

When binding matters: an ERP analysis of the development of recollection and familiarity

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Dual process models of recognition memory assume that memory retrieval can be based on two distinct processes: an assessment of a context-free feeling of familiarity or on the reinstatement of specific context attributes that have been bound together to form a representation of the study episode during encoding (recollection). Recent neurophysiological evidence suggests that familiarity and recollection are mediated by different medial temporal lobe circuitries and accomplished by different binding mechanisms. The assessment of familiarity has been associated with intra-item binding mechanisms of the perirhinal cortex, whereas the explicit retrieval of specific details of a study episode depends on inter-item binding mechanisms mediated by the hippocampal formation and the prefrontal cortex. A related line of evidence for the independence of these memory processes comes from the examination of patients with selective lesions: Vargha-Khadem et al. (1997) reported three cases of early bilateral hypoxic lesions restricted to the hippocampus. Although these patients were unable to acquire and to retrieve episodic information, they were unlike most adult amnesics clearly able to acquire semantic knowledge after their injury. We examined the developmental aspects of recollection and familiarity by means of an event-related potential (ERP) study in two groups of children (6-8 years, 10-12 years) and young adults (20-29 years). Topographical differences of ERP components between the age groups were found in the memory task, but not in an auditory discrimination (oddball) task, suggesting that ERP differences between groups can be ascribed to differential memory processes rather than to general age differences. Our findings support the view of a differential development of recollection and familiarity. We discuss these findings in the light of different memory strategies in children as indicated by a generally lower performance level and a more conservative response criterion.

Introduction

Seeing a familiar face without being able to tell under which circumstances it was previously encountered is a well-known example of familiarity-based recognition memory (cf. Mandler, 1980). Until now it remains unclear at which age during childhood this acontextual form of explicit memory develops and how it is related to contextual memory, i.e. the ability to recollect many specific details, thereby placing memories into the context of the study episode.

In this chapter, dual process models of recognition memory and its neural correlates that give rise to distinct event related potential (ERP) components are briefly resumed. Next, real-life consequences of memory structures that have been disrupted very early are illustrated in three cases with selective hippocampal lesions acquired during or shortly after birth (Vargha-Khadem et al., 1997, 2001, 2003; see also Gadian et al., 2000). These cases challenge traditional concepts of memory systems and raise new questions about memory development, which can be answered by investigating recognition memory performance and ERPs in healthy children.

Dual process models of recognition memory

A number of models have tried to explain the complex findings obtained while studying recognition memory in healthy individuals and amnesic patients. Most models agree on the distinction between explicit memory that can be consciously accessed and implicit memory that guides future behavior although no conscious memory trace is accessible (e.g. Squire & Zola, 1996, 1998). Implicit memory as measured by indirect tasks such as word stem completion or lexical decisions is usually unimpaired in amnesic patients (cf. Yonelinas, 2002).

Explicit memory has been further subdivided into episodic and semantic modules. In the Squire model, declarative (i.e. explicit) memory consists of two parallel subsystems that are responsible for personal events (episodic) or general facts (semantic). Both are considered to depend on the same medial temporal lobe structures on the basis of examination of amnesic subjects who were impaired in both memory for episodes and for general facts (Squire & Zola, 1998).

Memory abilities can be assessed using various retrieval tasks. In (cued) recall the task is to retrieve previously studied items with or without the help of specified retrieval cues. In recognition memory tasks, previously studied items are presented again at test along with new items and subjects are asked to indicate whether the items have been shown before or not. Dual process models assume that two qualitatively distinct processes are involved in recognition memory: a relatively fast process that is accompanied by a context-free feeling of familiarity and a slower, more controlled process that reinstates certain details of the study episode to be remembered (recollection). An extensive review of experimental manipulations that allow to differentiate between those two processes is given by Yonelinas (2002). Similar to this distinction, Tulving introduced an experimental technique to dissociate the subjective awareness during recognition (Tulving, 1985). It is possible to distinguish between

items for which subjects are able to become consciously aware of some aspects of the previous presentation ("remember") and those that give rise to a feeling of familiarity in the absence of remembering, so-called "knowing".

Personally experienced episodes typically contain many details connected with the original event, whereas semantic knowledge is usually not connected with a detailed reinstatement of the context in which the fact was learned for the first time. Although the distinction between episodic and semantic memories and the subprocesses of recognition memory, namely recollection and familiarity, come from different theoretical backgrounds and are based on different assumptions, there is growing evidence that semantic memory and familiarity-based recognition on the one hand and episodic memory and recollection on the other hand bear functional similarities and are mediated by at least partly the same brain systems (Vargha-Khadem et al., 1997, 2001, 2003). With respect to the development of these memory systems, the Tulving and Markowitsch (1998) model states that episodic memory develops considerably later than semantic memory, since children acquire semantic knowledge before they remember episodes like adults do (Tulving & Markowitsch, 1998). This in turn leads to the hypothesis that young children rely predominantly on familiarity and only gradually increase their use of recollection.

Neuronal correlates of familiarity- and recollection-based recognition

Strong evidence for two qualitatively different subprocesses of recognition memory comes from the search for the underlying neural substrate(s). Aggleton and Brown (Aggleton & Brown, 1999; Brown & Aggleton, 2001) were able to demonstrate that familiarity and recollection are mediated by different neuronal circuitries and accomplished by different binding mechanisms. The explicit retrieval of specific details of a study episode depends on inter-item binding mechanisms mediated by the hippocampus, whereas the perirhinal cortex has been associated with the assessment of familiarity. For instance, single cell recordings from the medial temporal lobe of monkeys during recognition memory tasks have demonstrated that some neurons respond to the first presentation of an item, but less so to repeated presentations (Brown & Aggleton, 2001; see also Wan et al., 1999; Xiang & Brown, 1998). Since this pattern holds for familiar as well as novel items, they appear to be specialized to detect relative recency. Other neurons respond to novel stimuli even when presented repeatedly, but respond less to familiar stimuli irrespective of whether they are presented for the first or for the second time, thereby signalling relative familiarity. Novelty is detected by a third type of neurons that responds less to repeated presentation of novel items, at the same time the duration of the response is shorter for familiar stimuli. These three types of neurons are found mainly in the perirhinal cortex and are the only neural substrate known so far that can provide a signal for the relative familiarity, relative recency or novelty of an item. In a recent event-related fMRI study, Eldridge et al. (2000) provided evidence for a selective involvement of the hippocampus during recollection-based recognition: activity in the hippocampus only increased when memory retrieval was accompanied by recollection and not during familiarity-based memory (Eldridge et al., 2000; but see Fan et al., 2003).

Studies recording ERPs in the test phase of recognition memory tasks have found a robust ERP difference between correctly judged old and new items: this ERP old/new effect starts around 300 msec and takes the form of more positive waveforms for correctly recognized old compared to new items that lasts for several hundred milliseconds (cf. Mecklinger, 2004).

An increasing number of recent ERP studies suggest that the topographical distribution and the time course of the old/new effect allow to disentangle both subprocesses involved in recognition memory. Familiarity-based memory has been associated with early (300-500 msec) old/new effects at midfrontal electrode sites, whereas recollection has been associated with a (left) parietal old/new effect between 400 and 600 msec (cf. Mecklinger, 2000, 2004). These dissociations have been demonstrated in a variety of ERP studies (Curran, 2000; Curran & Cleary, 2003; Friedman & Johnson, 2000).

