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Electrophysiological Evidence for the Involvement of the Approximate Number System in Preschoolers' Processing of Spoken Number Words

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Abstract

Little is known about the neural underpinnings of number-word comprehension in young children. Here we investigated the neural processing of these words during the crucial developmental window in which children learn their meanings and whether such processing relies on the Approximate Number System (ANS). Event-related potentials (ERPs) were recorded as 3- to 5-year-old children heard the words one, two, three or six while looking at pictures of 1, 2, 3 or 6 objects. The number word was incongruent with the number of visual objects on half the trials, and congruent on the other half. Children's number-word comprehension predicted their ERP incongruency effects. Specifically, children with the least number-word knowledge did not show any ERP incongruency effects, whereas those with intermediate and high number-word knowledge showed an enhanced, negative-polarity ERP incongruency response (N_{inc}) over centro-parietal sites from 200–500 ms after the number-word onset. This negativity was followed by an enhanced, positive-polarity incongruency effect (P_{inc}) that emerged bilaterally over parietal sites at about 700 ms. Moreover, children with the most number-word knowledge showed ratio dependence in the P_{inc} (larger for greater compared to smaller numerical mismatches), a hallmark of the ANS. A similar modulation of the P_{inc} from 700–800 ms for number words “one”, “two” and “three” was found in children with intermediate number-word knowledge. These results provide the first neural correlates of spoken number-word comprehension in preschoolers and are consistent with the view that children map number words onto approximate-number representations before they master the verbal count list.

Learning the meaning of number words is a gradual process that goes well beyond the age at which children first memorize the count list (Wynn, 1990, 1992). Children at the age of two are typically able to recite the count list, but do so with little understanding of how it relates to the number of elements in a set. Accordingly, young children exhibit only partial knowledge about the cardinal meaning of the counted number words (e.g., understanding just *one*, understanding just *one* and *two*, and so on) and are considered “subset-knowers”. It is only around the age of four that children understand that the last number reached when counting a set establishes its cardinality and are thus considered to be “cardinal-principle knowers” (CP-knowers) (e.g., Condry & Spelke, 2008; Le Corre & Carey, 2007; Le Corre, Van de Walle, Brannon, & Carey, 2006; Sarnecka & Carey, 2008; Wynn, 1990, 1992).

Before children learn the count sequence they already show robust evidence of representing number approximately without language. In fact, the approximate number system (ANS) is seen in a wide array of species and emerges early in human infancy (Feigenson, Dehaene, & Spelke, 2004). A hallmark of the ANS is ratio-dependence, that is, discrimination is dependent on the ratio between numerosities and not their absolute values. Thus, empirically ratio dependence is considered a litmus test for the ANS. Despite the existing behavioral and neural evidence that the ANS is employed in number processing in infancy (e.g., Berger, Tzur, & Posner, 2006; Brannon, Abbot, & Lutz, 2004; Feigenson et al., 2004; Hyde & Spelke, 2011; Libertus & Brannon, 2009; Xu & Spelke, 2000), there is much controversy over the nature of the nonverbal representations that serve in childhood as the basis for learning the meaning of number words and for counting (e.g., Carey, 2009; Huntley-Fenner & Cannon, 2000; Le Corre & Carey, 2007; Rousselle, Palmers, & Noel, 2004; Sarnecka & Lee, 2009; Slaughter, Kamppi, & Paynter, 2006; Wagner & Johnson, 2011). According to one view, the ANS serves as the foundation upon which arbitrary number words are mapped (e.g., Gallistel & Gelman, 1990; Gelman & Gallistel, 2004; Pica, Lemer, Izard, & Dehaene, 2004). A second view holds that children map number words onto enriched parallel individuation representations of up to 3 or 4 single items. Accordingly, this proposed object-file system encodes number implicitly, such that there are no set level numerical representations and instead each object in a set is represented individually (e.g., Carey, 2009; Le Corre & Carey, 2007; Sarnecka & Lee, 2009). Furthermore, and related to the lack of resolution of this issue, no previous studies have investigated the neural underpinnings of the processing of spoken number words in young children and whether there is neural evidence that such representations are mapped onto the ANS. To address this, we used ERPs to examine the neural bases of number-word comprehension to auditorily presented number words in preschool aged children.

Previous electrophysiological studies examining the development of word comprehension have used semantic incongruency paradigms to study how the child's brain processes words in meaningful contexts. The basic reasoning of this approach has been that detection of semantic incongruencies would depend on the child's word comprehension level. In these studies a picture of an object is presented, followed by an acoustic presentation of a word that is either semantically congruent or incongruent with the visual stimulus. The main two ERP effects that have been described for such incongruency paradigms are the N400 and LPC (for "late positive complex"). The N400 is a language-related negative-polarity potential that peaks about 400 ms post-stimulus onset over centro-parietal sites. It is a hallmark electrical brain response that is elicited in response to wide variations of meaningful stimuli and is thought to reflect neuronal mechanisms of semantic integration into context. The N400 is larger in amplitude for semantically incongruent than for semantically congruent trials, thereby marking the detection of a contextual mismatch, with its size generally reflecting the degree of mismatch or unexpectedness (for a review see Kutas & Federmeier, 2011). The elicitation of an N400 has been reported in the picture-word paradigm in infants (although usually peaking much later than the typical 400 ms latency in adults), as well as in older children and in adults (e.g., Byrne et al., 1999; Friedrich & Friederici, 2004; Henderson, Baseler, Clarke, Watson, & Snowling, 2011; McCleery et al., 2010).

