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Electrophysiological Dynamics of False Belief Understanding and Complementation Syntax in School-Aged Children: Oscillatory Brain Activity and Event-Related Potentials

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Abstract

A large body of research in developmental psychology has been devoted to the ongoing debate on which aspects of language are fundamental to false belief understanding (FBU). A key proposal from de Villiers and colleagues proposes the essential role of complementation syntax in FBU development. The present study using scalp EEG addressed one opposing hypothesis purporting that complementation is redundant to FBU, by characterizing the electrophysiological correlates of FBU and complementation syntax in school-age children. Time-frequency decomposition showed robust parieto-occipital low beta (12–16Hz) power reduction in the belief versus complementation conditions. This divergence was also supported by ERPs, with positive parieto-occipital late slow waves around 600–900ms distinguishing belief and complementation conditions. The false belief condition generated the lowest behavioral response accuracy, suggesting it is the most challenging condition. Together, the current findings provide evidence showing complementation is not redundant to FBU.

Keywords

False belief understanding; complementation syntax; beta oscillation; late slow wave; EEG; children

False belief understanding (FBU), a widely used indicator of theory of mind or mentalizing, refers to the fundamental socio-cognitive ability to represent other minds when they are inconsistent with the factual reality (Wimmer & Perner, 1983). It emerges during preschool years (Wellman et al., 2001) and continues to develop beyond early childhood (Saxe et al., 2009; Gweon et al., 2012). The critical role of language in FBU is supported by behavioral (see Milligan et al., 2007 for a meta-analysis) and neuroimaging evidence (Fletcher et al., 1995; Brunet et al., 2000; Vogeley et al., 2001). However, there is an ongoing debate on which specific aspects of language capacity-semantics, syntax, or both-are fundamental to

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explicit FBU development (Hughes & Devine, 2015). According to a linguistic determinism perspective, complementation syntax, a form of language proposition, provides the critical linguistic device for the representation of others' mental states and therefore is required to develop mentalizing (de Villiers & de Villiers, 2000; de Villiers & Pyers, 2002; de Villiers & de Villiers, 2014). For example, *Mom thinks that Dan is eating beans (tensed complement), but he is really eating candy*. The underlined embedded proposition following the mental state verb (i.e., *thinks*) is the tensed complement for the whole sentence and furnishes a direct description of people's mind. This syntactic structure allows embedded false propositions within true statements and makes it possible to separate the mind from reality. In this way, mastery of such a syntactic structure is required for FBU development (de Villiers, 2007). This account is supported by longitudinal data with complementation syntax, among multiple language measures, being the strongest predictor of FBU in preschool children (de Villiers & Pyers, 2002).

Alternatively, critics of the linguistic determinism perspective (Slade & Ruffman, 2005; Farrar et al., 2013) argue that general language capacities such as vocabulary, semantics, syntax, and pragmatics are sufficient for the development of FBU and that complementation syntax is not required (see Farrar et al., 2017 for a review). For example, researchers failed to identify unique and independent contribution of complementation (Hale & Tager-Flusberg, 2003; Lohmann & Tomasello, 2003; Cheung et al., 2004; Cheung et al., 2009; Farrar et al., 2013). One criticism comes from the hypothesis that the two constructs are conceptually the same—they measure the same internal processing, decoupling people's mistaken thoughts from reality (Cheung et al., 2004; Ruffman et al., 2003; Ng et al., 2010; Chen et al., 2012; Cheung et al., 2012). For example, in the false belief object-transfer task (Wimmer & Perner, 1983), participants need to understand the protagonist's false belief about the object's current location as a result of the transfer during the protagonist's absence. Similarly, in the complementation syntax task (de Villiers & Pyers, 2002), participants need to distinguish the protagonist's false belief from reality by means of the sentential complements following mental-state verbs or communication verbs. Contrary to the linguistic determinism perspective, this redundancy hypothesis rejects complementation being a necessary scaffolding to FBU development.