For instance, participants in the Curran and Cleary (2003) experiment studied pictures and were explicitly instructed to memorize each picture's left/right orientation. At test, old pictures were shown along with new pictures and similar old pictures that were left/right mirror reversals. The task was to respond 'old' only to stimuli that were repeated in the study orientation and to reject both similar and new pictures. Since both studied and similar pictures should elicit a feeling of familiarity, these were compared with new stimuli. In a similar line of argumentation, new items were compared with those conditions that required recollection for correct responses, namely correctly accepted old or correctly rejected similar stimuli. According to the predictions, an early (300-500 msec) midfrontal effect was associated with familiarity-based memory trials, whereas recollection-based memories were associated with a 400-800 msec parietal effect only for those subjects showing good discrimination between old pictures and their mirror images (Curran & Cleary, 2003).

Neuropsychological findings

Unlike the well-controlled lesion studies with animals, for a variety of reasons brain damage that occurs in human patients is quite often distributed broadly over several brain structures. Rare cases of selective lesions offer the opportunity to examine the functional consequences of the loss of a specific brain tissue for cognitive functions. Vargha-Khadem and colleagues (1997) reported three cases with early bilateral hypoxic lesions that were selective to the hippocampus. Although these patients were unable to retrieve episodic information, they were unlike most adult amnesics able to acquire semantic knowledge after their injury. Considerable debate is still ongoing whether the relative sparing of semantic memory is due to a) the selectivity of the insult to only the hippocampus sparing the subhippocampal cortices, b) the partial sparing of the hippocampus itself or c) some functional reorganisation occurring after this very early injury (Vargha-Khadem et al., 1997, 2001; Squire & Zola, 1998).

The most pressing problems that parents reported in the patients' everyday life involve extreme difficulties in spatial navigation, orientation in time and date as well as an inability to remember the days' activities. Neuropsychological testing confirmed these parental observations: in all tests of delayed recall, performance levels were significantly impaired and close to floor levels (Vargha-Khadem et al., 1997).

To elucidate the exact nature of the memory impairment, extensive testing of one of these patients, Jon, who was aged 23 at the time, and two age-matched controls was performed (Baddeley et al., 2001). Careful comparison of recognition and recall tasks that were matched for difficulty confirmed the earlier observations that recall performance was considerably impaired. On the other hand, performance in recognition tasks was within the normal range. Recall performance of a TV news show improved drastically when the material was presented repeatedly (4 vs. 1 presentations). However, the attempt to ask about the subjective experience during memory ("remember-know" judgments) failed because it was not possible to explain the meaning of "remember" to Jon (Baddeley et al., 2001).

In an ERP study with Jon, parts of these findings were confirmed by the ERP components. While the early (300-500 msec) midfrontal effect was found for previously studied compared to new words, Jon lacked the parietal ERP effect associated with recollection that was reliably elicited in normal controls between 500-700 msec (Düzel et al., 2001). These findings confirm the notion that recollection critically depends on the hippocampus, but that familiarity and semantic knowledge do not involve contextual information and therefore are not critically dependent on inter-item bindings mediated by the hippocampus (Baddeley et al., 2001; Düzel et al., 2001; Vargha-Khadem et al., 1997, 2001).

Two explanations are conceivable for these results: either children with developmental amnesia are still able to perform recognition tasks because children in general rely predominantly on memory processes that do not depend on the hippocampus (i.e. familiarity and semantic knowledge). The alternative explanation attributes the sparing of semantic memory in developmental amnesia to functional reorganisation, i.e. plasticity in young brains. According to this argument, the age of injury should affect the severity of the memory impairments with earlier injuries having less devastating effects on memory processes. Vargha-Khadem and colleagues (2003) were able to demonstrate that 6 children who suffered an early hypoxic-ischemic injury (within the first three months of life) did not exhibit fewer long-term memory problems than a second group of patients injured between the ages of 6 and 14 years. Vargha-Khadem concludes if developmental amnesia is critically dependent on an early timing of injury, then this critical period extends at least from birth to puberty (Vargha-Khadem et al., 2003).

McClelland and colleagues (McClelland et al., 1995) differentiate episodic (i.e. dependent on hippocampal activity) and semantic memories (i.e. not dependent on hippocampus, but rather neocortical structures) in terms of the rate of memory consolidation: while incorporation of newly formed memory representations into the neocortical system takes a long time, hippocampal incorporation rates are considerably shorter. When acquiring new semantic knowledge, this mechanism is able to reduce interference resulting from already existing semantic representations at the cost of a long learning period. Based on findings on retrograde amnesia and a connectionist model, they hypothesized that the rate of neocortical learning might vary with age, since there is no need to reduce interference due to former experiences at a young age. The acquisition of new information could be faster during a time when semantic knowledge needs to expand rapidly, and then gradually slow down to enable the integration of new semantic information to the already existing knowledge base. They made the prediction that in younger amnesics a '...much more rapid acquisition of the

shared structure of events and experiences ... than in older amnesic groups' should be seen (McClelland et al., 1995, p.447). This prediction could explain why Jon and the other cases of developmental amnesia were able to acquire new semantic knowledge unlike older patients with similar hippocampal lesions. Guillery-Girard and colleagues (2004) very recently demonstrated the acquisition of new semantic material in two young amnesic subjects using repeated presentation of the material in a prospective study (Guillery-Girard et al., 2004).

Frontal lobe contributions to memory encoding and retrieval

Selective memory impairments are also evident in another group of patients: damage to frontal structures typically affects recall more than recognition memory. On simple old/new recognition tasks patients with frontal lobe damage often perform quite normal. However, retrieval of specific details such as study context or the timing of an event is particularly difficult for them (e.g. Simons & Spiers, 2003). This deficit is sometimes called source amnesia (Simons et al., 2002). Whereas item recognition can be based on both familiarity and recollection, details about the study episode are necessary in order to successfully decide in which context the item has been presented before. Source memory requires the reinstatement of item features and their context (i.e. recollection). Often the recollected details about an item are not those that are used as test probes. Therefore successful source memory involves the recollection of the relevant item features and the specific search for these relevant item attributes. In this respect, source memory tasks resemble recall tasks, which in addition to recollection of the items require the use of specific retrieval strategies (Simons et al., 2002).

Memory impairments in frontal lobe patients are prominent in recall and source memory tasks, i.e. those tasks that critically depend on recollection. This pattern of impairment suggests that prefrontal structures modulate and control memory retrieval, since recollection is critically dependent on the selection of relevant item features (Dobbins et al., 2002). These control processes involve hierarchical top-down control and the selection and maintenance of task-relevant information. In the dynamic filtering theory, Shimamura (2002) distinguishes between four hierarchically organized aspects of executive control mediated by the prefrontal cortex (PFC): Selecting, Maintaining, Updating and Rerouting. Selection of relevant information and its maintenance in working memory are more basic abilities that are necessary for a variety of tasks. Updating or modulation of information (as measured for instance in the backward digit span) involves more complex operations. Rerouting refers to the ability to switch from one cognitive process to another and is assumed to be the most complex aspect of executive control (Shimamura, 2002).

Frontal lobe structures have been implicated to play a crucial role in memory formation at encoding (Buckner et al., 1999) as well as retrieval (Düzel et al., 1999; Rugg & Wilding, 2000; Wagner, 2002). At encoding, the areas within the mediotemporal lobes (MTL) receive input from many cortical structures. The binding of these inputs to item-context conjunctions or even to existing memory representations has been connected to the hippocampus.