The LPC is also elicited in both children and adults in incongruity paradigms, typically occurring at around 600–900 ms post-stimulus over midline and posterior sites in response to a variety of semantically meaningful visual and auditory stimuli (e.g., Friedman, Sutton, Putnam, Brown, & Erlenmeyer-Kimling, 1988; Juottonen, Revonsuo, & Lang, 1996; Kok & Rooijakkers, 1985; Licht, Kok, Bakker, & Bouma, 1988; Sitnikova, Kuperberg, Holcomb, 2003). Such late positive waves are elicited under different task conditions and show variability in peak latencies and scalp distributions, suggesting that they are unlikely to reflect a single cognitive process. Given that the LPC is often preceded by the N400 and can be evoked by semantic violations, with increased amplitude to semantic mismatches, it is also thought to reflect the later processing of stimulus meaning (Juottonen et al., 1996; Munte, Heinze, Matzke, Wieringa, & Johannes, 1998).

Incongruity-related ERP effects with some similarity to those described above are also elicited by paradigms that are used to study stimulus conflict processing, such as in the well-known Stroop task. In the classic Stroop task (Stroop, 1935) participants are visually presented with color words and are asked to respond to the color of the font, which can be congruent or incongruent with the meaning of the word. Congruent trials are responded to faster than incongruent trials, and the reaction-time difference between these trials (incongruent minus congruent) is typically referred to as the Stroop incongruity effect. Two ERP incongruity effects are typically elicited in the Stroop task: a centrally distributed negative-polarity wave peaking around 450 ms (N450), followed by a later (500–800 ms) posterior sustained positivity (SP) (e.g., Appelbaum, Meyerhoff, & Woldorff, 2009; Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez, & Mayberg, 2000; West, 2003). Similar components have been identified in an auditory version of the Stroop task, supporting supramodal conflict detection mechanisms (Donohue, Liotti, Perez, & Woldorff, 2012). Furthermore, both of these ERP effects have been reported in adults across various response modes, including where no verbal or manual responses were required (Donohue et al., 2012; Liotti et al., 2000). The N450, which has also been called the N_{inc} (for negative-polarity incongruity effect; Donohue et al., 2012), has been hypothesized to be related to conflict-processing activity in the anterior cingulate cortex (ACC) (Liotti et al., 2000; Szucs & Soltesz, 2012; West, 2003). According to another view, this negative-incongruity wave resembles the N400 by indexing semantic conflict at the stimulus level (Rebai, Bernard, & Lannou, 1997). The late SP component has been proposed to reflect additional semantic processing by posterior word-processing areas (Liotti et al., 2000), control processes related to trial completion (Larson et al., 2009), and to represent activity of a supramodal attentional control system that facilitates and suppresses task-relevant and irrelevant information (Donohue et al., 2012), respectively.

Similar incongruity ERP effects marked by a negativity (N450) followed by somewhat shorter-duration positivity have been reported in adults using a numerical version of the Stroop paradigm, typically testing the automatic processing of Arabic numerals (e.g., Szucs & Soltesz, 2007, 2012; Szucs, Soltesz, & White, 2009). ERP interference effects to Arabic numerals have also been observed in school-aged children, starting from the first grade (Gebuis, Herfs, Kenemans, de Haan, & van der Smagt, 2009; Soltesz, White, & Szucs, 2011; Szucs, Soltesz, Jarmi, & Csepe, 2007). The numerical Stroop task, as well as other numerical-processing tasks with children and adults such as numerical comparisons, same/

different numerical judgments and passive-viewing designs, have been shown to elicit ERPs that are modulated by numerical distance or ratio. Such distance-related ERPs were reported at both early (~200 ms after stimulus onset) and/or later latencies (usually about 400 ms after stimulus onset) (e.g., Dehaene, 1996; Gebuis et al., 2009; Hsu & Szucs, 2010; Hyde & Spelke, 2009; Libertus, Woldorff & Brannon, 2007; Paulsen, Woldorff, & Brannon, 2010; Soltesz et al., 2011; Szucs et al., 2007; Szucs & Soltesz, 2007; Temple & Posner, 1998). To our knowledge, only one prior study (Szucs & Csepe, 2005) has used an ERP paradigm to specifically examine the neural response to acoustically presented number words. That study, which was done with adults, reported ERP distance effects over frontal and parietal sites around 200 ms post-stimulus onset. Thus, numerical distance-related ERPs have been found with both visual and auditory stimuli in paradigms that require participants to make numerical judgments, as well as in more passive-viewing designs.

The goals of the present study were twofold. The first goal was to examine whether the brains of young children show incongruency-related ERP effects to spoken number words when they did not match a visual-object scene. The second goal was to explore the relationship between children's number-word knowledge and their mapping of number words onto approximate number system (ANS) representations, which we anticipated would be evidenced by numerical ratio ERP effects. To this end we implemented a version of the ERP picture-word paradigm (e.g., Byrne et al., 1999; Friedrich & Friederici, 2004; Henderson et al., 2011; McCleery et al., 2010) to test children's neural response to spoken number words that were either congruent or incongruent with the number of visible objects. We tested children between 3 and 5 years of age who showed a wide range in mastery of the verbal count list as measured by the Give-a-Number procedure (Wynn, 1990, 1992).

Given the age of the children and the fact that many children were expected to show behavioral evidence of understanding just a few numbers words (e.g., only "one" and "two") we limited the stimuli to the first number words that a typical child acquires ("one," "two," and "three") and included "six" to increase the possible ratios for the later testing of numerical ratio effects. It is important to note that even though three out of these four words represent small values within the subitizing range, prior studies across development and across species have shown that small numerical values can elicit ratio-dependent responses, consistent with the employment of the ANS (e.g., Brannon & Terrace, 1998; Cordes & Brannon, 2009; Cordes, Gelman, Gallistel, & Whalen, 2001).

