefore, we often associate the word takete with more sharp, spiky shapes and the word maluma with round figures.

Several studies showed that infants are sensitive to the takete-maluma effect and that they are able to map information across different modalities (Lourenco & Longo, 2010;

Walker et al., 2010; Yeung & Werker, 2009). In a recent study, Miyazaki and colleagues (2013) tested 14-month-old infants with a cross-modal takete-maluma paradigm (Köhler, 1947): a visual stimulus was followed by an auditorily presented novel word that was either sound-symbolically congruent (“moma”) or incongruent (“kipi”) with the visual stimulus (e.g., a round shape). The results revealed that infants looked faster and longer to shapes that were sound-symbolically congruent than incongruent. According to the *sound symbolism bootstrapping hypothesis* (Imai & Kita, 2014c), infants’ cross-modal mapping ability makes them biologically sensitive to sound symbolism. Sound symbolism helps infants to establish word–referent associations at early stages of language development and facilitates both language processing and acquisition (Imai et al., 2008; Maurer et al., 2006; Asano et al., 2015).

Similar results were found by Asano and colleagues (2015) who investigated sound symbolism in a group of 11-month-old infants during the presentation of pairs of novel words and visual stimuli that were either sound-symbolically match or mismatch. Their results suggested that 11-month-old infants map auditory linguistic information onto visual stimuli and are sensitive to sound symbolism. In this study, Asano and colleagues (2015) investigated sound symbolism in infants by analyzing the adult-like N400 response, a negative event-related brain potential that peaks roughly 400 ms after the onset of a stimulus (Kutas & Hillyard, 1980; Kutas & Federmeier, 2011). The N400 reflects the spreading activation in the access of semantic information by a stimulus in relation to its preceding context (Kutas & Federmeier, 2011) and is sensitive to semantic violations related to a large array of meaningful information. Asano and colleagues (2015) found an increased adult-like N400 response in the mismatch as compared to the match condition, revealing that, infants detected mismatches between sound and shape at a conceptual/semantic level. This suggests that sound symbolism elicits semantic processing in children, and that they might build

lexicons with the help of iconic relationship between sound and meaning (Imai & Kita, 2014).

The work on sound symbolism suggests that the semantic network of children is sensitive to a non-arbitrary relationship between speech sounds and meaning (Asano et al., 2015; Imai & Kita, 2014). However, other research demonstrated that children are also sensitive to the arbitrary semantic relatedness between speech sounds and meaning (Friedrich & Friederici, 2011; Junge et al., 2012). For example, Friedrich and Friederici (2011) used a cross-modal learning paradigm and observed the earliest N400 effects in 6-month-old infants in response to pairs of stimuli (i.e. object and word). N400 effects appeared for 9-month-old infants in response to incongruent conclusions of an observed action (Kaduk et al., 2016) and during the presentation of an object incongruent with the word that introduced it (Parise & Csibra, 2012). By 12 months, children show an N400 effect to picture-word semantic priming which is modulated by the size of children's vocabulary (Friedrich & Friederici, 2010). Rämä and colleagues (2013) recorded brain activity in 18- and 24-month-old children during a word-word priming task for spoken words that were either semantically related (e.g., train–bike) or unrelated (e.g., chicken–bike). The results showed a N400-like priming effect in 24-month-olds children and in the 18-month-olds children with higher word production ability. Moreover, cross-modal priming and semantic relatedness effects have been observed in children between 14 and 19 months, using word-picture paradigms (Friedrich & Friederici, 2005; 2004; 2008; 2010; Sirri & Rämä, 2015). In an ERP study, Friedrich and Friederici (2005) analyzed the brain response in 12- and 19-month-old children and in an adult control group during the cross-modal presentation of pictures of familiar objects and auditory pseudowords, nonwords, or words that were either congruous or incongruous to the picture contents. The results showed that in 19-month-olds and in adults, incongruous words and pseudowords elicited an N400 effect, suggesting that adult-like mechanisms of semantic

processing are already functional in 19-month-olds. In contrast, 12-month-olds did not reveal any N400 response, but showed a lexical priming effect as evident by a negativity at 100 ms after congruous words presentation.

