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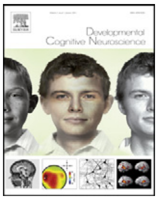

True- and false-belief reasoning in children and adults: An event-related potential study of theory of mind

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ABSTRACT

The understanding that another person's belief can differ from reality and that behaviour is guided by beliefs and not by reality reflects an important cornerstone in the development of a Theory of Mind. The present event-related potential (ERP) study had two aims: first, to reveal ERPs that distinguish between false- and true-belief reasoning and second, to investigate the neural changes in the development of false- and true-belief reasoning from childhood to adulthood. True- and false-belief cartoon stories were presented to adults and 6–8-year-old children. Results revealed two waveforms that differentiated between the two conditions: a late positive complex (LPC) associated with the reorientation from external stimuli to internal mental representations and a late anterior slow wave (LSW) associated with stimulus-independent processing of internal mental representations, a process that might be centrally involved in the decoupling mechanism. Additionally, we found developmental effects at an ERP level. Children showed a more posterior localization of the LPC and a broader frontal distribution of the LSW. The results may reflect developmental progress in conceptualizing the mental domain and support the idea that the cortical mentalizing network continues to develop even after children are able to master false beliefs.

1. Introduction

The ability to recognize and evaluate other people's mental states, such as desires, intentions and beliefs enables a person to navigate successfully through the social world and is referred to as Theory of Mind (ToM). An important milestone in the development of a ToM is gaining the ability to represent false beliefs: the understanding that a person's belief can differ from reality.

A classical task for testing false-belief understanding is the so-called unexpected transfer task, in which a character (e.g. Maxi) leaves an object in one location (e.g. the drawer) and while he or she is outside the room the object is transferred to a new location (e.g. the cupboard) (Wimmer and Perner, 1983). Whereas 3-year-olds typically fail this task and claim that Maxi would look for the chocolate in the cupboard, 4–5-year-olds understand that Maxi would search in the drawer. This indicates that they understand that Maxi's knowledge of the world and the real state of the world are different and that a person's behaviour is generally guided by beliefs about the world and not by reality (see Wellman et al., 2001 for a meta-analysis).

Although research has begun to study the neural underpinnings of the ability to attribute mental states to another person and revealed that areas like the dorsal medial frontal cortex and the right temporo-parietal junction are associated with false-belief reasoning (Amodio and Frith, 2006; Carrington and Bailey, 2009; Saxe and Kanwisher, 2003; Sommer et al., 2007), until now, only few event-related potential (ERP) studies have investigated mental

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state attribution (Liu et al., 2004; Liu et al., 2009a,b). ERP studies provide useful information about the time course of cognitive processes such as ToM reasoning. To date, only one ERP study has specifically investigated false-belief reasoning (Sabbagh and Taylor, 2000). This study contrasted a verbal false-belief condition in which an object had to be localized according to a person's belief to a verbal false photo condition in which an object had to be localized according to a photo (Sabbagh and Taylor, 2000). The results revealed that false-belief reasoning was associated with a late left anterior slow wave that was more positive in the false-belief condition than in the false photo condition. However, the meaning of the anterior slow wave for the decoupling between mental states and reality is unclear because the component was also found in studies that have not specifically investigated false-belief reasoning. Two ERP studies which investigated mental state judgements (Liu et al., 2004, 2009b) revealed a late slow wave divergence at left anterior sites but with a different polarity. In these studies participants had to make either a reality judgement concerning the real state of affairs or a think judgement concerning a cartoon character's mental state (false and true beliefs about a location of another character). In contrast to reality judgements, think judgements were associated with a late slow wave. In a recent study, Liu et al. (2009a) found an anterior slow wave associated with a condition in which certain beliefs must be attributed to a character. Participants were presented with stories about a mystery box that contained objects for a guessing game. For example, they read about a girl who thinks the box contains a special food and a boy who thinks the box contains a different food. Then one of the two objects was presented and the participants had to answer who of the two children thought that this object was in the box. The anterior late slow wave was not only associated with this "divergent beliefs" condition, which does not require a decoupling of mental states from reality, but also with judgements about desires. However, results revealed a right posterior slow wave that was specifically associated with belief judgements.

Taken together, ERP studies consistently show that judgements about the thinking of another person are associated with a late anterior slow wave. However, the significance of the anterior slow wave for the decoupling mechanism of false-belief understanding is not completely understood.

Thus, the first aim of the present study was to investigate the specificity of false-belief reasoning by using a contrast that taps the core of false-belief understanding. This can be achieved by comparing a condition in which a person's mental state is independent of reality (false belief) to a condition in which the person's mental state does not differ from reality (true belief) (Perner, 1991). The advantage of a false-belief versus true belief comparison is that both conditions require action prediction or explanation. In contrast, a comparison between a false-belief condition and a false photo condition (Sabbagh and Taylor, 2000) has the disadvantage that the two conditions are different in their representational demands. Whereas false beliefs require an understanding that a person's mental representation of the world differs from the present state of reality, the photo represents the world at a specific point in time and it is only necessary to know that the photo depicts reality at that time, i.e. the false photo is not really false (Perner and Leekam, 2008).