Based on previous findings with the picture-word and Stroop paradigms, we hypothesized that children's understanding of number words would modulate their integration of semantic information into the numerically incongruent versus congruent context, which would be reflected by a negative-polarity incongruency ERP effect (similar to the N400, N450 and N_{inc} components) and a late positive incongruency effect (similar to the LPC and SP components) both known to reflect the detection of semantic incongruency. We predicted that Cardinal Principle knowers (CP-knowers) who understood the meaning of all number words presented, would show larger ERP incongruency effects compared to children who exhibited only partial understanding (i.e., subset-knowers). Furthermore, since the semantic processing of incongruent trials hinges on the comparison of the number word with the number of visual objects, we expected a greater incongruency effect for larger ratio trials

(e.g., a picture of 2 objects paired with “six”) compared to smaller ratio trials (e.g., a picture of 3 objects paired with “six”) (e.g., Dehaene, 1996; Gebuis et al., 2009; Hsu & Szucs, 2010; Hyde & Spelke, 2009; Libertus et al., 2007; Paulsen et al., 2010; Soltesz et al., 2011; Szucs & Csepe, 2005; Szucs et al., 2007; Szucs & Soltesz, 2007; Temple & Posner, 1998). Such voltage differences as a function of numerical ratio will implicate the use of the ANS in young children’s processing of spoken number words. Furthermore, given that distance-related ERP effects are usually observed over parietal scalp sites, and that parietal brain regions have been associated with numerical processing using other methods such as fMRI (e.g., Ansari & Dhital, 2006; Cantlon, Brannon, Carter, & Pelphrey, 2006; Dehaene, Piazza, Pinel, & Cohen, 2003; Feigenson et al., 2004), we expected that the numerical ratio effect would be observed over parietal sites. A secondary question was whether subset-knowers would show any evidence of the same distance-related ERP effects as CP-knowers. Such evidence would indicate that number words are mapped onto ANS representations during the formative period where children are learning the meaning of number words rather than after this process is fully established.

Method

Participants

One-hundred and fifteen children (3.11 to 5.57 years, mean = 3.98, 59 female, 6 bilingual) from the greater Research Triangle, NC, community were included in the final analysis. Data from 35 additional children were discarded (see *EEG Recording and Analysis* section for details). All parents provided written informed consent for their children, using a protocol approved by the Duke University Institutional Review Board. Children received a small toy as a reward for participation. Parents were compensated for travel expenses (\$10 or \$15, depending on their zip code) and for the time spent in the lab (\$15 per hour).

Stimuli and Apparatus

EEG Picture-Number Word task—The visual stimuli consisted of color photographs of balls, chairs, dogs and shoes, presented on a computer monitor. To increase interest, four different exemplars of each category were used. The photographs were presented as arrays of one ($\sim 3.6^\circ$ high and 3.1° wide), two ($\sim 3.6^\circ$ high and 6.2° wide), three ($\sim 3.6^\circ$ high and 9.3° wide) or six ($\sim 7.1^\circ$ high and 9.3° wide) objects on a white background. Factorially crossing 4 exemplars of each of 4 categories with 4 numerical values created 64 different visual images. A black fixation cross ($0.6^\circ \times 0.6^\circ$) was present at the center of the screen at all times.

The auditory stimuli were two-word phrases spoken by a recorded female voice. Each phrase always began with the word “look”, followed by a number word (one, two, three or six; mean word length 409 ms; 10 ms rise and fall periods). The auditory stimuli were presented centrally through two speakers evenly spaced to the left and right of the monitor with an intensity of ~ 55 dB SPL. The presentation of the stimuli was controlled by Presentation software package (Neurobehavioral Systems, Albany, CA).

Each block consisted of 96 trials, with half the trials numerically congruent and the other half numerically incongruent. Specifically, on congruent trials the spoken number word matched the number of items in the picture (48 trials = 4 number words $\times$ 4 item types $\times$ 3 repetitions), while on incongruent trials the number word was inconsistent with the number of objects in the visual image (48 trials = 4 number words $\times$ 3 items number $\times$ 4 item types). The exemplar for each object category was randomly selected (with replacement) on each trial. Thus for a congruent trial, if two balls were presented, the accompanying auditory stimulus would be “Look, two!” In contrast, on incongruent trials in which two objects were presented the auditory stimulus could be one of three alternative phrases with the number word one, three or six. The 48 incongruent trials consisted of 12 trial types and 6 unique numerical contrasts (e.g., collapsing trials with the word “one” and six objects with trials that presented the word “six” but presented one object). Further collapsing by ratio allowed us to consider pairs with a 1:2 (pairs 1:2 and 3:6), 1:3 (pairs 1:3 and 2:6), 1:6 (pair 1:6) or 2:3 (pair 2:3) ratio between the number word and the number of objects. These ratios were collapsed yet again to compare incongruent trials with a large ratio (1:3 and 1:6 ratios) versus those with a small ratio (1:2 and 2:3 ratios).

Procedure

Children were first tested in the behavioral “Give-a-Number” task (Wynn, 1990, 1992), followed by the EEG picture-number word study.¹

Behavioral Assessment: Give-a-Number—The experimenter asked the child to give a puppet different numbers of small animal-shaped erasers as part of a game. First, the experimenter placed the puppet, a plate, and pile of fish-shaped erasers on a table in front of the child. Then she stated “In this game you will give fish to Elmo, like this”, while the experimenter placed two fish on the plate and slid the plate over to the puppet. The experimenter then placed the fish back in the pile and said “Can you give Elmo *one* fish?” After the child presented the plate to the puppet the experimenter asked “Is that *one*?” If the child said “Yes” the experimenter said “Thank you!” and placed the toys back in the pile. If the child said “No” the experimenter repeated the trial by asking the child again for *one* fish, with the same follow-up question. The experimenter did not provide any feedback to the child as to correctness. Trial length was determined by the child (there was no time limit), and children were allowed to fix or change their response.