While it is difficult to evaluate this redundancy hypothesis at the behavioral level, three neurophysiological studies, all with adults, have focused on the comparison between false belief and false complementation (Guan et al., 2018; Chen et al., 2012; Cheung et al., 2012). A fMRI study showed that the right temporo-parietal junction, a brain area responsible for understanding mental states (Sommer et al., 2007; Gobbini & Haxby, 2007; Bedny et al., 2009), was recruited by both false belief and false complementation (Cheung et al., 2012). An event-related potentials (ERPs) study found that both false belief and false complementation were distinguished from their respective control conditions (i.e., true belief and true complementation) via a late slow wave at around 400 ms post-stimulus (Chen et al., 2012). While these results indicate a common neural basis of false belief and false complementation, it is worth noting that the two also prompted divergent neural signatures: a late slow wave, which may reflect the shared process of decoupling mental state from reality, was more anterior in scalp distribution for false belief versus false complementation (Chen et al., 2012). Further, the left temporo-parietal junction and right middle frontal gyrus were

unique to false belief, while the left inferior frontal gyrus and right superior temporal gyrus were unique to false complementation (Cheung et al., 2012).

In addition to fMRI and ERPs, electroencephalography (EEG) oscillations, which reflect rhythmic fluctuations of neuronal ensembles within and across brain regions, are useful to study cortical information processing (Engel & Fries, 2010; Klimesch, 2012). In addition to conveying dynamic information on oscillatory activity in different bands, sustained low-frequency oscillations are a suitable dependent variable for work with developmental and clinical samples due to their desirable signal-to-noise ratios, even with few trials (Keil, 2013). Investigating EEG oscillations during belief and complementation tasks, Guan, Farrar and Keil (2018) found that oscillatory power in the alpha band (8–12 Hz), often taken to reflect heightened internal (as opposed to external sensory) processing (Jensen et al., 2002; Klimesch, 1999; Bartsch et al., 2015), was selectively increased throughout the trial in both false belief and false complementation compared to their respective true control conditions. The belief conditions prompted more reduction in oscillatory power in the low beta band (13–20 Hz) compared to the complementation conditions. In terms of inter-electrode interactions, heightened phase-locking in the low beta band between frontal and posterior brain regions was observed selectively during the false belief condition. This beta coupling difference was interpreted as reflecting different inter-area communication during false belief versus false complementation processing.

Summarizing the existing literature, the hypothesis of false complementation being redundant to FBU has yet to be addressed in a developmental sample. A study with children may shed light on two notions. First, it establishes the extent to which oscillatory correlates of the two tasks seen in adults are present earlier in development. Second, differences between adults and developmental samples may prompt new hypotheses regarding the relation of FBU and false complementation. In an effort towards these goals, we aimed to characterize the large-scale oscillatory correlates of these two fundamental neurocognitive processes in a sample of school-age children, utilizing the tasks and experimental materials from Guan et al. (2018) and comparing the electrophysiological signatures of belief and complementation tasks. If false belief and false complementation tasks prompt different electrophysiological responses in this age group, this would provide evidence against the redundancy hypothesis. Alternative outcomes may support the redundancy hypothesis and thus provide evidence in opposition to de Villiers' linguistic determinism account (de Villiers & de Villiers, 2000). We chose a sample of children aged 7 to 12 years. This is because while children typically acquire FBU at preschool years, FBU-related developmental changes in the brain continue to take place during school years (Saxe & Wexler, 2005; Saxe et al., 2009; Gweon et al., 2012). For example, Carter and Pelphrey (2006) showed the developmental changes of the functional specificity of the right posterior region of superior temporal sulci during 7 to 10 years. Specifically, posterior region of superior temporal sulci during this period increasingly responded to biological motion rather than non-biological motion. Other electrophysiological measures have also been linked to developmental changes in this age group: a late event-related potential slow wave in response to FBU tasks had a broader frontal distribution in children aged 6 to 8 years compared to adults (Meinhardt et al., 2011). Using functional imaging, Saxe et al. (2009) in a study with children aged 6 to 11 years, reported developmental changes in activation of the