The second aim of the current study was to investigate developmental changes of the electrophysiological correlates of false- and true-belief reasoning. Behaviourally, an explicit false-belief understanding develops around the ages of 4–5 years (Wellman et al., 2001) and an implicit understanding of false beliefs has recently been demonstrated in infants (Baillargeon et al., 2010). To date, only one ERP study has addressed the neural correlates of mental state attribution in children. In accordance with their previous study (Liu et al., 2004), Liu et al. (2009b) compared a think judgement concerning a character's mental state (false and true beliefs about a location of another character) with reality judgements by presenting animated vignettes to 4–6-year-old children and adults. In adults think judgements were associated with a left frontal slow wave. The same waveform but with a slightly more diffuse frontal scalp distribution was revealed in children who successfully passed the belief tasks. In children who did not pass the belief tasks a differentiation between belief reasoning and reality judgments was not found.

In the present study, we investigated developmental changes in the neural underpinnings of false- and true-belief reasoning. We presented an unexpected transfer task to adults and to 6–8-year-old children, that is, an age group who have begun to consistently represent false beliefs in everyday life. By comparing behaviourally competent children to adults, we are able to ensure that children are comparable to adults at a performance level, allowing interpretation of group differences at the neural level. Moreover, a comparison between competent children and adults can test the structural invariance hypothesis, i.e. is there a specialized system of ToM processing in the brain that underlies false-belief reasoning in children as well as in adults who have much more experience with belief reasoning, or is there evidence for an increase in efficiency and specialization.

Recent structural MRI studies have revealed that brain areas associated with belief reasoning, e.g. the medial frontal cortex and the temporal cortex, undergo considerable development throughout childhood. They provided evidence for age-related cortical thinning in brain regions crucially implicated in belief reasoning (Gogtay et al., 2004; Shaw et al., 2008; Sowell et al., 2003, 2004; Toga et al., 2006) which may reflect the use-dependent selective elimination of synapses (Huttenlocher and Dabholkar, 1997). For example, Shaw et al. (2008) showed that some areas such as the temporal and frontal cortex, which are also involved in belief reasoning, followed a cubic-like developmental trajectory. An increase in cortical thickness during childhood is followed by cortical thinning which dominates adolescence. These long-lasting structural changes may be correlated with developmental progress in conceptualizing the mental domain (Johnson and Munakata, 2005). This idea is supported by behavioural studies of ToM development showing that children's understanding of the mind undergoes important reorganization from middle childhood through adolescence. For example, during the elementary school years, children become increasingly aware of the mind as an active interpreter of information (Chandler and Lalonde, 1996). While children understand that beliefs can be false due to misinformation, adolescents begin to conceive of coherent systems of beliefs, such as interpretive frameworks.

In sum, the present study had two major aims. The first aim was to investigate ERP components that differentiate between false- and true-belief reasoning. With respect to previous ERP studies that investigated belief reasoning in general (Liu et al., 2004, 2009a; Sabbagh and Taylor, 2000; Sabbagh, 2004), we expect a late slow wave localized at frontal sites that distinguish between false- and true-belief reasoning. Related to the results of fMRI studies that compared false- and true-belief reasoning and found activity of temporo-parietal areas associated with false-belief reasoning (Saxe and Kanwisher, 2003; Sommer et al., 2007), we expect ERP components that differentiate between true- and false-belief reasoning and that are spatially or temporally distinguishable from the anterior slow wave. The second aim was to reveal developmental changes in the ERP components associated with true- and false-belief reasoning. Considering the structural changes the brain undergoes during this time and in respect to functional neuroimaging studies showing that social cognition tasks increase activity in frontal areas during childhood (for reviews see Blakemore, 2008a,b; Johnson, 2001), we expect a more diffuse recruitment of the frontal cortex in children compared to adults.

2. Methods

2.1. Participants

Twenty-four students from the University of Munich participated in the study for either course credit points or monetary compensation. Data from three adults were excluded from the analyses because of technical errors. Fourteen out of the remaining 21 participants included in the final sample (mean age = 24.33 years; SD = 5.40) were female. All adult participants were right handed and had normal or corrected-to-normal vision.

Thirty-four 6–8-year-old children participated in the study. Data from 12 children were excluded because of excessive movement artifacts (eye- or body movements) or technical errors during EEG recordings. This proportion of loss is common in ERP studies with young children (DeBoer et al., 2004). The final sample for analysis consisted of twenty-two 6–8-year-old children (13 girls, 9 boys; mean age = 7.7 years, SD in months = 10.1). According to their parents' accounts, all children were reported right handed and had normal or corrected-to-normal vision. Child participants were recruited from a list of parents who had previously indicated an interest in participating in developmental research. The children received monetary compensation for their participation in the experiment. The experimental methods had ethical approval from the institutional ethics committee. Informed consent was obtained from all adult participants and from all children and their parents.