Children were always asked for 1 fish on the first trial and for 3 fish on the second. If the child succeeded on both trials, then the child was asked for 5 fish; if the child failed on that request, she/he was asked for 2 fish. Subsequent requests depended on the child’s previous responses. If she or he succeeded at a given number (N), then N+1 was requested at the next trial was, if not then N-1 was requested. The requests continued until the child had at least two successes at a given N and at least two failures at N+1. The highest number requested was 6.

¹We also tested children’s ability to count aloud up to 10 but performance in this task did not yield enough variance to be included in the analyses.

Children were categorized by knower-level based on the highest number word the child knew. Children who were unable to generate sets of 6 but were able to reliably generate sets of fewer items were considered subset-knowers and categorized as one-, two-, three-, four- or five-knowers, depending on the highest number they successfully gave. For example, children who successfully constructed sets of 1 and 2 toys, but not 3 toys, were called two-knowers. Children who successfully constructed sets of 6 toys were categorized as CP-knowers (Wynn, 1990, 1992). For the purposes of the statistical analyses of the EEG task, subset-knowers were divided into two groups: one- and two-knowers and three- to five-knowers and their performance were compared with that of CP-knowers.

EEG Picture-Number Word task—Participants were seated in a sound-attenuated and dimly lit electrically shielded booth, approximately 74 cm from the center of a 20-in monitor. An experimenter sat in another chair, to the right of the child, facing the monitor. Children were instructed to attend to the screen and avoid movements. No overt responses were required. On each trial, a picture with one, two, three, or six objects appeared on the center of the computer screen for 2500 ms. The spoken word “look” was played at the onset of the picture and functioned to draw the child’s attention to the image. Nine-hundred ms after trial onset, while the picture was still present on the screen, a spoken number word was played. The 900 ms delay between the onset of the auditory and visual stimuli allowed for any evoked-responses to the visual stimuli to return to a baseline-level prior to the onset of the stimulus of interest (i.e., the spoken number word). The ITI varied between 1.1 and 1.3 s and displayed a white screen with central black fixation cross (Figure 1). For each experimental block the first trial displayed a number word and an array of objects that were numerically congruent and this trial was excluded from analysis. The remaining 96 trials within the block were composed of 50% congruent and 50% incongruent pairings of number words and arrays. The frequency of each number word and each numerical array of objects was equally distributed in each block. An animated movie was presented on the computer monitor for 40 seconds after every 24 trials with the goal of increasing children’s interest in looking at the screen. Each block lasted approximately 8 minutes. During a short break between blocks children were offered small rewards (e.g., snacks, stickers) and given feedback about her/his behavior (e.g., attentiveness, ability to sit still, etc). Fifty-three children completed 4 blocks (384 trials total). The remaining 62 children completed 3 blocks (288 trials total), due to loss of interest, impatience, fatigue etc.

EEG Recording and Analysis—The ongoing EEG was recorded from 32 channels mounted in a customized, elastic electrode-cap (Duke32 Waveguard cap layout, Advanced Neuro Technology, the Netherlands). Channels were equally spaced across the cap and covered the whole head from above the eyebrows to below the inion. The electro-oculogram (EOG) was monitored with an electrode below the left eye (vertical EOG) and two other electrodes on the left and right canthi (horizontal EOG). Recordings were referenced online to the average of all channels, low-pass filtered at 138 Hz, and digitized with a 512 Hz sampling rate. Electrode impedances were maintained below 10k Ω for the EOG channels, below 2k Ω for the ground and left and right mastoid channels, and below 5k Ω for all other channels.

Offline, data were subjected to artifact detection and rejection (implemented by means of an automated computer algorithm after the manual setting of artifact amplitude rejection levels). Trials with extreme eye artifacts and off-scale activity (muscle artifact, movement artifact, or electrode drift) were excluded from the analyses. The data were then digitally band-pass filtered between 0.016 and 30 Hz and re-referenced to the algebraic average of the left and right mastoids. Artifact-free trials for each participant were next segmented into epochs beginning from 500 ms before the onset of the spoken number word to the end of the trial, averaged into experimental conditions of interest (i.e., congruent, incongruent, incongruent large ratio (1:3 and 1:6 ratios), incongruent small ratio (1:2 and 2:3 ratios)), and baseline corrected to the average amplitude from -200 to 0 ms before the spoken word onset. Data from 34 participants were excluded because these participants had fewer than 50 usable trials for either the congruent or the incongruent condition. Data of 1 additional participant was discarded due to a recording system error. On average 103.2 (SD = 31.9) congruent and 103.3 (SD = 31.1) incongruent trials were retained for each child. The average number of small and large ratio trials in the incongruent condition was 51.3 (SD = 15.3) and 52.0 (SD = 15.4) respectively across participants. Finally, grand averages across all participants, as well as for the three different subgroups of knower level (1–2 knowers, 3–5 knowers, CP knowers), were computed for each congruency condition. In addition, incongruent minus congruent difference waves were computed for each ratio relationship, as well as collapsed across ratio for each of the knower level groups. Topographical maps for each difference wave (i.e., incongruent minus congruent, incongruent large ratio minus congruent, incongruent small ratio minus congruent) were also generated for each participants group and across all participants.