right temporo-parietal junction for mental state stories compared to physical stories only for the older children. These findings provide evidence of age-related differences in the organization and function of widely distributed networks involved in cognitive processes like mentalizing. Here, we examined the extent to which such differences in network organization between children and adults is reflected in large-scale oscillatory brain activity measured by means of scalp EEG. Neurophysiologically, fluctuations of time-varying EEG power in the alpha and beta range have been linked to interactions of local and distributed cortical mechanisms during cognitive tasks in children (e.g., Bryant & Cuevas, 2019). Computational modeling and animal model studies likewise suggest that different cortical mechanisms are involved in the generation of alpha (Jensen & Mazaheri, 2010) and beta oscillations (Sherman et al., 2016). Finally, both types of oscillatory activity have been shown to be sensitive to plastic changes during learning and development (Luk et al., 2020). In short, the present study quantifies event-related potentials and measures of oscillatory brain activity, collected in a sample of school-age children, to characterize the neural correlates of belief and complementation tasks in this age group. Basing hypotheses on the parallel adult study (Guan et al., 2018) we expected to observe divergent macroscopic correlates for the two tasks, in support of the notion that despite their similarities, FBU and complementation syntax involve markedly different large-scale cortical processes.

Method

Participants

A total of 36 children were recruited from local elementary schools in the United States. Two were excluded due to parents' report of attention-deficit disorder and Turner's syndrome respectively; one was excluded due to excessive movement and incomplete task performance; three more participants were excluded due to low accuracy (<85%) of verbal responses to the 48 stories (the story was marked wrong if the critical question or any of the follow-up memory control questions were answered incorrectly). The remaining 30 participants ($M_{\text{age}} = 10.91$ years; $SD = 1.51$ years; range 7.17–12.67 years; 13 girls; 5 left-handed; 3 Hispanic; 21 Caucasian, 3 Asian, 2 African American, 4 multi-racial) were included in data analysis.

Stimuli

We employed the same stimuli as used in a previous study with young adults (Guan et al., 2018). Specifically, 12 different stories based on the object-transfer scenario (Wimmer & Perner, 1983) were included in the false belief and true belief conditions, and 12 different stories based on de Villier and Pyers' (2002) paradigm were included in the false complementation and true complementation conditions (see Figure 1). A conflict between the protagonist's thought/statement and reality existed in the false conditions but not in the true conditions across the two task types. A total of 48 stories were presented in one of two pseudo-random orders using PsychToolbox (Brainard, 1997) in MATLAB.

Procedure

We closely followed the experimental procedures of the Guan et al. (2018) study with any exceptions noted. Participants sat 1.2 meters away from a 23-inch 3-D LED monitor

(Samsung S23A750D) with a 120 Hz refresh rate and were encouraged to limit any movements including eye blinks while watching each cartoon story. A female experimenter sat by the side of participants to record their verbal responses to each question on recording sheets. Parents waited in the room next door.

EEG Acquisition and Preprocessing

A 65-channel or 129-channel Electrical Geodesics sensor net was applied to each participant depending on the respective head size. Scalp impedance was kept below 70 K Ω . EEG was recorded continuously with the vertex electrode (Cz) as the recording reference and an online low-pass filter at 50 Hz, and digitized at a rate of 250 Hz.

Using EMEGS software (Peyk et al., 2011) for offline EEG preprocessing, we converted EEG data to the average reference, and set the high-pass filter at 1 Hz (1 dB point at 1 Hz, 2nd-order Butterworth filter) and low-pass filter at 40 Hz (3 dB point at 40 Hz, 18th-order Butterworth filter). We next extracted segments in each story from the 4th vignettes (i.e., 600 ms pre- to 4000 ms post-stimulus onset) during when participants engaged in belief or complementation reasoning. We then performed artifact detection using the Junghöfer et al. (2000) procedure, and obtained an average of 7.8, 8.8, 9.5, and 8.7 trials for false belief, true belief, false complementation, and true complementation condition respectively. A current source density representation of these data was then acquired using the Junghöfer et al. (1997) algorithm to increase the spatial specificity of the signals. To facilitate comparison between the groups, the current source density values were read out from the 65 electrode locations shared by all participants and used for statistical analysis. Control analyses targeting any effects of original montage did not show any differences related to montage density (i.e. 65 vs. 129 electrodes).