2.2. Stimuli

Non-verbal cartoon stories depicting a person acting on the basis of correct (true belief) or incorrect (false belief) representations of reality (Fig. 1) were presented. All stories consisted of 7 pictures and told a story according to the "Sally Anne Scenario" (Baron-Cohen et al., 1985). The first four pictures showed two children (e.g. Betty and Nick) and two boxes (e.g. a bag and a basket) in a room (picture 1). One child (e.g. Betty) puts an object into one box (e.g. a teddy-bear into the bag; picture 2). Then Betty leaves the room (picture 3). The other child (Nick) takes the teddy-bear out of the bag (picture 4). These four pictures are the same in the false- and true-belief conditions. Then the stories continue slightly differently. In the true-belief condition Betty comes back into the room (picture 5) and watches Nick putting the teddy into the basket (picture 6). In the false-belief condition Nick puts the teddy-bear into the basket while Betty is out of the room (picture 5). Then Betty comes back into the room (picture 6). The final picture of each story was marked by a red frame (picture 7) and was the same for the true and the false-belief story: Betty looks for the teddy-bear. In order to realize a violation of expectation task, 50% of the final pictures showed Betty looking into the correct box while in the other 50% of cases Betty was shown looking into the wrong box. Although all stories depicted a transfer of an object from one location into another location, the objects (e.g. ball, teddy, book, toy car), the places (e.g. cupboard, box, bag, basket) and the children differed between the stories.

2.3. Procedure

Participants sat comfortably in a dimly lit, sound-attenuated chamber while picture stories were presented on a computer monitor. The pictures were 12 cm in height and 26 cm in width and subtended a visual angle of 5.7° vertically and 12.4° horizontally. Each ERP eliciting picture was presented for 2000 ms after the presentation of a black screen for 300 ms (ISI).

The presentation of the final picture (picture 7) which depicted the outcome of each story was the target event to which the ERP data were time-locked. After the offset of the final picture and an ISI of 300 ms, a response cue remained on the screen until the response was registered. The response cue asked the participants "Did you think that the child would search there?" (Hast Du gedacht, dass das Kind da sucht?). Adults reported their decision by pressing one of two buttons with either their left or right thumb. 'Yes' and 'no' response hands were counterbalanced across adult participants. We separated the target picture from the response picture to prevent motor artefacts in the target picture. The children provided their decision verbally and the experimenter recorded their responses on a computer. Forty true-belief stories and 40 false-belief stories were presented. The task was presented in a pseudorandom order. Prior to the start of the ERP recording 16 practice trials were given that were different from the test trials. During this instruction phase, stories were narrated by the experimenter. The stimulus presentation was controlled using C software.