Overall, the results of the previous investigations suggested that, along with the increase of the vocabulary size, children may no longer expect sound symbolism in words because of the increasing number of vocabulary items that exhibit arbitrary relations between speech sounds and meaning (Imai & Kita, 2014; Monaghan et al., 2014). Here we asked how and when children start to build their vocabulary on the basis of arbitrariness rather than sound symbolism. In the context of sound symbolism, *onomatopoeia* represents a useful phenomenon to address this issue. Onomatopoeia is defined as the naming of an object or an action by a vocal imitation of the sound associated with it (such as buzz, hiss; Merriam-Webster dictionary, n.d.). Onomatopoeias occur in infant speech across many languages (Imai & Kita, 2014) and are generally very common in infant's production repertoire from 8 to 20 months (Kern et al., 2010). Different studies estimate that this type of word constitutes almost 40% of the vocabulary in 11-months-olds (Laing, 2014) and over a third between the ages of 8 and 16 months (Kern et al., 2010). Onomatopoeias become less prominent in the lexicon throughout early development (Kauschke & Hofmeister, 2002) and are systematically replaced with conventional words (Lockwood & Dingemanse, 2015). At the time when the use of ambiguous and onomatopoeic words usually decreases (around 16 and 20 months) other categories, that include common nouns, verbs, adverbs, adjectives, increase (Camaioni, 1995).

Onomatopoeias are part of the so-called *infant-directed speech* (IDS; Kuhl, 2004), a speech mode often used by adults to communicate with children that typically is characterized by exaggerated pitch (Cooper & Aslin, 1990), expanded intonation (Fernald & Simon, 1984), higher variable speech rate and rhythm (Lee et al., 2014; Leong et al., 2017),

and lexical and syntactic modifications (Soderstrom, 2007). Caregivers use onomatopoeias to depict objects and the sounds that those objects make. However, no previous studies have investigated how these categories are organized in children's semantic system and how the acquisition of linguistic abilities affects and modifies semantic processing of the different lexical information. One can assume that infants may associate an onomatopoeic word with its referent more easily due to the natural sound–meaning link (Jespersen, 1950; Nygaard, 2009). Furthermore, during early phases of language development caregivers often use onomatopoeias instead of words to communicate with children (Soderstrom, 2007). Therefore, we expect that the meaning of a familiar object is more strongly associated to onomatopoeic labels at an earlier stage of language development and to common nouns at later stage.

In a recent work, Laing (2017) used eye-tracking to analyze onomatopoeia processing in 10- and 11-month-old infants during a picture-mapping task. This task tested infants' ability to match onomatopoeic words and their corresponding conventional linguistic forms to their referents. The results showed that infants revealed an advantage for onomatopoeia processing compared to their conventional counterpart, but they also found that this advantage could be mediated by infants' experience of the linguistic forms (Laing, 2017).

In the present study, we investigated how and when semantic processing becomes sensitive to different types of lexical information (i.e. common nouns, onomatopoeias) and how this sensitivity develops across language development. In particular, we asked whether and if so, when, children start to show an advantage for processing conventional linguistic forms and consequently decreasing sensitivity to sound symbolic properties of the words. To this aim, we compared the semantic processing elicited by onomatopoeias and common nouns in two groups of children (16 to 20 months and 24 to 30 months) and a group of adults. Previous studies suggested that lexical-semantic processing is already present at this age,

although significant differences have been observed (Friedrich & Friederici, 2004, 2005, 2010). In the present study, brain activity was measured via ERPs during the presentation of four conditions in which either common nouns or onomatopoeic utterances were presented auditorily followed by the visual presentation of pictures of familiar objects either a congruent or incongruent with the acoustic stimulus.

We expected age-related differences reflected by differential N400 effects to onomatopoeic utterances and common nouns across the two age groups. If the onomatopoeic utterance is more strongly associated with the meaning of the object at an earlier stage of language development (Imai & Kita, 2014), this would result in a stronger N400 effect in response to onomatopoeic utterances compared to the common nouns in the younger group of children, compared to the older children and the adult group. In the older group of children, we expected an increased N400 effect to common nouns (and an attenuation of the N400 amplitude to onomatopoeic utterances) because at this age, children are expected to associate pictures of known objects with their correct name (Friedrich & Friederici, 2004). This result would reflect the replacement of the onomatopoeic utterance by the common noun associated with the meaning of a given object.

2. Methods

2.1 Participants

The sample consisted of $N = 60$ toddlers, half of them ($n = 30$, 14 males) at the age of 16-21 months (*younger age group*; mean age = 18.1 months, $SE = 1.6$) and half of them ($n = 30$ toddlers, 12 males) at the age of 24 – 31 months (*older age group*; mean age = 27.8 months, $SE = 2.3$). All toddlers were recruited from local birth records. They were born full term (week of gestation ≥ 37), had normal birth weight (≥ 2500 g), grew up in Swiss-German monolingual households and had right-handed parents. In addition, a group of 22 Swiss-

German speaking young adults (6 males) was included (age range: 19-35 years; mean age = 23.3 years, $SE = 4.3$).