To deal with the challenge of obtaining clean EEG data with children, who were not as cooperative as their adult counterparts, we employed eye movement correction, visually inspected the data for residual artifacts, and automatically rejected trials that had less than 90% artifact-free channels. We also focused on temporally sustained oscillations, decreasing the sensitivity of our dependent variable to transient changes in EEG that are known to produce broad-band artifacts in the time-frequency plane.

Time-Frequency Analyses

Time-frequency analyses were conducted to quantify the time-varying changes of spectral power in brain oscillatory activity between 4.35 and 21.73 Hz, with an emphasis on alpha (8–12 Hz) and beta oscillations (12–16 Hz) at posterior electrodes (see Figure 2). Note this data-driven range of beta band (12–16 Hz) is lower in our children sample than in the parallel adult sample (13–20 Hz; Guan et al., 2018). Similar phenomena and manipulations tend to affect lower frequencies in children compared to samples later in development as the frequency composition of the EEG and the functional specificity of frequency band of brain oscillations change with age (Bell & Wolfe, 2007; Ehlers et al., 2016). To this end, artifact-free EEG epochs were convolved with a family of complex Morlet wavelets that had a wavelet coefficient $F/\sigma F = 7$, where F is a given frequency of interest (here: between 4.35 and 21.73) and σF is the respective uncertainty or smearing (measured as FWHM)

associated with quantifying power at F , in the frequency domain. A baseline correction was applied by dividing each time-frequency point by the mean power of its frequency in a time window ranging from -500 to -152 ms pre-stimulus. The variation in power relative to the baseline window was indicated in percentages.

Event-Related Potentials (ERPs) Analyses

Condition-specific ERPs for each participant were formed by averaging artifact-free trials in the time domain. Grand mean ERPs waveforms were calculated for each condition across participants in a broad parieto-occipital cluster (Figure 2) as well as in electrode Fz, Cz, and Pz, respectively with a 200 ms pre-stimulus baseline. Based on previous studies on FBU and late slow waves (e.g., Sabbagh & Taylor, 2000; Liu et al., 2004, 2009a, 2009b; Meinhardt et al., 2011, 2012; Geangu et al., 2012), we focused on a time window between 600 and 900 ms post-stimulus. In line with previous studies, this time window in the current study also captured the late slow wave following the earlier P3-like component, with both components visible across all experimental conditions. Using the mean voltages over a longer time period, covering a temporally sustained late component defined in previous work, we followed the recommendations by Luck and Kappenman (2012), and Luck and Gaspelin (2017).

Statistical Analyses

Following the experimental design, a 2 Task Type (Belief or Complementation) $\times$ 2 Falsehood Type (False or True) repeated measures analysis of variance (ANOVA) was conducted on oscillatory power. Dependent variables were computed by pooling percent change values in a wide cluster of parieto-occipital electrodes, sites corresponding to Pz, P3, P4, P7, P8, Oz, O1, O2, and their respective nearest neighbors (total of 19 electrodes; see Figure 2). We included all parieto-occipital electrodes to make up for more variability in topography across individuals in the children sample. In addition to compensating for more noises in children's data, the larger cluster (19 compared to 14 electrodes in Guan et al., 2018) may reflect broader topographies in the developing brain due to less functional specificity (Carter & Pelphrey, 2006). We focused on sustained oscillatory activity to avoid sensitivity to artifactual, transient effects (see Guan et al., 2018, for a discussion of this issue), and to emphasize oscillatory states that characterized the entire viewing period, with the goal of increasing the robustness of the dependent variable. Because of the temporal smearing of the wavelet analysis, the actual time reflected in a mean power estimate will vary with frequency (higher frequencies have better time resolution and less smearing, lower frequencies include more information from outside the nominal analysis windows because of smearing). To accommodate these differences, and to capture the maximum energy in the data, we made small adjustments to the time window used in the Guan et al. (2018) study. Thus, power in the low beta band (12–16 Hz) was extracted by averaging across a time range between 500 and 3900 ms post-stimulus onset. Power in the alpha band (8–12 Hz) was extracted from 750 to 3500 ms post-stimulus onset. Similarly, a 2 Task Type (Belief or Complementation) $\times$ 2 Falsehood Type (False or True) repeated measures ANOVA was conducted on the grand mean ERP voltages in the parieto-occipital electrodes cluster (Figure 2), averaged between 600 and 900 ms post-stimulus. Next, in an exploratory step, ERP waveforms were analyzed for each electrode and time point using permutation-controlled t-