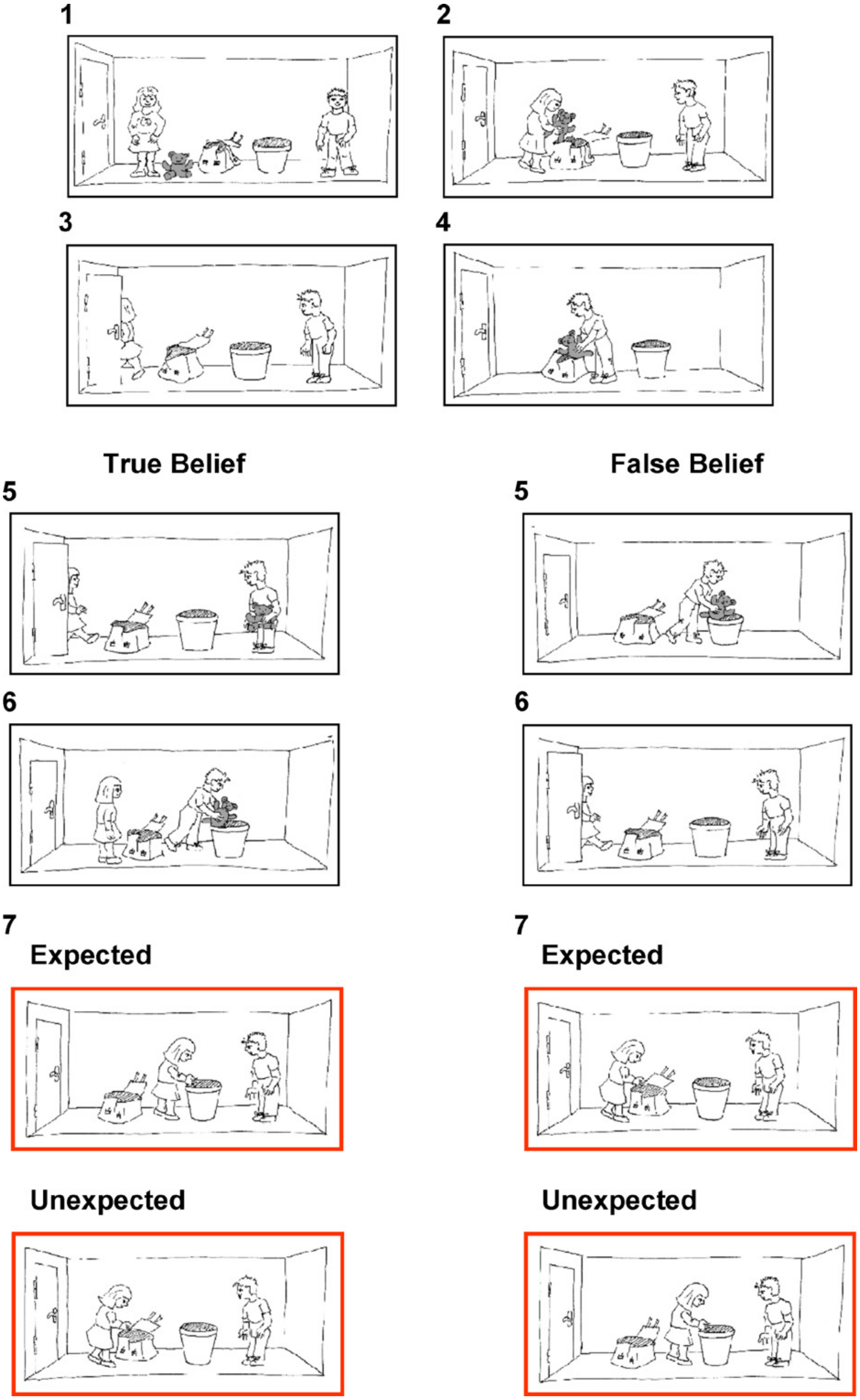

Fig. 1. Example of a typical true- and false-belief story: the pictures 1–4 were the same for the true- and false-belief stories, afterwards the true- and false-belief stories continue differently (picture 5 and 6, left and right column). Picture 7 was the ERP eliciting event.

2.4. EEG/ERP recording and analysis

The electroencephalogram (EEG) was recorded using EasyCap electrode caps appropriately sized for the children's and adults' heads. There were 6 midline electrodes (Fz, FCz, Cz, CPz, Pz, Oz) and 22 left/right hemisphere electrodes (FP1/FP2, F7/F8, F3/F4, FT7/FT8, FC3/FC4, T7/T8, C3/C4, FP7/TP8, CP3/CP4, P7/P8, and P3/P4) according to the International 10-20 system. The EEG was acquired with Cz reference. The vertical electrooculogram (EOG) was recorded from electrodes placed above and below the right eye and the horizontal EOG was recorded from electrodes placed at the outer canthi. The ground electrode was placed at position AFz. Additional electrodes were placed on both mastoids. The impedances of all electrodes were kept below 5 kΩ. The EEG and EOG signals were amplified by NeuroScan Synamps amplifiers with a bandpass of 0.01–40 Hz/−6 dB and were continuously sampled at 200 Hz. For all offline analyses, Vision Analyzer software (Brain Products, Germany) was used. Offline EEG data were re-referenced to average mastoids, and were digitally high-pass filtered at 0.1 Hz/−12 dB. Segments time-locked to the final picture of each story were extracted. The segments were 1100 ms long for adults (−100 to 1000 ms) and 1600 ms long for children (−100 to 1500 ms). A longer epoch was used with children because their ERP components occurred at longer latencies. The 100 ms interval before picture onset was defined as the pre-stimulus baseline. Segmented data were scanned for artifacts in three steps. First, segments were automatically eliminated if EEG exceeded ±100 μV for adults or ±150 μV for children. Second, segments with other artifacts that were previously undetected were manually excluded from the sample. Third, segments were corrected for ocular artifacts using the algorithm of Gratton et al. (1983). Artifact-free segments for correct responses were averaged separately for each participant and experimental condition. The criterion for further processing was a minimum of 16 clean segments per belief condition among the correctly responded trials. After artifact correction the average number of useable segments in the true-belief condition amounted to 28.7 (SD = 8.2) for adults and 24.8 (SD = 7.2) for children. For the false-belief condition, average number of useable segments was 29.8 (SD = 7.9) for adults and 25.3 (SD = 8.5) for children. The number of useable segments did not differ significantly between adults and children, $F(1, 41) = 3.16$, $p > 0.083$, did not differ significantly between the belief conditions, $F(1, 41) = 1.46$, $p > 0.23$, and did not interact between belief and group, $F(1, 41) = 0.18$, $p > 0.67$.

ERPs were measured as mean area amplitudes within specific time windows, as described below. The resulting data for each time window were analyzed with a 2 × 2 × 2 mixed-designed analysis of variance (ANOVA) with group as a between subject factor (2 levels: adults and children), belief (2 levels: true- and false-belief) and expectancy (2 levels: expected and unexpected) as repeated measure factors. Three separate ANOVA analyses were performed in order to examine columns of scalp electrodes along the anterior–posterior axis of the head. The midline analysis had six levels of the electrode site factor (Fz, FCz, Cz, CPz, Pz, and Oz). The superior analysis had five levels of the electrode site factor and two levels of the hemisphere factor (F3/F4, FC3/FC4, C3/C4, CP3/CP4, and P3/P4). The inferior analysis had six levels of the electrode site factor and two levels of the hemisphere factor (FP1/FP2, F7/F8, FT7/FT8, T7/T8, TP7/TP8, and P7/P8). For all analyses of variance (ANOVA), the Greenhouse–Geisser correction for non-sphericity was applied to all p-values associated with more than one degree of freedom. The corrected p-values and the original degrees of freedom are reported. We considered statistical significance to be $p < 0.05$. Because this report focuses on topographic interactions and not on overall group differences with respect to ERP amplitudes, the ERP data were not standardized. Therefore, only the experimental main effects (belief and expectancy) and interaction effects including the main factors were reported.