Visual inspection of the grand-average waveforms across participants for incongruent and congruent trials and their difference waves revealed two main effects of incongruency: a relatively early central-parietal incongruency-related negativity, followed by a late bilateral parietal positivity. The enhanced negativity, hereafter referred to as the N_{inc} (for incongruency negativity), resembled the negative incongruency effects previously found with the picture-word and Stroop ERP paradigms (e.g., Appelbaum et al., 2009; Byrne et al., 1999; Donohue et al., 2012; Friedrich & Friederici, 2004; Henderson et al., 2011; Liotti et al., 2000; Szucs, Soltesz, & White, 2009; West, 2003). The N_{inc} started about 150 ms earlier here than the N450 observed in adults with Stroop paradigms. This may be due to conflict processing in the auditory modality, which has been found to begin earlier (Donohue et al., 2012). We analyzed the N_{inc} from 200 to 500 ms sampling from 3 adjacent, centro-parietal, midline electrodes, as well as 3 immediately adjacent electrodes to the left and right of this midline (see Figure 2).

Similarly, the longer-latency positivity incongruency effect, hereafter referred to as the P_{inc} (for incongruency positivity), resembled the late sustained positive-polarity effect previously reported to follow the N400, N_{inc} and N450 effects (e.g., Appelbaum et al., 2009; Donohue et al., 2012; Friedman et al., 1988; Juottonen et al., 1996; Liotti et al., 2000; Sitnikova et al., 2003; Szucs & Soltesz, 2007; West, 2003), although the effect seemed to start about 100 ms later here for the CP-knowers and about 200 ms later for the 3–5 knowers. The P_{inc} was analyzed from 700 to 1,000 ms, sampling from 3 adjacent, more laterally located parietal

electrodes on the left, and the three corresponding group of lateral parietal electrodes on the right (see Figure 3).

A repeated-measures analysis of variance (ANOVA) on mean amplitude values was conducted for both the N_{inc} (200–500 ms) and the P_{inc} (700–1,000 ms) effects in the corresponding time windows. The factors were *knower-level* as a between-participants variable (1–2 knowers, 3–5 knowers, CP knowers) and *congruency* (congruent, incongruent) and *laterality* (for N_{inc} : left, midline, right; for P_{inc} : left, right) as within-participants variables. In cases of significant interactions with the knower level and congruency (and/or laterality), compatible follow up analyses were conducted separately within each *knower-level* group (i.e., 1–2 knowers, 3–5 knowers and CP knowers). To evaluate the prediction of the numerical ratio effect according to which large numerical incongruency (large ratio) would yield greater amplitude in the incongruency difference wave compared to small ratio incongruency, we conducted follow-up contrasts in cases of significant congruency effects in both the N_{inc} and P_{inc} analyses. This was tested by comparing large-ratio with small-ratio incongruent trials using one-tailed t-tests for dependent samples on the mean amplitude values. In cases of significant numerical ratio effects additional one-way repeated measures ANOVA on the mean amplitude of the difference waves was run within each ratio condition to test for the main effect of pair (3 levels; the pairs 1:2, 3:6 and 2:3 for the small-ratio condition and the pairs 1:3, 2:6 and 1:6 for the large-ratio condition). These analyses were done in order to test the possibility that the absolute values (i.e., the specific ratio magnitudes) modulated the effects. Significance level was defined as $p < .05$ and inferred for Greenhouse-Geisser corrected p values in all repeated measures ANOVAs.

Results

Give-a-Number Behavioral Task

Categorization based on the knower-level framework (Wynn, 1990, 1992) yielded 7 one-knowers, 24 two-knowers, 13 three-knowers, 7 four-knowers, 8 five-knowers and 56 CP-knowers. Thus there were 31 1–2 knowers and 28 3–5 knowers, overall a total of 59 children who were subset knowers.

EEG Picture-Number Word task

As can be seen in Figures 2 and 3, the data revealed two incongruency effects: an early centrally distributed negativity (termed here “ N_{inc} ”), and a later parietally distributed positivity (termed here “ P_{inc} ”) that were modulated by children’s knower level. Note that main effects of laterality and knower level (i.e., on the raw ERP waveforms) or of the interaction between these factors are not reported due to their lack of theoretical importance.

N_{inc} (200–500 ms)—A significant main effect of *congruency* [$F_{(1, 112)} = 30.1$, $MSE = 10.1$, $p < .000001$, $\eta_p^2 = .21$] manifested as a greater ERP negativity in the incongruent compared to the congruent condition. Importantly, *congruency* interacted with *knower level* [$F_{(2, 112)} = 4.7$, $MSE = 10.1$, $p = .01$, $\eta_p^2 = .08$] such that the N_{inc} was significant for both the 3–5 knowers [$F_{(1, 27)} = 30.8$, $MSE = 2.3$, $p = .000007$, $\eta_p^2 = .53$] and the CP knowers [$F_{(1, 55)} = 27.8$, $MSE = 2.6$, $p = .000002$, $\eta_p^2 = .34$], but not for the 1–2 knowers [$F < 1$, η_p^2

= .007] (Figure 2). Planned comparisons for the groups that produced a significant N_{inc} showed that it was not modulated by the numerical ratio [for the 3–5 knowers: $t_{(27)} = 0.6$, $SD = 2.7$, ns ; for the CP knowers: $t_{(55)} = 0.8$, $SD = 3.7$, ns]. Furthermore, no other interactions with congruency were found to be significant for the N_{inc} [$\text{congruency} \times \text{laterality}$: $F < 1$, $\eta_p^2 = .003$; $\text{congruency} \times \text{laterality} \times \text{knower level}$: $F_{(2, 224)} = 2.1$, $MSE = 1.0$, ns , $\eta_p^2 = .04$].