A critical part of the newly formed associations is the input the hippocampus receives from the PFC (Buckner et al., 1999). Successful memory retrieval of these bound representations from long-term memory involves the search for specific item attributes that have been studied. Rugg and Wilding (2000) distinguish between several classes of retrieval processes: retrieval mode (a maintained state associated with intentional retrieval), retrieval orientation (dependent on the specific task at hand, e.g. recognition vs. source judgements), retrieval effort (processing resources that vary along with task difficulty) and retrieval success (processes elicited only by true memories (Rugg & Wilding, 2000)). So far it is unclear by what age these processes are functionally mature. Düzel and colleagues (1999) compared ERPs and PET activation during episodic and semantic retrieval of old and new words denoting living and nonliving items. Episodic retrieval was accompanied by right prefrontal activation, whereas semantic retrieval was associated with left frontal and temporal lobe activity (Düzel et al., 1999). Combining the high temporal resolution of ERPs with the superior spatial resolution of PET allowed to trace the origin of the ERPs at frontal recording to activity within in the PFC.

The fact that the frontal lobes are not only implicated in the control of memory functions, but also among the latest brain structures to mature in the course of development reveals their relevance for studying memory development. In a recent structural MRI study, frontal lobe gray matter volume reduction was predictive of delayed verbal memory functioning in children aged 7-16 years, and more so than MTL gray matter volume or age (Sowell et al., 2001).

There is evidence that also other memory related brain structures continue to develop during middle childhood (i.e. 6-12 years). While most structures within the hippocampal formation are cytoarchitecturally mature prenatally, the dentate gyrus seems to have a more protracted development (Nelson, 1997). Although the hippocampal formation of newborn infants has the necessary synaptic connections for memory formation, a number of postnatal morphological changes suggest a significant modification of hippocampal circuits from birth until adulthood (Seress, 2001). While the total temporal volume appears stable between 4 and 18 years, hippocampal volume increases with age for females and amygdala volume increases with age for males. This process is probably related to the distribution of sex hormone receptors, namely predominantly androgen receptors in the amygdala and mainly estrogen receptors in the hippocampus (Casey et al., 2000). Giedd and colleagues report increasing temporal lobe gray matter throughout adolescence reaching its maximum size around 16 years (Giedd et al., 1999). Unfortunately, in studies of structural brain development the temporal gray matter is usually not further subdivided, thus the exact development of other memory-related temporal lobe structures, e.g. the perirhinal cortex, remains unclear. Both hippocampus and perirhinal cortex receive input from frontal areas implicated in the control of memory processes (eg. Simons & Spiers, 2003; Murray & Bussey, 1999) and which continue to develop during childhood and adolescence (Sowell et al., 2001).

Recognition memory at different stages of development: first pieces of evidence in children

Resuming the arguments so far, one could assume that children rely predominantly on familiarity as explicitly stated by Tulving & Markowitsch (1998). Alternatively, it is conceivable that both memory subprocesses depend heavily on input from late maturing frontal brain structures and thus are not working efficiently during childhood. This would be especially disabling in the case of recollection, since recollection critically depends on frontal control processes, e.g. the selection of relevant item features (c.f. section 1.4).

Many studies conclude that memory abilities develop during childhood (Gathercole, 1998), but most of them focus on other factors that influence memory performance, for instance the role of prior knowledge base (Tajika, 2002), the use of more or less effective memorizing strategies during encoding or retrieval (Bjorklund & Douglas, 1997; DeMarie & Ferron, 2003) or memory for typical vs. atypical events (Bauer, 1997; Fivush, 1997). Other issues investigated include the reliability of children's memories in face of suggestive questions as might be the case in a courtroom situation (Bjorklund, 1997 & Douglas; Giles et al., 2002; Roebbers & Howie, 2003). All these aspects of memory performance have been studied in recall tasks, which are known to rely to a great extent on frontal lobe structures that continue to develop during childhood. In recognition memory paradigms, the contribution of frontal lobe control processes (e.g. the need to structure the information to be memorized) is minimized since the task demands are reduced as far as possible to the core ability of recognizing stimuli that are presented repeatedly. Only a handful of studies have examined this ability to recognize stimuli during childhood.

Recognition memory: behavioral findings in children

As part of a larger study contrasting implicit and explicit memory performance across age groups, Billingsley and colleagues (2002) found that picture recognition memory performance was lower in 8-10 year olds compared to older subjects (11-13, 14-16, 17-19 years). This was not true for implicit memory tasks in which no age differences were seen. The youngest group did not only show a lower performance level, but also gave fewer "Remember" judgements than the older groups, whereas the amount of "Know" responses was at floor level for the corrected recognition scores across groups. When false alarms connected with "Know" judgements were included into the analysis, it became apparent that the youngest children used this category more often than older children and adolescents, but were unable to discriminate between old and new items of this category (Billingsley et al., 2002). The process of reflecting on the state of awareness of a memorized item seems to be closely related to the concept of metamemory with continues to develop within the age groups studied here (Gathercole, 1998).

Cycowicz et al. (2001) used a recognition memory test to compare item and source memory in 7-9 year old children and young adults. Subjects studied red or green line drawings twice. In the item retrieval task, they were asked whether a given item drawn in black had been shown before or not. In the source retrieval task, this question was more specific and required the retrieval of the previous color (i.e. three buttons, old-

green, old-red or new). In both groups performance in the source task was lower than on the item task. This effect was more pronounced for children than for adults, but statistically independent of the lower item performance. In other words, the effect of age on source memory performance was still reliable when performance in the item task was used as a covariate. Additionally, performance in the source task varied more within the group of children, with some children being at chance level while others were closer to adults' performance levels. In an attempt to tear apart mediotemporal and frontal aspects of the memory tasks, neuropsychological tasks were administered that measured immediate and delayed story memory (subtests of the WMS and the WRAML) that were presumed to tap mediotemporal functioning, as well as verbal fluency (controlled word association test) and task-switching performance (competing programs task) that were both presumed to rely mainly on frontal structures. Item memory performance was correlated with mediotemporal functioning, whereas performance in the source task was correlated with tasks assumed to tap frontal lobe functioning. This dissociation suggests that frontal lobe functioning plays an important role in successful source memory (Cycowicz et al., 2001).

ERP findings in children

Only very few studies have examined ERPs during recognition memory in children so far. For example, Hepworth and colleagues (2001) used a continuous recognition paradigm to compare short-term memory for words and faces in 11-14 year old subjects. Unfortunately, the performance even in immediate repetitions was very low (e.g. close to 50 % of new faces elicited false alarms) so that few correct trials were available for the analyses. No adult sample was examined to compare developmental effects in the same task. ERPs from 26 electrodes revealed old/new effects at parietal electrodes, and a reversed polarity old/new effect at frontal electrodes in this task (Hepworth et al., 2001).

Cycowicz and colleagues (2003) recorded EEG from 62 scalp sites during a task similar to the one described above. Subjects were 9-10 year old children, 12-13 year old adolescents and young adults. The item task was identical to the one described in detail above. In the source task, subjects had to indicate whether an item had been presented in a given target color (exclusion task, e.g. red-other). Source memory performance was defined as hits minus false alarms to new items, i.e. erroneous responses to nontargets were not taken into account. Since the distinction between the two study contexts is one of the defining aspects of source memory, a common mistake in exclusion tasks are false alarms to items presented in the nontarget condition, i.e. intrusion errors (Simons et al., 2002). Performance levels were in general higher for older children and adolescents compared to the earlier study in which younger children took part. One potential reason for this might be that older children and adolescents performed better in the source memory task simply because of their age. Another reason could be the way that source memory performance was operationalized. Since the potentially substantial number of intrusion errors was not counted, source memory performance may have been overestimated.