3. Results

3.1. Behavioural results

Response accuracy (in percent) was analyzed by a 2 × 2 × 2 (group × belief × expectancy) mixed-designed ANOVA with group as a between subject factor and belief and expectancy as a repeated measure factor. The significant main effect of group ($F(1, 41) = 11.49$, $p < 0.02$) showed that adults ($M = 96.83$, SD = 2.54) were slightly more accurate than children ($M = 92.22$, SD = 5.71). There was no other significant main effect or interaction. Further, there were no significant correlations between children's age and accuracy on true-belief tasks or on false-belief tasks (all $ps > 0.19$). On the basis of the accuracy data it can be assumed that both groups performed the task in a controlled fashion and that developmental differences between children and adults are not related to differences in the understanding of true and false beliefs.

3.2. ERP results

For the analysis of the ERP data, only trials with correct responses were included. The grand average waveforms elicited in the true- and false-belief conditions are shown in Fig. 2 for adults and children for selected electrodes. Visual inspection revealed that in adults and children both conditions elicited a comparable sequence of early and late waveforms. As expected from developmental ERP data for children the overall amplitude of the waveforms were greater and the latencies of some components were later than for adults. A differentiation between the true- and false-belief condition was predominantly pronounced in two waveforms: the first deflection – a late positive complex (LPC) – was most pronounced at parietal regions. With respect to latency and the posterior scalp distribution this waveform might be a P3-like component. For statistical analysis the mean amplitudes in a time window of 300–600 ms were extracted for adults and children. The LPC was followed by a late slow wave (LSW) divergence at anterior regions. This LSW showed a longer duration in time for children than for adults. Therefore, for adults the mean amplitude values were extracted between 600 and 900 ms and for children between 750 and 1450 ms. These time windows were determined by using mean separate grand averages for children and adults in true- and false-belief conditions. The grand average ERPs in adults and children for true- and false-belief reasoning are shown in Fig. 2 and the topographic maps of the belief effect are shown in Fig. 3 for the LPC and LSW.

3.2.1. Belief effect

During the LPC epoch (adults and children: 300–600 ms) false-belief tasks elicit significantly more positive waveforms than true-belief tasks at midline (main effect of

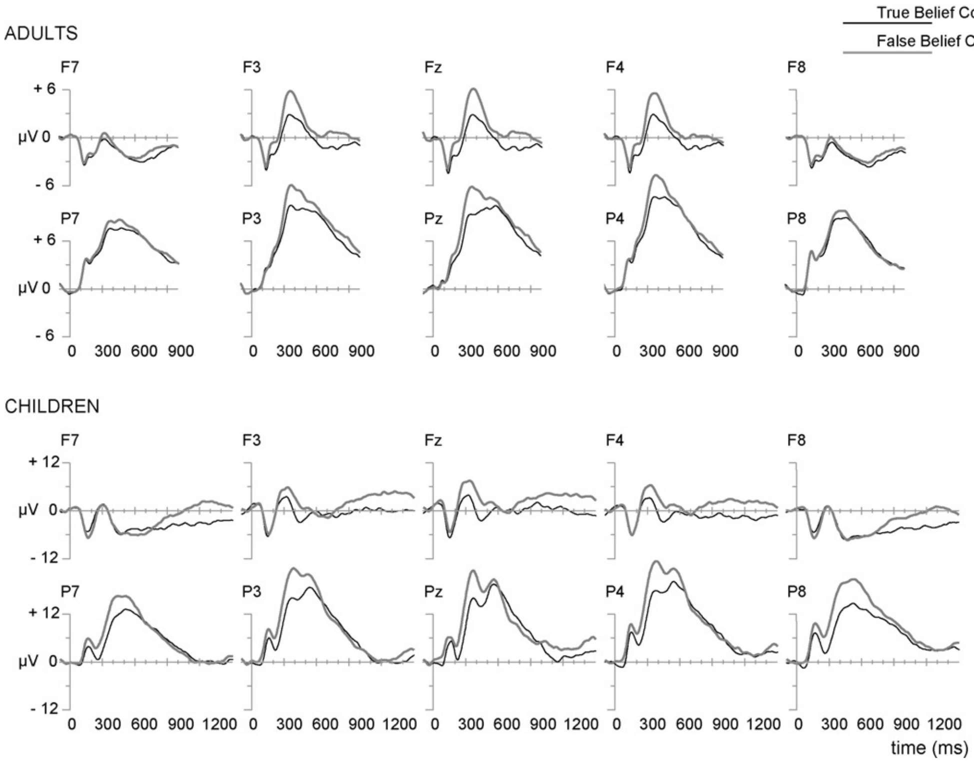

Fig. 2. Grand average ERPs in adults and children: ERPs are elicited by the final picture in the true-belief and false-belief condition at frontal and parietal electrode locations.