tests, in which t-maps for the two main effects were generated. The rationale for this analysis was to seek convergent evidence with the repeated measures ANOVA on an a-priori time and electrode cluster, and to more precisely localize any transient ERP effects in space and in time. To avoid alpha error accumulation, we used a $t_{\max}$ permutation approach as described by Blair and Karniski (1993), in which the labels of the conditions are randomly shuffled 5000 times and the maximum t-value of each resulting time-by-electrode matrix enters a permutation distribution of 5000 $t_{\max}$ (and a separate distribution for $t_{\min}$) values. The .025 and .095 tails of this distribution are then used to establish statistical significance, controlled for multiple comparisons.

An important concern is related to fact that different experimental conditions and trial types may contain systematically different linguistic stimuli in the auditory questions from the 4th vignette, and language may unfold differently in the belief compared to the complementation tasks. To address this possibility, we conducted a post-hoc analysis comparing the low beta decrease between the belief and complementation conditions (top vs. bottom panels in Figure 3) for each time point, controlling for false positives by means of the same permutation control as described for ERP data above. A sustained and stationary difference between these conditions at the same frequency would not support the notion that the beta-band power changes observed here result from tracking linguistic changes that unfold over the duration of the trial, but would be more consistent with the notion that the context provided before vignette 4 together with the graphical representation of vignette 4 prompts the sustained cortical response observed here.

Results

Behavioral results.

Response accuracy was 92.5%, 96.9%, 99.7%, and 98.6% for false belief, true belief, false complementation, and true complementation condition, respectively. A 2 Task Type (Belief or Complementation) $\times$ 2 Falsehood Type (False or True) repeated measures ANOVA on the response accuracy showed a difference between the belief and complementation syntax conditions, $F(1,29) = 9.530$, $p = .004$, $\eta_p^2 = .247$, and a significant interaction between Task Type and Falsehood Type, $F(1,29) = 5.631$, $p = .024$, $\eta_p^2 = .163$. Such results suggest false belief condition is the most challenging condition for school-aged children. Only correct responses were included in the subsequent electrocortical data analyses.

Time-frequency results.

Wavelet analyses showed strong modulation of parieto-occipital oscillatory brain activity in the range of low beta (12–16 Hz) as a function of Task Type (Figure 3). Specifically, reliable and sustained power reduction above the alpha frequency (~ 10 Hz) was observed from 500 to 3900 ms post-stimulus in the belief versus complementation conditions.

Repeated measures ANOVA on low beta power at the parieto-occipital electrodes cluster (Figure 2) showed a main effect of Task Type, $F(1,29) = 5.465$, $p = .027$, $\eta_p^2 = .159$, across false and true conditions, driven by a sustained decrease of low beta power in the belief versus complementation conditions (Figure 4). There was no effect of Falsehood, $F(1,29)$

$= .771$, $p = .387$, $\eta_p^2 = .026$, or interaction between the two factors, $F(1,29) = 1.078$, $p = .308$, $\eta_p^2 = .036$. Results on alpha power showed no effect of Task Type, $F(1,29) = 2.005$, $p = .167$, $\eta_p^2 = .065$, Falsehood, $F(1,29) = 1.939$, $p = .174$, $\eta_p^2 = .063$, or interaction between the two, $F(1,29) = .554$, $p = .463$, $\eta_p^2 = .019$.

In addition, pointwise comparison of the time-varying power of the wavelet tuned to 13.9 Hz was conducted over the parieto-occipital electrodes cluster. Results of the permutation-controlled t-tests for the main effect of Task Type across 5000 iterations of random permutations of condition labels showed a greater 13.9 Hz power decrease during belief versus complementation trials (i.e., crossing the t_{perm} threshold of -2.88), in the time segments between 440 and 1644 ms, and between 1904 and 3596 ms, following the 4th vignette onset. The early onset and sustained nature of these differences throughout the trial is consistent with a different neurophysiological process, initiated by the beginning of the 4th vignette. Therefore, the notion that the observed beta power differences is due to different linguistic stimuli contained in the auditory questions from the 4th vignette is not supported.