All procedures were approved by the local ethics committee and performed in accordance with the ethical standards of the 1964 Helsinki declaration and its later amendments. All parents gave informed consent. The toddlers received a small age-appropriate toy worth approximately CHF 5,- and a printed certificate for their participation in the study. The adult participants were students at the University of Zurich and received course credits for their participation.

Ten participants from of the younger age group, ten participants of the older group and two adult participants were excluded from the ERP statistical analyses because of EEG artifacts, including excessive blinking, eye-movements, and muscular movements. This resulted in 20 final participants in the younger age group (male/female), 20 participants in the older age group and 20 participants from the adult group. A sample size of 20 is typical for N400 studies on children (Asano et al., 2015; Hendrickson et al., 2018) and adults (Bridger et al., 2012). In addition, a sensitivity power analysis conducted using G*Power 3.1 (Faul et al., 2007) revealed that with $N = 20$ we could detect medium-sized effects of $f = 0.27$ for a within/within-between repeated measures ANOVAs with $\alpha = 0.05$ and a statistical power of $(1 - \beta) = 0.80$.

2.2 Stimuli

We presented an auditory and a visual stimulus by using a cross-modal priming paradigm, described in the next section. The auditory stimulus material included 18 common nouns (16 animal labels and 2 artifact labels) and 18 onomatopoeic words (16 animal sounds and 2 artifact sounds). To create the onomatopoeic words list, we created two online questionnaires: In the first one we asked Swiss-German-speaking parents of children aged 12

to 24 months to assign a sound to a depicted animal/object. After creating the onomatopoeic words and common nouns lists, we developed a second questionnaire in which Swiss German speaking parents of children aged 12 to 24 months were asked to select the nouns and onomatopoeic words that were familiar to their children. For the EEG study, we selected the onomatopoeia and the words that were evaluated as familiar by the parents.

Two native Swiss German speakers (one male and one female) produced the auditory stimuli which were recorded in a single session in a sound attenuating booth. Common words and onomatopoeic utterances were balanced in duration (mean duration = 817 ms, $SD = 141$ ms) and sound quality (44.1 kHz, 16 bit, stereo) using the software Praat. A t-test revealed no significant differences ($p = 0.07$) between the duration of onomatopoeic words ($M = 847$ ms, $SD = 156$ ms) and common nouns ($M = 788$ ms, $SD = 119$ ms).

The visual stimulus material consisted of simple and colored pictures depicting familiar object, such as an animal or a car (the complete dataset is available at <https://osf.io/nhztd/>). Because children's books often include illustrations rather than photographs, cartoon-images of the objects were used rather than realistic photographs because the children would have easily recognized them.

The auditory onomatopoeic words and the common nouns were either congruent or incongruent with the content of the pictures. We created four conditions by modulating the type of auditory words (i.e. common nouns and onomatopoeic words) and their congruence with the visual images (congruent vs. incongruent): The *congruent common nouns condition* contained an auditory noun coherent with the contents of the image, the *incongruent common nouns condition* used a noun incoherent with the image, the *congruent onomatopoeic words condition* contained an auditory onomatopoeia coherent with the image, and *incongruent onomatopoeic words condition* used a onomatopoeia incoherent with the image (see Figure 1).

A group of 10 Swiss German speaking adults evaluated whether the auditory word (common noun vs. onomatopoeia) did or did not match with the content of the image. Congruent stimuli that were rated as incongruent and incongruent stimuli that were evaluated congruent by at least 20% of these evaluators were discarded. This procedure resulted in two lists including 36 word-pictures stimuli (18 congruent, 18 incongruent). The order of presentation was counterbalanced between participants. The recording of the ERPs was synchronized to the onset of the auditory word.

Figure 1. Example of images used as experimental stimuli. We synchronized a congruent common noun, an incongruent common noun, a congruent onomatopoeic word and incongruent onomatopoeic word to the picture.

2.3 Procedure

Upon arrival at the lab, the caregivers were asked to provide information about years of education and handedness of both parents. Furthermore, to assess common nouns and onomatopoeic production, the caregivers filled out an online questionnaire in which they reported whether their toddler understood and spontaneously produced (i.e. vocalized) the common nouns and the onomatopoeic words presented in the EEG paradigm. Language

status was not assessed directly, because parent reports have poor validity, especially for the second year of life (Tomasello & Mervis, 1994; Eriksson et al., 2002; Feldman et al., 2005).