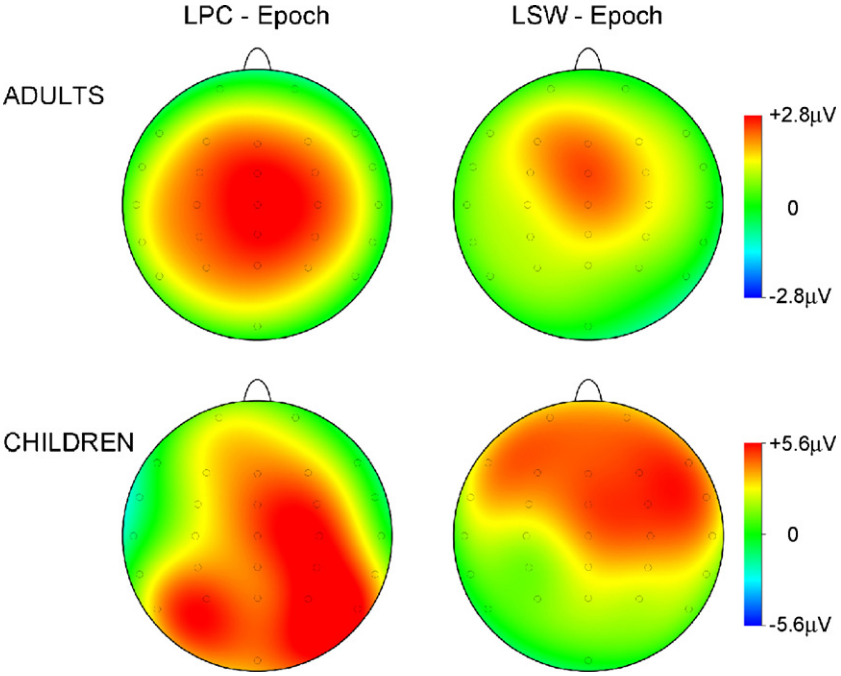

Fig. 3. Topographic maps of the belief effect: mean amplitude difference between ERPs of the true-belief condition subtracted from the false-belief condition separated for adults and children. The LPC represents the 300–600 ms post-stimulus epoch for adults and for children. The LSW represents the 600–900 ms post-stimulus epoch for adults and the 750–1450 ms post-stimulus epoch for children.

belief: $F(1, 41) = 28.43$, $p < 0.001$), superior (main effect of belief: $F(1, 41) = 30.52$, $p < 0.001$), and inferior sites (main effect of belief: $F(1, 41) = 8.24$, $p < 0.006$).

False-belief tasks continued to elicit significantly more positive waveforms than true-belief tasks during the LSW epoch (adults: 600–900, children: 750–1450 ms) at midline (main effect of belief: $F(1, 41) = 20.01$, $p < 0.001$), superior (main effect of belief: $F(1, 41) = 13.76$, $p < 0.001$), and inferior sites (main effect of belief: $F(1,41) = 9.65$, $p < 0.003$). The belief effect was most expressed over anterior regions as indicated by the belief by electrode site interaction at midline sites, $F(5, 205) = 7.55$, $p < 0.001$, superior sites, $F(4, 164) = 4.84$, $p < 0.009$, and inferior sites, $F(5, 205) = 3.36$, $p < 0.028$.

3.2.2. Expectancy effect

For the LPC the factor expectation showed a significant main effect at midline sites, $F(1, 41) = 8.97$, $p < 0.005$). Unexpected story outcomes elicited more positive waveforms than expected story outcomes. No reliable effect for expectancy was obtained for the LSW epoch.

3.2.3. Developmental effect

Additionally, results indicated a developmental effect for the LPC and the LSW.

During the LPC epoch for adults the belief effect was widely distributed over central sites, whereas in children the differentiation between true- and false-belief reasoning was more pronounced at posterior sites, as indicated by the significant group by belief by electrode site interaction at inferior sites, $F(5, 205) = 8.20$, $p < 0.001$. See Fig. 2 for the waveforms and Fig. 3 for the topographic maps (left column).

The results of the LSW revealed a significant group by belief interaction, $F(1, 41) = 5.14$, $p < 0.029$, and indicated a different scalp distribution for the belief effect between both groups. To further confirm this effect, a subsidiary analysis with factor belief was separately conducted for each group at inferior sites. For children the main effect of belief, $F(1, 21) = 8.17$, $p < 0.009$ and the belief by electrode site interaction, $F(5, 105) = 3.48$, $p < 0.028$, were significant. In contrast for adults neither a main effect of belief nor an interaction of belief with any other factor was obtained (all $ps > 0.15$). These results indicate that the scalp distribution of the belief effect was more diffuse for children encompassing the anterior regions at midline, superior and inferior sites than the belief effect for adults which was restricted to the anterior regions at midline and superior sites. See Fig. 2 for the waveforms and Fig. 3 for the topographic maps (right column).