Event-related potentials results.

A divergence between the belief and complementation conditions in grand mean ERPs waveforms at Pz as well as at a parieto-occipital electrodes cluster (Figure 2) was clearly observed around 600–900 ms post-stimulus onset (Figure 5). This ERP response was consistent with a late slow wave, typically observed with complex, meaningful, visual stimuli such as nature scenes, cartoons, or photos depicting human beings, in this time interval and widespread across posterior electrodes (Keil, 2013). Repeated measures ANOVA on the late potential voltages across the parieto-occipital electrodes cluster (Figure 2) resulted in a main effect of Task Type, $F(1,29) = 4.49$, $p = .043$, $\eta_p^2 = .134$, with more positive voltages in the belief versus complementation conditions.

In addition to a focused analysis of the parieto-occipital late positivity, we conducted permutation-controlled t-tests for the two main effects, the main effect of task type and the main effect of falsehood. Across 5000 iterations of random permutations of condition labels, the critical t values were -4.01 and 4.01 . Four parieto-occipital electrodes (corresponding to sites Pz, P3, Poz, and Po3) crossed the positive threshold for the task type effect only, in a time period between 742 ms and 810 ms after the 4th vignette onset, indicating greater positive voltage for false, compared to true vignettes in that time range. Figure 6 shows the time course of the t-values at electrode Pz and the topography of the t-values.

Discussion

The present study compared the brain oscillatory correlates of false belief, true belief, false complementation, and true complementation in school-aged children. Using this approach, we addressed the hypothesis of false complementation being redundant to FBU. Reliable and sustained oscillatory power variations in parieto-occipital low beta band were observed as a function of Task Type, regardless of false or true conditions. Such results of the low beta power reduction in the belief versus complementation conditions were consistent with the parallel adult study (Guan et al., 2018). While the role of beta oscillation in the literature is currently debated (Spitzer & Haegens, 2017), the present effects in the beta band may reflect

differences of cognitive and linguistic features in the belief and complementation conditions. For example, it is possible that the sustained differences in oscillatory power, or at least some of the observed variance in oscillatory power arise from the mentalizing processing which is necessary for correctly performing the belief task (Wellman et al., 2001) but not for the complementation task. Little is known about brain oscillations during theory of mind tasks in developmental samples. Thus, more specific experimental manipulations may address this hypothesis in future work.

It is also conceivable that the oscillatory power differences are due to the higher-level syntactic unification requirement in the complementation conditions (de Villiers, 2007). According to a predictive coding framework on sentence-level language comprehension (Lewis & Bastiaansen, 2015), while increases in beta power reflect active maintenance of the current NeuroCognitive Networks (NCNs; Bressler & Richter, 2015), decreases in beta power reflect change or revision of NCNs, arising from the mismatch between the top-down signaling and bottom-up input, which induces updating of predictions (Lewis & Bastiaansen, 2015; Bressler & Richter, 2015; Engel & Fries, 2010; Bastiaansen & Hagoort, 2006). Thus, it is possible that relatively heightened low beta power in the complementation conditions reflects processes of active memory maintenance in support of the sentence-level meaning construction, with increased syntactic unification load in the sentential complements. Note that we focused on sustained oscillatory effects (i.e., the stable parieto-occipital topography of beta band power reduction compared to baseline in the same fashion throughout the trial), which reflect sustained cognitive processing rather than initial sensory processing (e.g., auditory questions; Guan et al., 2018). As a limitation, the systematic difference in auditory questions in the 4th vignette for the belief and complementation conditions represents a potential confound. However, the topographical and temporal stationarity of oscillatory differences observed in the beta band suggests that the onset of the vignette prompts a sustained oscillatory process that arises from the combination of visual and auditory information, above and beyond the differences in specific language content. The latter prompts non-stationary effects in oscillatory activity as reflected in topographical variability over the duration of a trial (e.g., Meyer, Obleser, and Freiderici, 2013). Therefore, the observed beta differences are related to task manipulation (i.e., task type) rather than differences in lower-level language structure.