The EEG session took place in a dimly lit, electrically shielded, and sound-attenuated room. The toddler sat on the caregiver's lap, at an approximate distance of 60 cm from a 17-inch computer screen with adjacent loudspeakers. Stimuli were presented using the software E-Prime (Version 2.0; Psychology Software Tools, Inc., Pittsburgh, PA). The EEG paradigm consisted of four separate blocks, in which the trials were presented in random order. Each block consisted of a maximum of 36 trials (18 trials per condition) but was terminated by the experimenter if the toddler was not attending to the stimuli anymore (i.e. inattention for more than 6 trials in a row). After every third trial, an attention grabber was presented. Attention grabbers consisted of a cartoon presented for 3 s without speech (taken from Baby Tv channel). The blocks were separated by short breaks that usually lasted few seconds (max. break duration was 60 s). After the first two blocks the participants were invited to take a longer break that could last 2 to 3 minutes.

During stimulus presentation, a picture appeared for 2 s on the screen. After an interval of 1 s from picture onset, either a common noun or an onomatopoeic word was acoustically presented while the picture was still presented on the screen. These words were either semantically congruent or incongruent with the object depicted in the picture. Each stimulus stayed on screen for 2000 ms, separated by an ISI of 500 ms.

2.4 Electroencephalographic recording parameters

The electroencephalogram (EEG) was recorded from 128 electrodes at a sampling rate of 250 Hz (online bandpass-filtered between 0.01–100 Hz). The EEG was recorded and analyzed using the Net station software (Geodesic EEG Net Station, EGI, Eugene, OR) (Figure 2). The impedance of all electrodes was kept below 50 k Ω over the experiment. All recordings

were referenced to Cz electrode during data acquisition. This solution allowed us to analyze the mastoid-temporal lobe activity in addition to all other important sites for the linguistic processing.

Figure 2. Schematic showing the 128-channel array of scalp electrodes from which the EEG was recorded.

2.5 Statistical analysis of ERPs

Trials contaminated by blinks, muscle tension (EMG), channel drift, and/or amplifier blocking were discarded before averaging. The artifact rejection criterion was based on peak-to-peak amplitudes exceeding 50 μV . Approximately 9% of epochs were rejected due to such artifacts, with losses distributed approximately evenly across the conditions. Participants with more than 20% of all trials being marked bad were removed from analysis. Each participant's EEG was time-locked to auditory word onsets.

Evoked response potentials (ERPs) from 100 ms before stimulus onset to 1500 ms after stimulus onset were averaged off-line. Finally, a 30-Hz lowpass filter was applied and data were re-referenced to an average reference.

ERP components (including the site and latency to reach maximum amplitude) were identified and measured with respect to the average baseline voltage over the interval from -100 to 0 ms. Our analysis focused on three epochs of interest. We investigated the mean amplitude voltage of the N400 in the 350-550 ms (after stimulus onset) epoch and two subsequent time windows of 550-750 ms and 750-950 ms to investigate any later effects (i.e. P600 and/or sustained negativity/positivity). These responses were measured at 72 electrode sites (8 in each region) in fronto-left (23, 24, 26, 32, 33, 27, 34, 28), fronto-central (18, 16, 10, 22, 9, 15, 21, 14), fronto-right (3, 124, 2, 123, 122, 1, 117, 116), centro-left (39, 40, 45, 46, 41, 47, 50, 51), central (7, 106, 31, 80, 55, 30, 105, 79), centro-right (104, 103, 102, 98, 101, 97, 115, 109), parieto-left (58, 59, 60, 70, 66, 65, 69, 64), parietal (61, 62, 78, 67, 72, 77, 71, 76), parieto-right (96, 85, 91, 83, 84, 90, 95, 89) electrode sites (see Manfredi et al., 2018). Because we might expect a different scalp distribution of the ERP responses for each type of lexical information (Manfredi et al., 2017; Manfredi et al., 2018) and because this is the first study to use EEG to compare common nouns and onomatopoeias comprehension, we selected these sites to avoid missing any possible non-expected effects and to provide a broad scalp representation of the ERP responses.

We used a repeated measures ANOVA to analyze the mean amplitude of N400 and later components in the two groups of children. The ANOVA included the between-subjects factor Age Group (2 levels: younger, older) and the three within-subjects factors Stimulus type (2 levels: common nouns, onomatopoeic words), Congruency (2 levels: congruent, incongruent) and Regions (9 levels, see previous paragraph). In the adult control group, the mean N400 amplitude and the later components were analyzed using a separate repeated

measures ANOVA with the three within-subjects factors Stimulus type (2 levels: see above), Congruency (2 levels: see above) and Regions (9 levels: see above).