4. Discussion

The present study investigated ERPs that distinguish between false- and true-belief reasoning in children and adults. Following a well-established paradigm in Developmental Psychology we compared false- and true-belief reasoning in parallel tasks by presenting cartoon stories that depicted an unexpected transfer task (Perner, 1991; Wellman et al., 2001). Both conditions required action explanation, but in contrast to the true-belief condition, false-belief reasoning additionally requires the representation of a person's mental state independently of reality. Thus, the present findings provide evidence on the specific neural response associated with the decoupling mechanism that is critical for false-belief understanding.

The findings provide two waveforms that distinguish between false- and true-belief reasoning: a late positive complex (LPC) and a late anterior slow wave (LSW), both showing higher positive amplitudes for false- than true-belief reasoning. Additionally, the results indicate that both waveforms show developmental effects.

With respect to latency and the posterior scalp distribution, the LPC showed similarities with a P3 potential (Donchin and Coles, 1988; Polich, 2007). Besides being associated with neural generators in frontal areas, the P3 component is associated with activity in the temporoparietal junction (TPJ; Kirino et al., 2000; Knight et al., 1989; Polich, 2007), an area that is often found in neuroimaging studies that have investigated belief reasoning (Saxe and Kanwisher, 2003; Sommer et al., 2007). The important role of the TPJ in false-belief reasoning is supported by an fMRI study with adults that used the same stimuli as the present study and that also contrasted false- and true-belief reasoning (Sommer et al., 2007). This study revealed that false-belief reasoning induced significantly higher activity in the right TPJ than true-belief reasoning. The involvement of the TPJ in false-belief reasoning is consistent with theories that discussed the TPJ as part of the ventral attentional system (Corbetta et al., 2008) which detects salient and behaviourally relevant stimuli in the environment. Unlike in the true-belief condition, in the false-belief condition differences between the subject's own knowledge and the protagonist's knowledge need to be considered. The subjects had to shift attention from the observed protagonist's behaviour to their knowledge about the protagonist's mental representation. Attention signals in the TPJ may be important for the reorientation from the visual input (i.e. the protagonist's search of the object) to the protagonist's mental representation (Mitchell, 2008).

These assumptions are also compatible with the context-updating hypothesis suggesting that the P3 component represents the process invoked when one needs to update a mental model of the environment. Also, this process may be depicted by the fact that a larger amplitude of the P3 is related to a larger change in the mental model (Donchin and Coles, 1988). In the true-belief condition the observer's knowledge about the protagonist's mental representation and the knowledge about reality do not differ and therefore no update is required. In the false-belief condition, the observer's memory needs to hold two different mental models: knowledge of where the object really is and knowledge about the protagonist's mental representation of the object's location. The judgment about the protagonist's behaviour may induce a comparison process that evaluates both mental models and eventually demands a revision of one of these mental models.

In addition to the results of the LPC concerning the belief effect, the LPC also distinguished between expected and unexpected events. The amplitude of the LPC was enhanced in response to unexpected endings compared to expected endings. This result supported the interpretation of the LPC with respect to the context update hypothesis.

Following the LPC, the late anterior slow wave (LSW) was associated with belief reasoning in adults and also in children. These results are in line with other ERP studies that found a late anterior slow wave associated with mental state attribution (Sabbagh and Taylor, 2000; Liu et al., 2004, 2009b). Nevertheless, there is a difference in slow wave polarity between the studies. Consistent with Sabbagh and Taylor (2000), in the present study false-belief reasoning was associated with a more positive slow wave. In contrast, in the two cartoon studies a more negative waveform related to general belief reasoning was found (Liu et al., 2004, 2009b). These differences in polarity may be due to the use of different mentalizing tasks contrasting different conditions. The present study and the study of Sabbagh and Taylor (2000) investigated the specificity of false-belief reasoning. Sabbagh and Taylor (2000) contrasted a false-belief condition with a false photo condition to identify ERP components that distinguish between mental and non-mental representations in adults. The present study focussed on ERP components associated with the decoupling mechanism of false-belief reasoning by comparing false and true beliefs. In both conditions participants had to explain another person's behaviour, but false-belief reasoning in contrast to true-belief reasoning requires the representation of a person's mental state independent of reality. In contrast, by comparing mental judgements that involved false and true beliefs with reality judgements, Liu et al. (2004, 2009b) did not investigate the core aspect of false-belief reasoning, the decoupling between mental states and reality. In sum, the results of the different ERP studies indicate that a positive LSW may be specifically associated with false-belief reasoning, whereas more general mental state attribution processes seem to be associated with a negative LSW which confirm the critical role of the prefrontal cortex for belief reasoning (Frith and Frith, 2006; Sommer et al., 2007).