In contrast to task type, the manipulation of falsehood did not induce any differences in oscillatory brain activity in the present study with children. In a previous study with the present task in young adults, greater alpha power, sensitive to internal processing, was observed in the false compared to the true conditions, across Task Type (Guan et al., 2018). Such an alpha power difference was not observed here. This age-related difference in EEG oscillations may reflect increased functional specificity of alpha or the maturation of neural networks through development (Bell & Wolfe, 2007; Yordanova & Kolev, 2009; Ehlers et al., 2016). It is also likely that other brain process, not examined here, discriminate these outcomes. Longitudinal and cross-sectional studies of oscillatory brain activity during rest and during different tasks are needed to address these notions.

Consistent with the experimental effect observed in the low beta band, ERPs results showed the same divergence between the belief and complementation conditions in late slow waves.

This observation is consistent with previous ERPs studies on FBU where a late slow waveform around 800 ms post-stimulus distinguished belief reasoning from control conditions (e.g., physical reasoning; Sabbagh & Taylor, 2000; Liu et al., 2004, 2009a, 2009b; Meinhardt et al., 2011, 2012; Geangu et al., 2012). Thus, we interpret this divergence in late slow waves as reflecting differences of mentalizing processing rather than syntactic processing between FBU and complementation conditions. The potential confounding effects induced by different speech stimuli (i.e., the first three words in the auditory questions) between these two conditions are possible (Luck, 2005), but may not be likely given the ERPs' topography (i.e., the broad and sustained parieto-occipital distribution on the scalp) and time course (i.e., its latency suggests it is not evoked by word three, but rather by the onset of the vignette picture, in interaction with words 1 or 2, which again were different in each trial). These voltage changes are more likely to be driven by the visual stimulus, the luminance change of which is more time-locked, more similar across trials, and thus contributes more to the ERP, compared to the speech stimuli which vary in terms of envelope and spacing (Dell'Acqua et al., 2010; Knowland et al., 2014). There are many cases in studies of higher order cognition or emotion, where highly robust effects have been observed over studies with complex, non-identical scenes. For example, late positive potentials (LPP) broadly distributed over parieto-occipital cortex are evoked by naturalistic scenes differing in motivational relevance (Thigpen, Keil, & Freund, 2018; Simola et al., 2015).

Behavioral results showed that children made more mistakes in the false belief compared to other conditions, indicating that it can be considered the most challenging task among the four. This result mirrors the finding in the parallel adult study, where the false belief condition prompted selectively higher beta coupling between the frontal and parieto-occipital brain regions (Guan et al., 2018). Note that phase information was not analyzed in the present study because we used low-density EEG and we used different montages within our sample.

Together with previous fMRI and EEG evidence (Cheung et al., 2012; Chen et al., 2012; Guan et al., 2018), results from the present study suggest that false belief and false complementation prompt different responses at the behavioral and neurophysiological levels. These findings are likely due to differences in mentalizing processing between the two, consistent with the notion that false complementation is not redundant to FBU. Such findings provide an important foundation to further study the relation between false complementation and FBU. However, it does not provide information regarding the validity of the linguistic determinism account (de Villiers, 2005), because we did not examine the causal role of complementation syntax in the development of FBU. To further explore this issue, future developmental studies may separate semantics and syntax of sentential complementation by having tensed complement following mental-state verbs and communication verbs respectively. Tensed complement following communication verbs isolates complementation syntax from semantics and thus is a stricter test for possession of complementation syntax (de Villiers & de Villiers, 2000). Another promising hypothesis to explore is whether the neurophysiological differences are quantitative rather than qualitative. That is, the two tasks rely on similar neural systems but FBU recruits those systems a little

more due to its a little more of that computational demands from the additional mentalizing processing needed in the FBU task.