In addition, to observe potential differences in semantic processing between the two different age stages, we analyzed the mean amplitude of the onomatopoeic and common words congruity effects, in each case anomalous minus congruent ERP. To this aim, we compared the amplitude of the N400 difference ERPs. Mean amplitude of the difference ERPs was analyzed using repeated measures ANOVAs with 1 between-groups factor Age Group (2 levels: younger, older) and 2 within-groups factors: Condition (2 levels: onomatopoeic words difference wave and common nouns difference waves) and Regions (9 levels). All statistical analyses were performed using Statistica software (Statsoft version 7.0, USA). Multiple comparisons of means were performed by using post-hoc Fisher's tests.

3. Results

The results section is structured in the way that we start by presenting the results of the two toddler groups (N400, sustained negativity, later effects) followed by the same results of the adult participants.

3.1 Results of toddlers

N400 – Children

The ANOVA across regions for the mean amplitude of the N400 component (range = 350 to 550 ms) showed a significant Stimulus type x Congruency x Region x Age Group interaction, $F(8, 304) = 3.52$, $p = .001$, $\eta_p^2 = 0.08$, revealing that only the older children showed a greater N400 effect to incongruent common nouns compared to the congruent ones in the parietal sites (incongruent: $-2.22 \mu V$, $SE = 1.00$; congruent: $0.18 \mu V$, $SE = 1.00$; $p < .001$). No differences were found between the incongruent and the congruent common

nouns in the younger children at any scalp sites (all $ps > .10$; Figures 3). Conversely, only the younger children showed a greater N400 amplitude in response to incongruent onomatopoeic words ($-5.00 \mu\text{V}$, $SE = 0.99$) compared to the congruent ones ($-2.83 \mu\text{V}$, $SE = 0.84$) in the centro-parietal sites (all $ps < .001$). No differences were found between the incongruent and the congruent onomatopoeic words in the older children at any scalp sites (all $ps > .10$), see Figures 4.

In addition, the ANOVA performed on the difference waves (mean amplitudes of the incongruent onomatopoeic words minus congruent onomatopoeic versus incongruent common nouns minus congruent common nouns waveforms) revealed larger amplitude of the onomatopoeic N400 congruity effect in the younger children than the older children, $F(8, 288) = 4.53$; $p < .001$, $\eta_p^2 = 0.08$, over central (younger children: $-0.11 \mu\text{V}$, $SE = 0.80$; older children: $0.56 \mu\text{V}$, $SE = 0.84$) and parietal sites (younger children: $-0.60 \mu\text{V}$, $SE = 0.98$; older children: $-0.02 \mu\text{V}$, $SE = 1.05$). Conversely, the statistical analysis showed a larger amplitude of the common nouns N400 congruity effect in the older children than the younger children over the central (younger children: $0.18 \mu\text{V}$, $SE = 0.85$; older children: $-0.05 \mu\text{V}$, $SE = 0.90$) and parietal sites (younger children: $0.11 \mu\text{V}$, $SE = 1.02$; older children: $-2.41 \mu\text{V}$, $SE = 1.05$).

Figure 3. Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (blue) and Incongruent (red) common nouns in the younger (left panel) and the older children (right panel).

Figure 4. Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (orange) and Incongruent (green) onomatopoeic words in the younger (left panel) and the older children (right panel).

Sustained negativity – Children

The ANOVA performed on children groups in the 550-750 ms time window revealed a significant Stimulus type x Congruity x Region interaction, $F(8, 304) = 1.97$; $p = .04$, $\eta_p = 0.04$, a greater sustained negativity to incongruent common nouns ($0.24 \mu V$, $SE = 1.12$) compared to congruent ones ($2.03 \mu V$, $SE = 1.00$) in the parietal sites ($p = .010$), see Figure 4. No differences were found between the incongruent and the congruent onomatopoeic words any scalp sites (all $ps > .10$).

Later effects – Children

The ANOVA performed in the 750-950 ms time window revealed a significant Stimulus type x Congruency x Region interaction x Age Group three-way interaction, $F(8, 304) = 2.10$, $p = .03$, $\eta_p = 0.05$, showing that the younger children showed a greater late positivity to incongruent common nouns ($-0.79 \mu V$, $SE = 1.03$) compared to the congruent ones ($-3.89 \mu V$, $SE = 0.99$) in the centro-left sites ($p = .01$). No differences were found between the incongruent and the congruent onomatopoeic words in the younger group at any scalp sites (all $ps > .10$).