P_{inc} (700–1,000 ms)—A significant main effect of *congruency* manifested as an enhanced parietal positivity for incongruent compared to congruent trials [$F_{(1, 112)} = 11.3$, $MSE = 7.0$, $p = .001$, $\eta_p^2 = .09$], resembling the late positive-polarity effects seen in conflict tasks in adults. Importantly, as in the N_{inc} analysis, *congruency* was modulated by the *knower level* [$F_{(2, 112)} = 3.4$, $MSE = 7.0$, $p = .04$, $\eta_p^2 = .06$]. This interaction resulted from there being a significant P_{inc} effect for both 3–5 knowers [$F_{(1, 27)} = 6.3$, $MSE = 7.5$, $p = .02$, $\eta_p^2 = .19$] and for CP knowers [$F_{(1, 55)} = 17.6$, $MSE = 6.2$, $p = .0001$, $\eta_p^2 = .24$], but not for 1–2 knowers [$F < 1$, $\eta_p^2 = .0008$] (Figure 3). The P_{inc} manifested as a bilateral parietal positivity for the CP knowers and seemed more left lateralized for the 3–5 knowers, although no significant *congruency* $\times$ *laterality* interaction was found for the latter group of participants [$F_{(1, 27)} = 2.7$, $MSE = 2.4$, $p = .11$, $\eta_p^2 = .09$]. Planned comparisons revealed that the P_{inc} effect found for the 3–5 knowers was not modulated by the degree of numerical mismatch [$t_{(27)} = 0.7$, $SD = 3.4$, ns]. In contrast, a significant numerical ratio effect was obtained for the CP-knowers such that trials with larger numerical congruency ratios elicited a larger P_{inc} compared to small numerical ratios [$t_{(55)} = 2.1$, $SD = 4.1$, $p = .02$] (Figure 4). Moreover, no significant main effects of the absolute-value ratio pairings were found for CP-knowers [small ratio: $F < 1$, $\eta_p^2 = .003$; large ratio: $F_{(2, 110)} = 1.4$, $MSE = 53.4$, ns , $\eta_p^2 = .02$], indicating that there was no effect of absolute value. No other significant interactions with *congruency* were obtained in the P_{inc} analysis [*congruency* $\times$ *laterality*: $F_{(1, 112)} = 1.9$, $MSE = 2.3$, ns , $\eta_p^2 = .02$; *congruency* $\times$ *laterality* $\times$ *knower level*: $F < 1$, $\eta_p^2 = .01$].

We next tested whether 3–5 knowers showed ratio-dependence in the P_{inc} for pairings that did *not* include the number word “six” or a visual array of 6 objects. Specifically, we computed a linear trend to test whether the mean amplitudes of the P_{inc} difference waves (incongruent minus congruent) found for 3–5 knowers show a linear decrease for the audiovisual incongruency pairings of 1:3, 1:2 and 2:3, respectively². A linear trend computed on 3 levels is equivalent to comparing the highest (2:3) with the lowest level (1:3) (Keppel, 1993). This analysis yielded a marginally significant linear trend for the difference waves computed on the whole 700–1,000 ms time window used for the P_{inc} analysis [$t_{(27)} = 1.58$, $SD = 8.34$, $p = .06$]. We then tested the significance of the same linear trend over smaller, consecutive 100-ms time windows (i.e., 700–800 ms, 800–900 ms and 900–1,000 ms). We found a significant linear trend [$t_{(27)} = 1.98$, $SD = 8.84$, $p = .03$] from 700–800 ms post-stimulus onset, reflecting an apparent ratio-dependence resulting from the gradual decrease in the mean amplitudes of the P_{inc} with the decrease in the level of the numerical

²Note that only a subset of the congruent number words was used for the computation of the difference wave (incongruent minus congruent) for each pair. For example, when considering the incongruent pair 1:3 (i.e., trials with one object and the word “three” or three objects and the word “one”), only trials with congruent pairings of one and three (i.e., trials with one object and the word “one” or three objects and the word “three”) were used for the subtraction.

mismatch. The ratio effect was marginally significant in the 800–900 ms time window [$t_{(27)} = 1.48$, $SD = 9.07$, $p = .07$] and non-significant in the latest, 900–1,000 ms, time window [$t_{(27)} = 0.97$, $SD = 8.85$, ns] (Figure 5).

Discussion

The objective of the present study was to explore the neural bases of number-word comprehension in young children. Specifically, we first asked whether children would show incongruity-related electrical brain responses to spoken number words that were incongruent versus congruent with concurrently displayed arrays of objects. A second goal was to examine whether ERP data could speak to the debate over which nonverbal representations children first rely on when learning the meaning of number words. Children who showed the most limited knowledge of the meaning of number words (i.e., 1–2 knowers) showed no ERP effects when presented with number words that were incongruent visually presented arrays. In contrast, two ERP components differentiated congruent and incongruent trials in children with intermediate knowledge level (3–5 knowers) and in children who comprehended the cardinal meaning of all of the number words presented (CP-knowers): an early, central-parietal, negative-polarity effect (N_{inc}) from 200–500 ms and a longer-latency, parietal, positive-polarity effect (P_{inc}) from 700–1,000 ms.

The earliest effect, a negative-polarity incongruity (N_{inc}), elicited from about 200 to 500 ms after the onset of the spoken number word had a central-parietal topography, similar to the N400 effect found in situations of semantically violated vs. expected contexts (e.g., Byrne et al., 1999; Friedrich & Friederici, 2004; Henderson et al., 2011; McCleery et al., 2010; for a review see Kutas & Federmeier, 2011). This central ERP negativity was also similar to the N450/ N_{inc} effects observed in other stimulus-conflict paradigms, such as the classical Stroop task tested both in the visual (e.g., Appelbaum et al., 2009; Larson et al., 2009; Liotti et al., 2000; Szucs & Soltesz, 2007; West, 2003) and auditory (Donohue et al., 2012) modalities, as well as in the numerical Stroop task (e.g., Szucs & Soltesz, 2007, 2012; Szucs, Soltesz, & White, 2009). The N450 was previously suggested to resemble the N400 by indexing semantic conflict at the stimulus level (Rebai et al., 1997). An alternative view suggests that the N450 is linked to conflict effects arising from the anterior cingulate cortex (ACC), as modeled by source localization analyses (Liotti et al., 2000; West, 2003; Szucs, Soltesz, & White, 2009). This view is consistent with fMRI studies indicating that the anterior cingulate and other superior midline frontal regions play a role in stimulus conflict detection (e.g., Melcher & Gruber, 2009; Van Veen & Carter, 2005) and with combined ERP/electromyography studies suggesting that the N450 is related to stimulus and not response conflict (e.g., Szucs & Soltesz, 2012; Szucs, Soltesz, & White, 2009).