Compared to adults' ERPs, children's and adolescents' ERPs had larger amplitudes and a negative deflection that was largest over frontal electrodes between 500-650 msec in all conditions. Nevertheless, a reliable old/new effect was found in all groups and in

both tasks. Although the distinction between familiarity and recollection was not explicitly made by the authors, the fact that the old/new effect was parietally distributed in the 415-615 msec time window suggest children's memories were mainly based on recollection in both tasks. This finding clearly contradicts the predictions made by Tulving and Markowitsch (1998) who expected children to rely predominantly on familiarity.

Marshall and colleagues (2002) examined picture recognition memory in young adults and 4 year old children while recording the EEG from 10 channels. No response latencies were reported, since children indicated their responses orally to the experimenter who pressed the appropriate response button. In children, the latency of the old/new effect was 400-500 msec later compared to the adults and right-lateralized in contrast to the bilateral old/new effect found in adults. The authors interpreted this asymmetry in children's ERPs as indication that children might rely less on verbal strategies (i.e. naming of the pictures). Note that ERPs could only be evaluated from 14 out of 34 children since a sufficient number of artifact free trials was necessary. Adults performed better than the complete group of children, but when performance was evaluated only for the subset of 14 children, the two groups no longer differed significantly in performance (Marshall et al., 2002). A potential reason for the lack of difference in performance might be ceiling levels in the adults' performance, i.e. that the task might have been too easy to detect performance differences between the age groups. This example illustrates that it is possible to study recognition memory with the help of ERPs even in very young children. At the same time it stresses the need for appropriate experimental settings while studying children and careful interpretations of the findings.

Choosing appropriate experimental settings for studying recognition memory in children

Since reading ability develops considerably during the first years of schooling, especially the youngest group studied here (6-8 years) is not as fluent in reading as adults. Since words that cannot be read correctly give rise to less accurate and slower recognition responses (Berman & Friedman, 1993), differences in memory performance using any kind of written material cannot be clearly attributed to memory performance per se. For this reason the choice of material was restricted to auditory verbal material or pictorial stimuli. As children's memory performance in general is known to be lower compared to that of adults, it was necessary to develop a task that is easy enough to maximize the children's motivation to perform the task. We decided to use the exact same material for adults and children and compare their performance levels while doing the same task instead of giving the children fewer items to study in order to keep the performance rates comparable.

Children's ERPs vary from adults' for a variety of reasons. The longer reaction times that are quite typical for children are often accompanied by longer ERP component latencies. Differences in structural brain maturation as well as a thinner skull likely contribute to differences in amplitudes with generally larger amplitudes for children irrespective of the task. Any differences in ERPs between adults and children could be due to anatomical differences and physiological processes on the one hand and

cognitive maturation or changes in cognitive processing on the other hand (cf. Casey et al., 2000). Most likely both reasons contribute to the observed age differences (Cycowicz, 2000). In order to ascribe changes in the ERPs during the memory task to age related changes, we also recorded ERPs during an auditory classification (oddball) task. In this task, a series of standard and rare target tones was presented along with unique environmental sounds. Subjects were instructed to count the rare targets and ignore the standards. Comparing the P300 component typically obtained in this task and the old/new effects during recognition memory enables to examine memory-related differences in ERPs as a function of age as well as those unrelated to memory processing and presumably caused by general age effects.

Aim of the study

Recognition memory has been demonstrated to rely on two distinct subprocesses in a variety of studies using both behavioral dissociations and distinct ERP components (cf. Mecklinger, 2004). Functional MRI studies (Eldridge, 2000) have demonstrated that only one of them, namely recollection, is connected with hippocampal activation. This pattern of results has been confirmed in several studies with amnesic patients with selective hippocampal lesions acquired early in life: first, recall was unproportionately affected compared to item recognition (Baddeley et al., 2001). Second, the ERP component for recollection was absent in patient Jon, who was studied extensively as an adult (Düzel et al., 2001). Third, patients suffering from developmental amnesia were able to acquire new semantic knowledge, which was presumably based on relatively intact familiarity after their hippocampal injury. While hippocampal damage disrupted recollection in these patients, familiarity-based memories were still intact (Baddeley et al., 2001; Vargha-Khadem et al., 1997, 2001).

A related line of evidence concerns the role of prefrontal cortex modulation for the control of memory processes. Evidence from frontal lobe patients and electrophysiological studies on healthy controls confirm that prefrontally guided control processes are critical for successful memory (Simons et al., 2002; Dobbins et al., 2002). Late maturation of those structures (e.g. Sowell et al., 2001) might contribute to the increasing memory performances during middle childhood.

So far, it is unclear whether recollection and familiarity share the same developmental trajectory and both become increasingly efficient during middle childhood due to unspecific maturational effects. Alternatively, recognition memory in childhood could rely predominantly on one of these subprocesses and therefore be qualitatively different from adults' memory processing. Tulving and Markowitsch (1998) expected a predominance of familiarity in children. Since recollection relies on prefrontal modulation, it is reasonable to assume that this subprocess continues to develop along with the maturation of the frontal lobes. Tasks that require the reinstatement of the study episode should be particularly difficult for children. On the other hand, first ERP studies with children found a parietal topography of the old/new effect (cf. Hepworth et al., 2001; Cycowicz et al., 2003) that can be taken as evidence that at least some recognition responses were based on recollection in children. With respect to the topography of the ERP effects, young children might differ from adults.

Specifically, a less verbally mediated strategy might give rise to a more right-lateralized old/new effect (cf. Marshall, 2002).

The main goal of the study was to compare recognition memory across developmental stages. In particular we examined whether the relative contribution of familiarity and recollection changes with age. In order to draw a distinction between these two kinds of memories, ERPs were used in the present study. The same task was used for 6-8 year olds as well as 10-12 year olds as well as young adults to be able to evaluate recognition memory with the same task characteristics at several points of development.

Methods

Participants

Three age groups participated in this study, with twenty participants in each group. Young children were 6-8 years old (mean age of 7 years, 10 months, range 6:3 years - 8:11 years, 9 male), older children were 10-12 years old (mean age 11 years, 5 months, range 10: 2 -12:8 years, 10 male) and young adults (mainly college students) were 20-29 years (mean age of 25 years, 12 male).

A number of additional participants, especially from the younger group, were excluded from further analysis because we could not obtain a sufficient number of artifact free ERP trials (criterion: minimum of 10 trials per condition). This was the result of a combination of low performance level and excessive movement artifacts. Nine young boys, 4 young girls, 4 older boys and 2 older girls had to be excluded. Three adult subjects were excluded because of technical problems during data collection. One adult was excluded because of an extremely low performance level. In order to keep group sizes comparable, more subjects were tested until there were 20 participants in each group.

All participants were right-handed and native German speakers. They reported to be in good health and to have normal or corrected-to-normal vision and hearing ability (as indicated by the parent in the case of the children). Children were recruited from local schools and both them and their parents were thoroughly informed about the EEG procedure. Participants (respectively children's parents) gave informed consent and received € 7,50 /h payment for their participation.

Procedure

Participants were seated in a comfortable chair throughout the experiment. After the electrode cap was fixed on each participant's head, the oddball task was conducted, followed by the memory task. Short breaks were given after the oddball task and between the 3 parts of the memory task. The whole session lasted approximately two hours. The oddball task (section 3) and the memory task (section 4) are described in detail below.