In addition, older children showed a greater late negativity to incongruent common nouns ($-1.25 \mu V$, $SE = 1.18$) compared to the congruent ones ($1.36 \mu V$, $SE = 0.98$) in the central sites ($p = .04$), see Figure 3, and a greater late positivity to incongruent onomatopoeic words ($7.93 \mu V$, $SE = 1.55$) compared to the congruent ones in the parietal sites ($5.29 \mu V$, $SE = 1.24$; $p = .04$), see Figure 4.

3.2 Results of adults

N400 – Adults

In the adults, the ANOVA performed on the N400 time window showed the significance of the Congruency x Region interaction, $F(8, 152) = 4.11, p < .001, \eta_p = 0.17$ revealing a greater N400 to incongruent stimuli than the congruent ones in the central (congruent: $0.14 \mu V, SE = 0.20$; incongruent: $-0.39 \mu V, SE = 0.19$) and in the parietal sites (congruent: $-0.16 \mu V, SE = 0.13$; incongruent: $-0.68 \mu V, SE = 0.18$) (see Figure 5).

Sustained negativity – Adults

No significant results were found in the adult participants in this time window (all $ps > .10$), see Figure 5.

Later effects – Adults

In the adult groups, the ANOVA performed on the latest time window showed the significance of the Stimulus type x Region interaction, $F(8, 152) = 4.10, p = .001, \eta_p = 0.17$, revealing a greater positivity to onomatopoeic words ($1.87 \mu V, SE = 0.27$) compared to the common nouns ($1.07 \mu V, SE = 0.30$) in the parietal sites and a greater negativity to onomatopoeic words ($-2.50 \mu V, SE = 0.42$) compared to the common nouns ($-1.71 \mu V, SE = 0.40$) in the frontal ones (Figure 5). No congruency effects were found in this time window.

Figure 5. Top: Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (orange) and Incongruent (green) onomatopoeic words in adults. Below: Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (blue) and Incongruent (red) common nouns in adults.

4. Discussion

In this work we investigated when and how children start to build the semantic lexicon relying more on arbitrary conventional linguistic signs and less on the sound symbolic properties of the words. For this, we compared semantic processing of different types of lexical information (i.e. onomatopoeic words, common nouns) in two different age groups with different language skills. To achieve this aim, we recorded brain activity via ERPs during a picture-word matching task in children from two age groups (i.e. a group of younger children aged 16 to 20 months and a group of older children aged 24 to 30 months) and in an adult control group. The ERPs were measured during the presentation of auditory common nouns and onomatopoeic words that were either semantically congruent or incongruent with the picture of a familiar object. Our results showed different N400 effects to onomatopoeic utterances and common nouns across the different age groups: the younger children revealed a N400 effect only to incongruent onomatopoeic words as compared to congruent ones, while the older children showed a N400 effect only to incongruent common nouns compared to congruent ones. Finally, the adults revealed a N400 effect to both incongruent common nouns and onomatopoeic words. These findings support the hypothesis that the meaning of a familiar object is more strongly associated with onomatopoeic labels at an earlier stage of language development and with common nouns at later stages. In addition, our findings suggest that the onomatopoeic labels associated with a given object at the early stages of language acquisition, are replaced by the common ones at later stages. Overall, our findings suggest that the knowledge gained from linguistic experience along development influences the semantic processing of different types of lexical information. In the following, we discuss the findings of the current study in more detail, focusing on the comparison between the semantic processing related to the elaboration of different stimuli in the two groups of children and in the adults at different stages of the processing. We will first focus

on the N400 time window, where the semantic processing elicited by onomatopoeias and common nouns in children and adults occurred; then we will focus on the later brain responses, reflecting re-analysis processing both in the two groups of children and in the adults. Finally, we will discuss about some aspects that need further attention in future studies.

Semantic processing of onomatopoeic words vs. common nouns

We observed an N400 effect to incongruent onomatopoeic words over the parietal sites and to incongruent common nouns compared to congruent ones in the centro-parietal sites. This result is in line with previous studies that investigated cross-modal semantic processing both in adults (Bach et al., 2009; Proverbio & Riva, 2009) and in children (Friedrich & Friederici, 2005; 2010), confirming that verbal stimuli associated with incongruent visual images elicited N400 congruity effects.