A series of case studies in opposition to the linguistic determinism account showed that patients with severe agrammatic aphasia who were unable to understand or produce language propositions were able to pass non-verbal false belief tasks (Varley et al., 2001; Varley & Siegal, 2000), questioning the unique role of complementation syntax in FBU. While the findings from these case studies provide compelling evidence, the extent to which these observations can be generalized to other tasks and populations is unknown. Future studies are needed to replicate this finding in other populations such as typically developing populations, to clarify the role of complementation syntax in FBU development. Such findings would also provide insight into interventions to etiological models regarding FBU deficits (see Farrar et al., 2017).

One limitation of the current study is that the linguistic features of the auditory questions in the 4th vignette were not strictly controlled. The reason for using these versions of the task included that these two paradigms are the ones commonly used in the literature where the controversy (i.e., whether the two are redundant or not) arose. The current study is merely the first step trying to disentangle the redundancy issues in a development sample using electrophysiological measures. Future work may implement a stricter control of the auditory questions across conditions and exploratory analyses that look at the EEG at the offset of the auditory questions.

In conclusion, by comparing the dynamic EEG signal characteristics in both time and frequency domains of false belief, false complementation, and their respective control conditions in school-aged children, the current study provides a more comprehensive view on our understanding of the development of FBU. The study also offers a demonstration of using EEG oscillations as a promising tool to study human social cognition in a developing population.

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Highlights

- Parieto-occipital beta power distinguished belief from complementation conditions.
- Positive posterior late slow waves (600–900 ms) showed the same divergence.
- The false-belief condition, among the four, had the lowest behavioral accuracy.
- Together, results suggest false complementation is not redundant to false belief.

Figure 1.

Experimental stimuli examples in each of the four conditions. Each story consisted of five vignettes (picture-sound pairs), with the duration being 3 sec, 5 sec, 7 sec, and 7 sec for the first four, respectively. The first three vignettes were the narratives of the story, and the 4th vignette included the critical question for the belief conditions (e.g., *When Elmo comes back, where does he think his car is?*) or for the complementation conditions (e.g., *What did Kevin think Lily was doing?*). During the 5th vignette, participants were asked to verbally answer the critical question from the 4th vignette and any memory control questions (e.g., *Where did Elmo put his car in the beginning? Where is the car now?* or *What was Lily really doing?*) and press the mouse button to proceed. A 500 ms gray screen was embedded between consecutive vignettes within each story. EEG analysis focused on the 4th vignette. The auditory questions of the 4th vignette on average have a duration and word count of 3.63 sec and 11 words for the false belief condition, 3.78 sec and 11 words for the true belief condition, 2.46 sec and 8 words for the false complementation condition, and 2.52 sec and 8 words for the true complementation condition. Time-frequency analysis was based on the first 4 sec; ERP analysis was based on the first 1 sec, which on average included 3 words. For example, in the belief conditions, it would be “When Elmo comes...”; in the complementation conditions, it would be “What did Kevin...”.

Figure 2. The parieto-occipital electrodes of the 65-channel electrode montage selected for time-frequency analyses, ERPs analyses, and statistical analyses.

Figure 3.

Grand mean ($N = 30$) time-frequency planes displaying relative power variations at electrode Oz after a pre-vignette baseline. Note the modulation of power variations by the main effect of Task Type (i.e., belief vs. complementation) in low beta frequency range (12–16 Hz). Topographical maps on the right show averaged power decrease of low beta rhythm in a cluster of parieto-occipital electrodes (see Figure 2) during 500–3900 ms after the 4th vignette onset.

= .019.

Figure 4.
Parieto-occipital low beta (12–16 Hz) power variations as a function of task type.

Figure 5.

Grand mean ($N = 30$) ERPs waveforms at electrode Fz, Cz, and Pz, respectively in panel (a) and at a cluster of posterior electrodes (Pz, P3, P4, P7, P8, Oz, O1, O2, and their nearest neighbors as a total of 19 electrodes) at panel (b). Note the divergence between the belief and complementation conditions at Pz and at the cluster of posterior electrodes around 600–900 ms after the 4th vignette onset.

Figure 6.
Time course of the t-values at electrode Pz and topography of the t-values.