The N_{inc} effect observed here appears to be more related to conflict detection, possibly arising in part from the ACC, rather than to difficulties in carrying out semantic integration into context. This interpretation is supported by the fact that the N_{inc} was *not* modulated by the degree of the numerical mismatch even in CP-knowers and is also consistent with a previous numerical Stroop study (Szucs, Soltesz, & White, 2009) in adults that found no sensitivity in the N450 amplitude to numerical distance. With regard to the latency of the N_{inc} , it seemed to onset here about 150 ms earlier than the N450 in classical visual Stroop

tasks (e.g., Liotti et al., 2000; Szucs, Soltesz, & White, 2009), but was similar to timing observed in an auditory version of the Stroop task (Donohue et al., 2012). Donohue et al. (2012) suggested that these latency differences might be related, at least in part, to faster sensory processing in the auditory compared to the visual modality. This possibility is consistent with an adult study by Szucs and Csepe (2004) that found early differences (< 250 ms) in ERPs on fronto-central electrodes to auditory number words vs. visually presented numbers (written number words and Arabic numerals).

Children who exhibited intermediate and high levels of number-word knowledge also showed a sustained, positive-going deflection (P_{inc}) from 700 to 1,000 ms after the onset of the spoken number word, distributed over parietal sites. This effect was similar in topography to the SP incongruity effect reported to follow the N450 in adult studies of the Stroop task (e.g., Appelbaum et al., 2009; Larson et al., 2009; Liotti et al., 2000; West, 2003; Szucs & Soltesz, 2007, 2012), although its onset in the current study was about 200 ms later. The functional role of the SP has not been clearly established. Some accounts suggest that the SP is related to late control processes relevant in tasks that require responses (Donohue et al., 2012; Larson et al., 2009); however the current study involved children passively attending to multisensory stimuli, without any instruction of make an overt response. Another interpretation suggests that the effect might reflect additional semantic processing of word meaning given its tendency to be more prominent over left hemisphere sites and its proximity to Wernicke's area (Liotti et al., 2000). This explanation seems more probable with regard to the P_{inc} observed here, particularly since the effect was modulated by the degree of numerical incongruity. On the other hand, we found no statistical evidence for a lateralization of the P_{inc} . Late posterior positivities (often termed LPC) have also been reported to follow the N400 incongruity effect and were suggested by some researchers to reflect processes of reanalysis triggered by semantic violations (e.g., Juottonen et al., 1996; Munte et al., 1998).

In line with the semantic-related interpretations of late posterior positive waves, the P_{inc} observed in the present study seems likely to be associated with semantic processing of the multisensory numerical-meaning mismatch. More specifically, the fact that children who showed mastery of the cardinal principle exhibited a P_{inc} that was modulated by the numerical ratio of the mismatch between the auditory and visual stimulus suggests that, unlike the N_{inc} , the longer-latency parietally-distributed P_{inc} is sensitive to the degree of the semantic conflict. Although the obtained modulation of the P_{inc} by numerical ratio is the first to show ratio-dependence in the neural processing of spoken number words in young children it is consistent with studies that have found ratio and distance ERP effects for other numerical stimuli, in adults, children, and infants in diverse tasks (e.g., Berger et al., 2006; Dehaene, 1996; Gebuis et al., 2009; Hyde & Spelke, 2009, 2011; Libertus et al., 2007; Paulsen et al., 2010; Soltesz et al., 2011; Szucs & Csepe, 2005; Szucs et al., 2007, 2011; Szucs & Soltesz, 2007; Temple & Posner, 1998). Such effects typically emerge over parietal electrodes, but have been seen in multiple distinct ERP components. While the bilateral parietal distribution observed here for the P_{inc} in the CP-knowers is consistent with the neuroimaging and neuropsychological literature implicating the intraparietal sulcus in number processing (e.g., Ansari & Dhital, 2006; Cantlon et al., 2006; Dehaene et al., 2003; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Feigenson et al., 2004), we make no

claim that the P_{inc} reflects brain activity uniquely related to number processing. The P_{inc} emerges in response to other kinds of auditory and/or visual mismatches (e.g., Appelbaum et al., 2009; Donohue et al., 2012; Friedman et al., 1988; Juottonen et al., 1996; Liotti et al., 2000; Sitnikova et al., 2003; Szucs & Soltesz, 2007; West, 2003), and it remains possible that its amplitude would be modulated by the degree of non-numerical semantic mismatch. Nevertheless, the modulation of this later brain activity by numerical ratio provides clear evidence that the CP-knowers' brains were performing processing of numerical relationships consistent with engagement of the ANS.