To our knowledge, the present study is the first to examine the neurocognitive processing of onomatopoeic words, and their comparison with common nouns, in healthy young children. Our findings suggested that semantic processing of these two classes of words changes across the development: the statistical analysis revealed that younger children showed a N400 effect to incongruent onomatopoeic words compared to the congruent ones in the centro-parietal sites but no differences were found between incongruent and the congruent common nouns in the younger group at any scalp sites. This result is in line with previous studies on sound symbolism and onomatopoeia production in children. In fact, according to *the sound symbolism bootstrapping hypothesis* (Imai & Kita, 2014b), infants' cross-modal mapping ability makes them biologically sensitive to sound symbolism, a phenomenon that facilitates both processing and language acquisition (Imai et al., 2008; Asano et al., 2015; Maurer et al., 2006).

Infants benefit from sound symbolism during the acquisition of new concepts, which explains the stronger link between onomatopoeic labels and meaning at early stages of language development. However, this word mapping facilitation usually decreases as language development proceeds (Ma et al., 2011). Nevertheless, onomatopoeic forms are very common in infant's production repertoire and constitute almost 40% of their vocabulary (Lockwood & Dingemanse, 2015; Laing, 2017). Our study revealed a greater brain response to onomatopoeic words compared to their conventional counterparts in younger children. This result is in line with the previous evidence on the advantage for onomatopoeia processing compared to their conventional counterpart at early stages of language development (Camaioni, 1995; Kern, 2010; Laing, 2017).

Moreover, the statistical analysis revealed that only the older children showed a N400 effect to incongruent common nouns compared to the congruent ones in the centro-left and parietal sites. This result is in line with previous findings that, using a priming task or a word-picture matching task, found an N400 incongruity effect to familiar words in children (Friedrich & Friederici, 2004, 2005, 2010; Rämä et al., 2013). Thus, our findings confirmed that at this developmental stage (i.e. 24 months) children associate pictures of known objects and animals with their common nouns (Friedrich & Friederici, 2005). These results indicate that increasing familiarity with words (Conboy & Mills, 2006; Thierry et al., 2003) affects the brain responses during word presentation (Rämä et al., 2013) probably due to the increasing of the vocabulary size.

In addition, the analysis indicated that the older group of children did not show any N400 congruity effect to onomatopoeic words. Observational studies pointed out that the use of ambiguous and onomatopoeic words usually decreases between 16 and 20 months of age while linguistic categories such as common nouns, increase in children's vocabulary (Camaioni, 1995). Therefore, our result might reflect the replacement of the onomatopoeic

utterance by the corresponding conventional linguistic form learned through acquired linguistic experience. Compared to observational studies we found this effect later in the development. The reasons for these differences may be several: first, Camaioni's study adopted a longitudinal approach while we chose a cross-sectional one; in addition, the sample size of their study was relatively small ($N = 15$) and homogeneous in terms of socio-economic and socio-cultural status, that was medium-high. Moreover, it is important to underline that when Camaioni analyzed word-tokens instead of word-types, the proportions of common nouns and onomatopoeic words did not differ significantly between 16 and 20 months of age (Camaioni, 1995).

Finally, the congruity effect (i.e. difference wave) comparison of the common nouns and onomatopoeic words in the two groups of children in our study, showed a reverse effect: older showed a congruity effect to common nouns while younger revealed a congruity effect only to onomatopoeic words. This difference in the N400 congruity effects confirmed that incongruent onomatopoeic word-picture pairs were easier to recognize in younger children compared to older and conversely, incongruent common noun-picture pairs were easier to recognize in older children compared to younger ones.

Overall, the analysis performed on the N400 time window in the two groups of children, confirmed the hypothesis that the meaning of an object is more strongly associated with onomatopoeic words at an earlier stage of language development, and with common nouns over later stages of the development. In the adult group, the analysis revealed a greater N400 effect to incongruent stimuli than the congruent ones in the central and parietal sites.

These findings are in line with a previous ERP work on adults (Manfredi et al., 2017) in which the potential influence of lexical information on the semantic processing and the integration of images within a visual narrative have been examined. To this aim, the lexical type and semantic congruity of written words have been crossed in visual narrative

sequences. Specifically, onomatopoeic words, which phonetically imitate action sounds (Pow!) and descriptive words, which describe an action (Punch!), that were (in)congruent within their sequence contexts, have been compared. The results of this previous study pointed out qualitatively similar semantic congruity effects, namely a greater N400 to anomalous words than semantically congruent words, regardless of lexical category. Similar to these findings, in our work herein, there were no reliable differences in N400 scalp distributions or timing in response to the different types of words (i.e. onomatopoeic words and common nouns) in the adult group. This result suggests that the different types of meaningful auditory information associated with a visual information engaged similar semantic processes in young adults.