EEG recordings

EEG was recorded with 32 Ag/AgCl- electrodes at the following sites (adapted from the standard 10-20 system: FP1, FP2, F7, F3, FZ, F4, F8, FC5, FC3, FCZ, FC4, FC6, T7, C3, CZ, C4, T8, CP3, CPZ, CP4, P7, P3, PZ, P4, P8, O1, O2) at the sampling rate of 500 Hz with a right mastoid reference, and re-referenced offline to linked mastoids. EOG was recorded with additional electrodes located above and below the right eye and outside the outer canthi of both eyes. Electrode impedance was kept below 5 k Ω . Both EEG and EOG were recorded continuously and were A-D converted with 16-bit resolution at a sampling rate of 500 Hz.

Offline data processing involved low pass filtering at 20 Hz and additional high pass filtering at 0.5 Hz. For each group, ERP averages were formed time-locked for standard and deviant tones in the oddball task and for correct responses to new items (correct rejections) and to old items (hits) in the memory task. The duration of the epochs was 1700 msec (1000 msec for the oddball because of the shorter inter-stimulus interval). Each epoch included a 200 msec prestimulus interval that was used for baseline correction.

Prior to averaging, each epoch was scanned for EOG and other artifacts. Because many children would continue moving during the EEG recording, more trials had to be rejected for children compared to adults (mean number of trials: for young children 18 (range 10-43), for older children 23 (range 15-36), for adults 33 (16-57)). Ocular artifacts were corrected using a linear regression approach.

Analyses

Repeated-measures analyses of variance (ANOVAs) were used to analyse the data. In order to compare the age groups, between-group ANOVAs were used along with Bonferroni adjusted pairwise comparisons. To correct for violation of the sphericity assumption, Greenhouse-Geisser corrections were used where appropriate. Corrected p-values are reported along with uncorrected degrees of freedom.

For statistical analysis of the ERP data, nine electrodes were selected: three midline electrodes (FZ, CZ, PZ) along with bilateral frontal (F3, F4), central (C3, C4) and parietal (P3, P4) recording sites. ANOVAs were conducted with the factors Condition (old vs. new) x AP (frontal vs. central vs. parietal) x Lat (left vs. midline vs. right). Only effects that include the factor of Condition are reported and were followed up by subsidiary tests to assess where the old/new effects were located. Treatment magnitudes were quantified as ω^2 to allow comparison of the effect sizes at the electrode sites (Keppel & Wickens, 2004).

When comparing the topographical distribution between the groups, ANOVAs with the factors Group x AP x Lat were performed on the respective difference waves (i.e. oddball: deviants -standards, memory task: hits - correct rejections). To ensure that resulting interactions involving Group were not merely attributable to differences in amplitudes, the mean amplitudes of the respective difference waves were rescaled using the vector length method (McCarthy & Wood, 1985). The rescaled data were then subjected to the same Group x AP x Lat ANOVA.

Oddball task

Stimuli

Two pure sine tones with a frequency of 600 and 1000 Hz and unique environmental sounds (novels) were used for the oddball task. The higher tone was used as the less frequent deviant. All tones had a duration of 200 msec with an interstimulus interval of 550 msec from offset to onset.

Procedure

The auditory oddball task consisted of 80% standard stimuli, 10% deviants and 10% novels. The task was to silently count the deviant tones whereas the novel sounds were not mentioned in the instructions. Analyses will focus here on the target oddball P300, i.e. the difference between standards and the deviant stimuli (targets).

Analyses

For each group, ERP waveforms were quantified by measuring the mean amplitudes and the individual peaks at PZ in the following time windows: 300-500 msec for the adults and 450-750 msec for both groups of children. The selection of the time windows was based on previous research and based on visual inspection of the waveforms (e.g. Johnstone et al., 1996). As topographical differences as a function of Group were the main focus of analyses, an ANOVA with the factors Group x AP x Lat was conducted on the difference waves between standard vs. deviant tones.

Results

In all groups, target waveforms showed a positive peak that had a considerably longer latency and larger amplitudes for both groups of children. The mean individual peak latency (mean of the individual peaks measured at PZ) was 429 msec for adults, 539 msec for the older children and 572 msec for the young children. In all three age groups the P300 showed a symmetrical topographical distribution and was largest over parietal electrode sites. The amplitudes were largest for the youngest group and decreased with increasing age. In all conditions, the children showed a pronounced negative deflection that was largest over frontal sites.

The ERPs to standard and deviant tones at the FZ, CZ and PZ electrode sites in all three age groups are depicted in Figure 1. The topography of the deviant minus standard difference waves was compared between the age groups to be able to evaluate group differences in topographical distributions. Before scaling there was no reliable effect of Group [$F(2,51) < 1$], but a Group x AP interaction [$F(4,102)=4.39, p<0.5$]. After scaling this interaction was no longer reliable [$F(4,102)=1.03, p=0.39$],

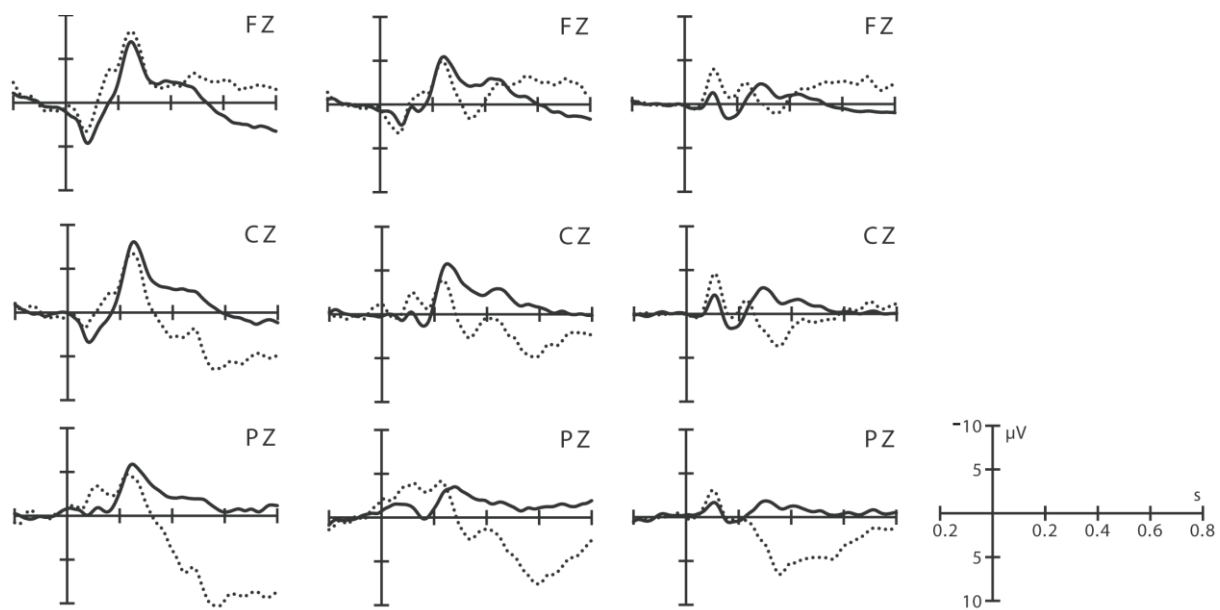


Figure 1. Mean amplitude at midline electrodes for 6-8 year olds (left), 10-12 year olds (middle) and adults (right) during the oddball task. Standard stimuli in solid lines, deviants in dashed lines. Time windows used for analyses were 300-500 msec for adults and 450-750 msec for children. Note the same amplitude scaling in the three age groups to demonstrate differences in amplitudes.

suggesting that the discrimination processes involved in the detection of target stimuli do not show differences in topographical distribution as a function of age.