Accordingly, our study may also provide the first neural data that can speak to the ongoing debate regarding whether approximate number representations or object-file representations serve as the basis for children's acquisition of number words (e.g., Carey, 2009; Le Corre & Carey, 2007; Gallistel & Gelman, 1990; Gelman & Gallistel, 2004; Pica, Lemer, Izard, & Dehaene, 2004; Sarnecka & Lee, 2009). We found a bilateral modulation of the P_{inc} by ratio and no sensitivity to the absolute numerical values within each ratio condition in children who have already mastered their count list. The fact that only the CP-knowers showed robust modulation of the P_{inc} as a function of ratio might be interpreted as consistent with the idea that the grounding of number-word meaning takes place first with object-file representations and that the mapping to ANS representations occurs afterwards (e.g., Huntley-Fenner & Cannon, 2000; Le Corre & Carey, 2007; Rousselle et al., 2004; Sarnecka & Lee, 2009; Slaughter et al., 2006). However, our results cannot serve as strong support for this claim, given that we also found a ratio-dependence in the P_{inc} from 700–800 ms in 3–5 knowers when our analysis was limited to the number words “one”, “two” and “three”. Instead, the ratio-dependence found in the P_{inc} provides strong evidence that CP-knowers have mapped spoken number words onto ANS representations, while further suggesting that number word mapping onto ANS representations has probably already begun while children are still in the process of learning the meaning of number words. Accordingly, we argue that our results are most consistent with the view that the ANS serves as the foundation upon which number words are mapped (e.g., Gallistel & Gelman, 1990; Gelman & Gallistel, 2004; Pica, Lemer, Izard, & Dehaene, 2004; Wagner & Johnson, 2011).

Our data do not, however, rule out the alternative hypothesis that children first map number words onto object-file representations and only later map number words onto the ANS (e.g., Huntley-Fenner & Cannon, 2000; Le Corre & Carey, 2007; Rousselle et al., 2004; Sarnecka & Lee, 2009; Slaughter et al., 2006). Future work is necessary to test this hypothesis. The more limited ratio-dependence observed in 3–5 knowers (i.e., only from 700 to 800 ms for small values) compared to CP-knowers may be attributed to the passive nature of our task design. If children had been asked to actively detect multisensory mismatches 3–5 knowers may have shown more robust ratio dependence. Future work is needed to test whether tasks that require children to provide overt responses and include a larger set of number words would show ratio-dependent ERPs for number words that are beyond children's current cardinal mastery. Such work can also potentially provide better understanding with regard to the neural processing of number words in children who have very limited number word knowledge (e.g., one and two-knowers).

In sum, the patterns observed in the current study for children with intermediate and high levels of number-word knowledge are consistent with the idea that two processing stages were evoked by the multisensory numerical mismatch. First, the earlier-latency N_{inc} marks an identification of the presence of a semantic conflict. Second, the longer-latency P_{inc} marks a subsequent evaluation of the degree of the numerical incongruity between the number word and the visual array, reflected by the modulation of the P_{inc} by numerical ratio. This modulation of the P_{inc} in CP knowers provides neural evidence for the mapping of number words onto ANS representations. In addition, the modulation of the P_{inc} in 3–5 knowers provides suggestive evidence that the ANS serve as a prelinguistic conceptual substrate as children acquire the meaning of number words.

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An example of a congruent trial:

An example of an incongruent trial:

Figure 1.

Illustration of trial structure, duration, and stimuli in the EEG Picture-Number Word task. In congruent trials (top panel) the spoken number word matched the number of items in the picture, while in incongruent trials (bottom panel) the number word did not match the number of items in the picture. The extracted ERPs were time-locked to the onset of the spoken number word.

Figure 2.

(a) ERP traces for congruent and incongruent conditions by knower level, time-locked to the onset of the spoken number word. An early negative-wave incongruency effect (N_{inc}) emerged starting at around 200 ms. Each tick mark represents 100 ms. Sites used for testing the N_{inc} effect are highlighted. (b) Topographic distributions for incongruent minus congruent trials from 200 to 500 ms. The N_{inc} effect was found both in 3–5 knowers and CP knowers and had a central distribution. (c) Mean amplitude values (microvolts) of congruency by knower level. Error bars denote 0.95 confidence intervals.

Figure 3.

(a) ERP traces averaged across the six highlighted channels by knower level for congruent and incongruent conditions. Traces are time-locked to the onset of the spoken number word. A late positive-wave incongruency effect (P_{inc}) emerged at around 700 ms. Each tick mark represents 100 ms. (b) Topographic distributions for incongruent minus congruent trials from 700 to 1,000 ms. The P_{inc} effect was parietally distributed and observed in 3-5 knowers and CP knowers. (c) Mean amplitude values (microvolts) of congruency by knower level. Error bars denote 0.95 confidence intervals.

Figure 4. CP-Knowers

(a) ERP traces averaged across the six highlighted channels showing the P_{inc} (700–1,000 ms) for congruent, incongruent large ratio, and incongruent small ratio conditions. Traces are time-locked to the onset of the spoken number word. Each tick mark represents 100 ms.

(b) Topographic distributions of numerical-ratio effects: incongruent small-ratio minus congruent trials and incongruent large-ratio minus congruent trials, from 700 to 1,000 ms. The P_{inc} effect was significantly larger for the large compared to the small ratio condition.

(c) Mean amplitude values (microvolts) of congruency for CP-knowers. Error bars denote 0.95 confidence intervals.

Figure 5. 3-5 Knowers

(a) Difference waves (incongruent minus congruent) for the P_{inc} (700–1,000 ms) for pairs 1:3, 1:2 and 2:3 averaged across the six highlighted channels. A significant linear trend was found from 700 to 800 ms indicated a gradual decrease in the P_{inc} with the decrease in the level of the numerical mismatch. Traces are time-locked to the onset of the spoken number word. Each tick mark represents 100 ms. (b) Topographic distributions of the difference waves (incongruent minus congruent) for the P_{inc} (700–800 ms) for pairs 1:3, 1:2 and 2:3, from 700 to 800 ms. The P_{inc} effect was significantly larger for the large (1:3) compared to the small (2:3) ratio pair. (c) Mean amplitude values (microvolts) of the P_{inc} difference waves (incongruent minus congruent) by pair from 700 to 800 ms post-stimulus. Error bars denote 0.95 confidence intervals.