Therefore, our results pointed out that while it seems that the onomatopoeic words have been replaced by the common ones in the older children, adults are able to recover the meaning of the onomatopoeic words. A possible reason for such different responses between adults and older children may be that whereas at an early stage of the development the onomatopoeic word corresponds to the meaning of the object (that has then been replaced with the conventional linguistic form), later in life the onomatopoeic words are part of the lexicon again but constitute a specific feature of a given object (i.e. the sound it makes) and not its label. However, further investigation is needed to shed more light on this matter.

Later stages of comprehension processing

Following the N400, in the 550–750 ms time window we observed a greater sustained negativity to incongruent onomatopoeic words compared to congruent ones in the parietal sites in children. This result might reflect a continuation of the N400 effect for onomatopoeic words.

Finally, the ANOVA performed in the 750-950 ms time window in children revealed that only the older children showed a greater sustained negativity to incongruent common nouns compared to the congruent ones in the central sites. Similar sustained negativities have been observed following N400s in response to visual anomalies in sequences of visual narratives or visual events (Cohn et al., 2012; West & Holcomb, 2002). In our study, this sustained frontal negativity could reflect a general cost of further processing the inconsistent interaction between auditory verbal and visual information in older children.

In addition, both groups of children showed a greater late positivity to incongruent onomatopoeic words compared to the congruent ones in the centroparietal sites. The late positivity is often elicited together with the N400 and has been related to a process of re-analysis of the incongruent situation produced by inconsistent meaning (Ibáñez et al., 2011; Sitnikova et al., 2003; Van Petten & Luka, 2012), particularly when the incoming word disconfirms predictions created by a preceding context (Quante et al., 2018). In our study, this late response could indicate that both groups of children recognized the discontinuity of incoming onomatopoeic word relative to its prior context. Even if older children did not show a N400 effect to incongruent onomatopoeic words, this late response suggests that they identified incongruities in this class of stimuli at later stages.

Finally, we found that the adults group showed a greater negativity to onomatopoeic words compared to the common nouns in the parietal sites, regardless the congruency. In a review work, Mecklinger and colleagues (2016) analyzed the functional meaning of the late posterior negativity, an ERP effect frequently reported in episodic memory tasks. The authors concluded that the late negativity could be associated to a general mechanism involved both in episodic and in semantic memory tasks, in particular in contexts which require very specific recovery processing or continuous analysis of the recovered information. Therefore, the greater late negativity in response to onomatopoeic words in the adults group might

suggest that this class of words have become less familiar and therefore require a greater recovery effort.

Future considerations

Our results raise several questions regarding early lexical–semantic processing both in children and in adults. In this study, cross-modal semantic processing was examined by contrasting brain activity in response to onomatopoeic words and common nouns in monolingual children. Because some onomatopoeias are shared across languages, it would be interesting to investigate the processing of lexical-semantic information in monolingual and early bilingual children at different critical stages of language development.

Moreover, because we found that, unlike the older children, adults are able to recover the meaning of the onomatopoeic words, it would be worth to investigate how the semantic processing of the onomatopoeic words changes over the course of development until adulthood. In particular, it would be interesting to analysis whether different types of external factors (i.e. experience in comics reading) might influence the ability to recover the meaning of the onomatopoeic words in adulthood.

Conclusion

In conclusion, this work revealed similar semantic processing to onomatopoeic words and common nouns in children. However, these processes change along the language development and with the acquisition of new linguistic abilities. Specifically, this study revealed that at the age of 24 months children start to replace onomatopoeic words with conventional linguistic signs such as common nouns. This result suggests that at this age, children start to build the semantic lexicon relying more on arbitrary conventional linguistic signs and less on the sound symbolic properties of the words.

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Figure captions

Figure 1. Example of images used as experimental stimuli. We synchronized a congruent common noun, an incongruent common noun, a congruent onomatopoeic word and incongruent onomatopoeic word to the picture.

Figure 2. Schematic showing the 128-channel array of scalp electrodes from which the EEG was recorded.

Figure 3. Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (blue) and Incongruent (red) common nouns in the younger (left panel) and the older children (right panel).

Figure 4. Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (orange) and Incongruent (green) onomatopoeic words in the younger (left panel) and the older children (right panel).

Figure 5. Top: Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (orange) and Incongruent (green) onomatopoeic words in adults. Below: Grand-average ERP waveforms recorded at frontal, central and posterior midline sites in response to Congruent (blue) and Incongruent (red) common nouns in adults.