Memory task

Stimuli

Three kinds of stimuli were used for the memory task: photos and spoken words were presented during study, whereas line drawings¹ of the corresponding objects were used

¹ **Pretest - naming agreement:** To decide which items were suitable to use for a group of young children whose native language is German, in a first step the original 400 items from the original Snodgrass and Vanderwart (Cycowicz et al., 1997; Snodgrass & Vanderwart, 1980) black and white line drawings were rated by 7 German adults (to eliminate items that were culture specific for the US) to minimize testing time with the children. The remaining 330 pictures were rated by 9 children aged 5-6 years recruited from a local kindergarden. For every picture they were asked if they knew the object on the picture and to give the name of the object if possible. Only those pictures that all children recognized and at least 6 out of 9 children spontaneously gave the same label were used (for some of these objects, several names are equally correct and common in German).

as test probes. The test items ('pictures') consisted of a subset of the Snodgrass and Vanderwart (Cycowicz et al., 1997; Snodgrass & Vanderwart, 1980) black and white line drawings¹. The German names of those objects spoken by a female voice ('words') as well as colorful photos closely corresponding to the original black and white line drawings ('photos') were used as study items.

The items were divided into 3 sets each containing the same number of items belonging to one of the following categories: animals (subgroups of insects, fish, birds and four-footed animals), plants, body parts, furniture, food, musical instruments, vehicles, toys and things around the house. All items were used in all three modalities (i.e. photos, words and pictures) across participants. For each participant, study words, study photos, and new test pictures were taken from different sets. All participants saw all line drawings at test. During the study phase one third of the objects were presented as photos and another third of the objects' names were presented as words. Only the assignment to the modality varied between participants (e.g. whether the item 'ball' was presented as a 'word' or a 'photo' during study or used exclusively as a new item at test).

Procedure

The memory experiment was divided into three parts with a short break in between. Each part contained two study and two test blocks. During study, participants were shown one block of 20 photos, in the other block they heard 20 spoken words. Each stimulus was preceded by a fixation cross (300 msec) and a black screen baseline period (200 msec) and was presented for 1000 msec. After 1000 msec the next fixation cross appeared on the screen. The study task was to indicate whether the item was more typically found outdoors or indoors. During the photo presentation, the screen background was illuminated in red, during the presentation of the words this color changed to blue or vice versa. The order of the blocked presentation and the pairing of modality and color was counterbalanced across participants, as was the assignment of right/left hands to response buttons.

In the first test blocks (i.e. inclusion task with 14 old and 17 new stimuli), participants were shown black and white line drawings. Participants were asked if the test picture corresponded to an item in the study phase, irrespective of the modality it had been presented in before (old-new decisions). Each stimulus was preceded by a fixation cross (300 msec) and a black screen baseline period (200 msec) and was presented for 1500 msec after which the screen turned black for a maximum of 3000 msec or until the response button was pressed. Following the response, a visual feedback was given for 500 msec to indicate if the response was correct (happy face) or not (unhappy face) before the screen turned black for another 1000 msec. In order to prevent recency

When children gave the less frequent name first, they were asked if they knew another word for the same thing to ensure no objects were included that the children would label differently). The excluded objects seemed to be unknown in their function to several children or visually difficult to identify. Thus, only 198 of the original 400 line drawings were considered appropriate as stimulus material. Thirty additional items which children would recognize, but not necessarily give the same label were retained as practice items.

Table 1. Overview of performance data

Group	Pr (SEM)	Br (SEM)	Proportion hits (SEM)	Proportion cr (SEM)	RT hits (SEM)	RT cr (SEM)
6-8 years	0.40 (0.03)	0.36 (0.02)	0.62 (0.02)	0.78 (0.02)	1149 (49)	1162 (46)
10-12 years	0.51 (0.03)	0.38 (0.04)	0.70 (0.02)	0.80 (0.03)	1003 (26)	997 (25)
20-29 years	0.70 (0.03)	0.50 (0.04)	0.85 (0.02)	0.85 (0.02)	899 (26)	960 (37)

Note. Mean (standard error of the mean in parentheses) performance accuracy (Pr) and bias measure (Br) for the 3 groups. Mean proportion of correct responses and reaction times (msec) for hits and correct rejections.

effects for items immediately following the study phase, four additional buffer items that were not analysed were included at the beginning of each inclusion test phase.

Items numbers were chosen to ensure that the ratio between responding with right and left response buttons was similar in both tasks.

For the second test blocks (exclusion task), the same procedure was used (13 old target items, 13 old nontarget items, 9 new items). This time participants were asked to indicate whether the item had been shown in a given target context before or not (i.e. seen - not seen or heard - not heard, respectively). The target context was the same in all three blocks and counterbalanced across participants (i.e. for 25% of the participants this was 'words' presented in front of a red screen background, for another 25% of the participants this was 'photos' presented on a blue screen background and vice versa). The results of the exclusion task are presented elsewhere (Czernochowski, Brinkmann, Mecklinger & Johansson, in preparation) and a description of the task is only included here to give an exhaustive account of the procedure.

To ensure that participants would understand the procedure, a practice phase including both study and test blocks was run before the experiment was started. In addition, children were asked to explain the instructions to the experimenter in their own words before each block and were corrected if necessary.

Behavioral analyses

Memory accuracy was defined as Pr (Pr = hits - false alarms) and response bias as Br (Br = false alarms / (1 - Pr), cf. Snodgrass & Corwin, 1988). Between-group ANOVAs were used to compare memory accuracy (Pr) and bias (Br) between the groups. To compare reaction times for hits and correct rejections between groups as well as within subjects, a two factorial ANOVA with the within-subject factor Response and the

between-subject factor Group was performed. All group differences were followed up by planned pairwise comparisons using Bonferroni corrections.

adults performed better compared to older children ($p < .001$) as well as to younger children ($p < .0001$). Also, older children performed better than younger children ($p < .017$).

A reliable main effect of group [$F(2,59)=5.31$, $p < .01$] was also found for the bias measure (Br). Planned contrasts revealed that older children showed a more conservative bias than adults ($p < .003$), as did younger children ($p < .017$). This means that in case of uncertainty, both groups of children had a stronger tendency than adults to respond 'new' to old items. The two groups of children did not differ in response bias.

An ANOVA on the reaction times to hits as well as to correct rejections of new items yielded reliable main effects of Group [$F(2,57)=10.94$, $p < .0001$], of Response [$F(1,57)=4.39$, $p < .05$] as well as an interaction of response by Group [$F(2,57)=3.46$, $p < .05$]. Further analysis for each group revealed no effect of the factor Response for both groups of children [$F_s(1,19) < 1$, n.s.], but for adults [$F(1,19)=9.38$, $p < .01$], indicating that only adults were faster for hits compared to correct rejections.