Slow positive potentials over frontal areas seem to be related to conceptual load (Rösler and Heil, 1991; Pauli et al., 1994). In true-belief stories it suffices to compare the outcome of the story (where the children search for the object) to reality (where the object really is). But in the false-belief condition participants had to reason about the protagonist's mental representation about the object's location independently of the real location of the object. The anterior slow wave may index the conceptual load associated with the decoupling between the protagonist's mental representation and the real state of affairs (Liu et al., 2004). The assumption that the late anterior slow wave represents cognitive processes that involve the processing of mental states independently of reality is underscored by our fMRI study that used the same stimuli as the present study (Sommer et al., 2007). Besides activity of the right TPJ, the neuroimaging results revealed involvement of the dorsal anterior cingulate cortex and the lateral prefrontal cortex, areas that are involved in stimulus-independent cognitive processes and in switching attention between stimulus-dependent and stimulus independent thought processes (Gilbert et al., 2006).

Taken together, the current findings showed two late waveforms, the LPC and the LSW, that distinguished between true- and false-belief reasoning. These late potentials are more likely associated with controlled than with automatic processing. In contrast to modularity theory that proposes that mental operations associated with ToM processes are executed in a fast automatic mode with perception-like speed (Leslie, 1994), the present results indicate a more controlled processing of beliefs. Therefore, consistent with previous ERP studies (Liu et al., 2004; Sabbagh and Taylor, 2000), our results provide further evidence against the idea that belief reasoning is performed in an automatic manner with perception-like speed.

Interestingly, our results revealed not only an influence of true- and false-belief reasoning on the LPC and the LSW, but also an effect of development on both components. In adults, the LPC divergence showed a broad distribution with a focus on central sites whereas in children, the LPC was broader distributed at posterior regions. The LSW showed a broader scalp distribution at frontal regions for children than for adults. In adults, the late anterior slow wave distinguished true- and false-belief reasoning at midline and superior regions whereas for children the LSW divergence encompassed midline, superior and also inferior sites.

The broader scalp distribution of the LSW expands Liu's et al. (2009b) findings that also showed a broader distribution of the children's LSW in a belief–reality contrast and indicates developmental effects especially associated with false-belief reasoning.

The differences in the topography between children and adults may be associated with developmental changes of the brain. During childhood and adolescence the brain undergoes substantial structural changes (Blakemore, 2008a,b; Giedd et al., 1999; Huttenlocher and Dabholkar, 1997; Shaw et al., 2008). Research showed that especially areas of the frontal cortex, but also of the temporal and parietal cortex show changes in grey- and white-matter volume. Possibly, the different distribution patterns of the LPC and the late anterior slow wave mirror the developmental progression in cortical areas. Johnson (2001) argues that changes in the response properties of cortical regions during development are determined by their connectivity to other regions and their current activity status. Therefore, behavioural abilities that do not differ between children and adults may be associated with different patterns of cortical activation. This suggestion is supported by developmental studies that observe less localized ERP activity in children than in adults (Johnson and Munakata, 2005) and also by functional neuroimaging studies of social cognition that revealed activity increase in the medial PFC between childhood and adulthood (Blakemore, 2008a,b). Also, these topographical differences may reflect different cognitive strategies for solving false-belief tasks. Children, who are able to solve first order false-belief tasks, still lack the conceptual repertoire of advanced ToM reasoning. Moreover, adults have a huge advantage in experience with false-belief situations. Therefore it is possible that children recruit divergent, and more cumbersome cognitive strategies and need more effort for solving false-belief tasks than adults. This idea is also supported by the observation that compared to adults children's LSW showed a longer duration in time. Since the temporal extension of the LSW reflect the duration of the cognitive process, this may indicate that children take longer to process another person's mental state.

As can be derived from the time windows for the statistical analysis, the LSW evoked later in children than in adults. The latency shift is consistent with a general age-related change in the latency of ERP components and has been demonstrated over a wide range of cognitive functions and different ERP components (Taylor and Baldeweg, 2002). The current findings expand these results to false-belief reasoning. An age-related latency shift may reflect the development of faster information processing throughout childhood (Kail, 1991) and may be related to a variety of maturational factors such as synaptic density, skull thickening and brain size (DeBoer et al., 2004). The latency shift of the late anterior slow wave in contrast to the LPC may indicate that especially the late anterior slow wave was affected by these factors.

5. Conclusion

Results revealed two ERPs that distinguished between true- and false-belief reasoning in children and adults: a late positive complex (LPC) most expressed at parietal regions and a late anterior slow wave (LSW). Considering these ERPs, we propose two cognitive steps associated with the decoupling mechanism of false-belief reasoning. The LPC may reflect attention signals for the reorientation from external stimuli to internal mental representations, followed by the LSW that may indicate the processing of these internal mental representations independent of external stimuli. The greater amplitude of the ERP components associated with false-belief reasoning may indicate a higher cognitive load imposed on these computational steps.

Additionally, results revealed a developmental effect in the topography of the ERPs. The topographic differences between children and adults support the idea that the cortical mentalizing network continues to develop even after children are able to master false-belief tasks (Blakemore et al., 2007). These differences may reflect the developmental structural changes that the brain undergoes during childhood, which in turn is correlated with developmental progress in conceptualizing the mental domain (Johnson and Munakata, 2005) as well as progress in the fast and accurate processing of belief-relevant information.

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