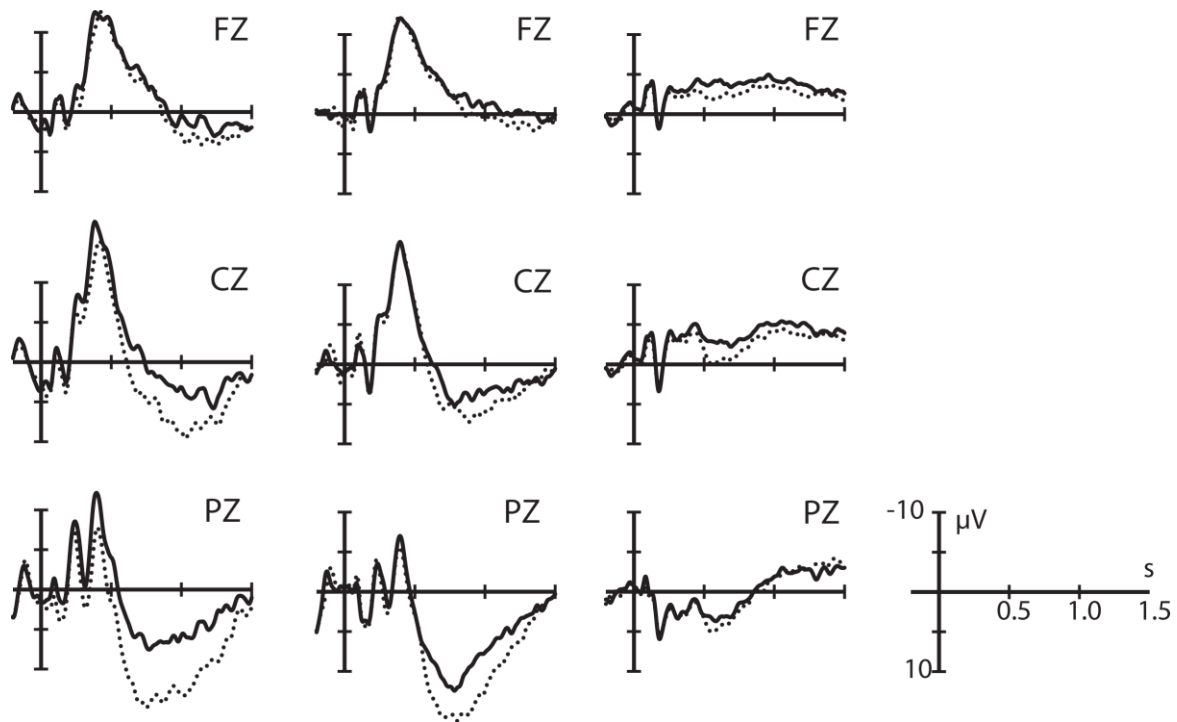


Figure 2. ERPs at the midline electrodes for 6-8 year olds (left), 10-12 year olds (middle) and adults (right) during the memory task. Correct rejections of new items are depicted in solid lines, hits in dashed lines. Time windows used for analyses were 400-600 msec for adults and 700-900 msec for children. Note the same scaling in the three age groups to demonstrate differences in amplitudes.

Subsidiary analyses for each item type revealed a main effect of Group for hits [$F(2,59)=12.66$, $p<.0001$] as well as for correct rejections of new items [$F(2,59)=8.44$, $p<.01$], reflecting the fact that younger children were slower for both responses than older children and adults (all $ps <.01$).

ERP analyses

Since response latencies varied between groups and based on visual inspection of the waveforms, group specific time windows were chosen for the statistical analyses of the old/new effects. For both groups of children, mean amplitudes were evaluated during a time window from 700-900 msec, whereas for the adults the mean amplitudes during the 400-600 msec time window were evaluated, reflecting their shorter reaction times and earlier old/new effects.

To be able to evaluate early and late frontal components for the adults, two additional time windows were chosen at 250-400 msec and 700-1100 msec. Grand average ERPs elicited by hits and correct rejections recorded at three midline electrode sites for the three groups are depicted in Figure 2. In all groups there was a main effect of condition, that is, ERPs to hits were more positive than ERPs to correct rejections of new items.

Even though old/new differences were obtained in all groups, the groups differed in terms of latency, overall magnitude and topography of the old/new effect: in the groups of children the old/new effect showed long latencies compared with the adult group. Typical for children's ERPs are the overall larger amplitudes and a pronounced negative going deflection that was evident for all conditions around 400-600 msec (see Figure 2). The overall larger amplitudes for both groups of children are also illustrated in the amplitudes of the difference waves (hits-correct rejections) displayed in Figure 3. The topography of the old/new differences for the three groups can be seen in Figure 4. For 6-8 year olds, the old/new effect was clearly bilateral with a parietal focus. The group of 10-12 year olds demonstrated a left-lateralized old/new effect over parietal electrodes. For adults, the old/new difference showed a central to right frontal distribution, presumably reflecting the combination of a centrally focused old/new effect and the early onset of the late right frontal effect within the 400-600 msec time window. For the adults, additional old/new differences were evident frontally at earlier (250-400 msec) and later (700-1100 msec) time windows that were not seen in children.

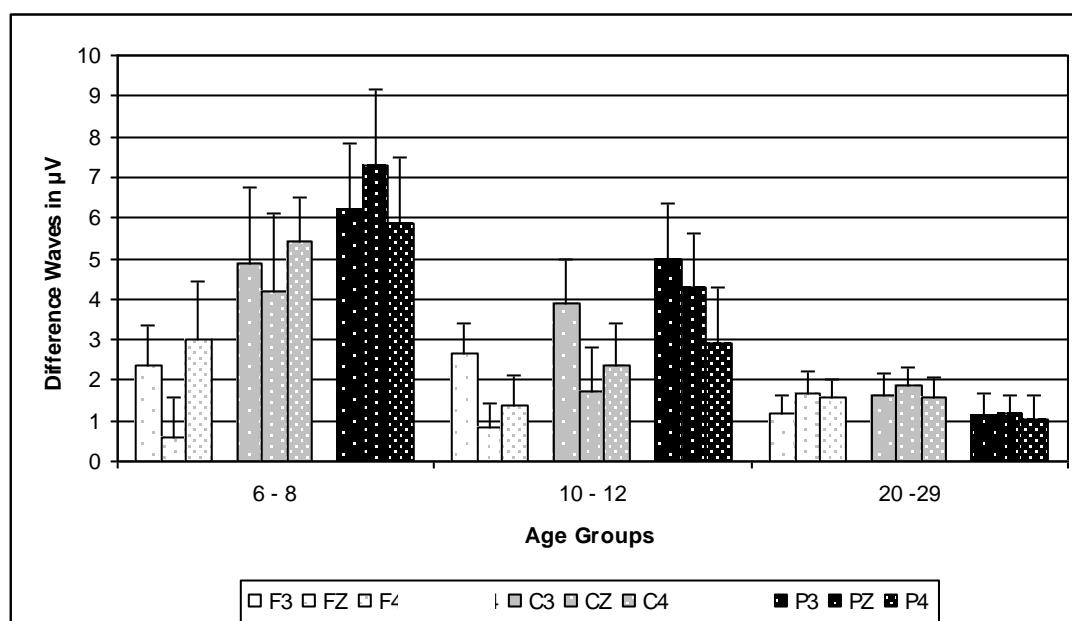


Figure 3. Mean amplitude differences between hits and correct rejections at nine selected electrode sites for young children (700-900 msec, left), older children (700-900 msec, middle) and young adults (400-600 msec, right). Note the age difference in amplitudes. Error bars represent standard errors of the mean.

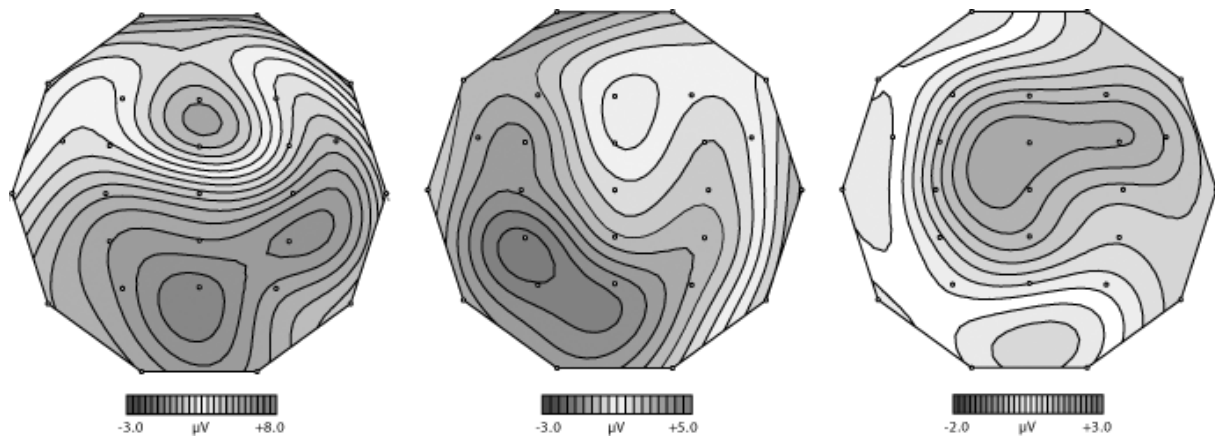


Figure 4. Topographies of the old/new effect for young children (left), older children (middle) and adults (right) during the time windows that were used for analyses (400-600 msec for adults 700-900 msec and for children). Note the different scaling to illustrate the topographical distribution

In addition to a main effect of condition, the group of younger children showed a significant interaction of Condition by Lat as well as a significant 3-way interaction (see Table 2 for F and p values). Because of this interaction, subsidiary analyses were performed at the nine single electrode sites and revealed significantly more positive amplitudes for hits vs. correct rejections for all electrodes with the exception of FZ. The highest treatment magnitude was found at P3 ($\omega^2=0.60$). For illustration, the mean amplitudes of the difference wave for all groups at the nine electrode sites are depicted in Figure 3.

The group of older children showed a main effect of Condition, a significant interaction of Condition by Lat and a significant interaction of Condition by Ap. Subsidiary analyses revealed reliable effects of Condition for frontal, central as well as for parietal electrodes [all $F_s > 8.54$, all $p_s < .01$]. For midline electrodes there was an additional interaction of Condition x AP [$F(2,38)=7.2$, $p < .01$]. As can be seen in Figure 4, the initial interactions reflect the fact that the old/new effect tended to show a left asymmetry and to be larger over parietal than more anterior electrodes. The highest treatment magnitude was found at P3 ($\omega^2=0.49$).

For the group of adults, in the 400-600 msec time window there was a main effect of Condition, which indicates that the old/new effect could be seen across the selected electrodes. The largest treatment magnitude was found at CZ ($\omega^2=0.31$). Mean amplitudes of the difference wave are depicted in Figure 3. Note that the old/new effect was seen across electrode sites for the adults, whereas for the children it was largest at parietal electrodes as evident in the interactions of Condition by electrode sites.

Two additional time windows were specified for the adults. In the early (250-400 msec) time window, the main effect of Condition was only marginally significant. However, as the early old/new effect is typically distributed midfrontally (e.g. Curran & Cleary, 2003, Düzel et al., 2001), analyses for single electrodes were conducted. They revealed an effect at CZ [$F(1,19)=5.44$, $p < .05$] and marginally significant effects

Group	Time window (msec)	Condition $F(1,19)$	Condition x Lat $F(2,38)$	Condition x Ap $F(2,38)$	3-way interaction $F(4,76)$
6-8 years	700-900	12.84**	12.28**		3.24 *
10-12 years	700-900	14.24 **	4.83*	3.72*	
20-29 years	400-600	7.2 *	3.14 °		
20-29 years	250-400	3.26 °			
20-29 years	700-1100	3.74 °			

Table 2: Summary of statistical results for the initial ANOVA performed for each group in the memory task (Note. * $p < .05$ ** $p < .01$ ° $p < .10$)

at F3 [$F(1,19)=3.01$, $p=.09$], FZ [$F(1,19)=3.56$, $p=0.07$] and F4 [$F(1,19)=3.68$; $p=0.07$]. Treatment magnitudes were largest at CZ ($\omega^2 = 0.17$).

In the late time window (700-1100 msec) the main effect of Condition approached significance ($F(1,19)=3.74$, $p=.06$). Since the late effect is typically distributed right frontally, analyses at single electrodes were conducted here despite the lack of a reliable 3-way interaction and revealed a reliable effect at F4 [$F(1,19)=9.35$, $p < .01$] and at C4 [$F(1,19) = 4.95$, $p < .05$] and a marginally significant effect at CZ [$F(1,19)=4.18$, $p=0.05$]. Treatment magnitudes confirmed these analyses and were largest at F4 ($\omega^2 = 0.28$). At C4 ($\omega^2 = 0.16$) and CZ ($\omega^2 = 0.13$) the treatment magnitude was considerably smaller.

To sum up the ERP results, all groups showed reliable old/new effects. The effects were largest at left parietal electrodes in both groups of children and showed a more widespread distribution with a maximum at central electrodes for the adults. Additional early (250-400 msec) midfrontal and late (700-1100 msec) right frontal effects were observed only for the adults.

Across group comparisons

As for the P300 elicited in the oddball task, we also examined whether the topography of the old/new effect differed reliably between the age groups. The interaction between the factors Group and AP was reliable before [$F(4,114)=5.94$ $p < .01$] and after scaling of the data [$F(4,114)=4.64$, $p < .01$], indicating that the between group differences in topography were not merely attributable to differences in amplitudes but rather arose from different sets of neuronal generators in the three groups (McCarthy & Wood, 1985).

Pairwise comparisons indicated that both groups of children did not differ reliably in topography, either before [$F(1,38)=1.3$, $p > .26$] or after scaling [AP x Group: $F(2,76) < 1$, n.s., Lat x Group: $F(2,76)=2.09$, $p > .13$]. Comparing the young children to adults, there was a main effect of Group [$F(1,38)=5.27$, $p < .05$], an interaction of AP x Group [$F(2,76)=12.61$, $p < .0001$], and a 3-way interaction [$F(4,152)=3.24$, $p < .05$]. After

eliminating the main effect of Group by scaling, both interactions remained reliable (3-way interaction only marginally so [AP x Lat x Group: $F(4,152)=2.36$, $p=.06$, AP x Group: $F(2,76)=8.63$, $p<.01$]). Comparing older children to adults, there was a reliable interaction between the factors AP and Group [$F(2,76)=5.83$, $p<.05$] as well as between Lat and Group [$F(2,76)=3.88$, $p<.05$]. After scaling, both interactions were still reliable, the latter only marginally so [AP x Group: $F(2,76)=5.61$, $p<.05$, Lat x Group: $F(2,76)=3.17$, $p=.06$]. These interactions statistically confirm the observation that the topography of the old/new effect is distributed more parietally for the children and more centrally for the adults.

Discussion

The main issue of the study concerned the subprocesses contributing to recognition memory across age groups. More specifically we wanted to examine whether recollection and familiarity share the same developmental trajectory or develop at different rates. To this end, we used the ERP old/new effects linked to familiarity and recollection as dependent measures in a recognition memory paradigm with three age groups. The logic of this analysis is based on the observation that in adults the parietal proportion of the old/new effect is usually considered as an electrophysiological correlate of recollection-based memory processing, whereas the early midfrontal component is considered as a correlate of familiarity-based recognition (Curran, 2000; Curran & Cleary, 2003; Friedman & Johnson, 2000; Mecklinger, 2000, 2004; but see Yovel & Paller, 2004). An additional late right frontal old/new effect has been associated with post-retrieval evaluation processing occurring after a decision is made and quite often lasts until the end of the recording epoch (cf. Mecklinger, 2000, 2004). In order to evaluate whether the differential ERP components obtained in the three age groups are specifically tied to differential memory processes across age groups, we first compared ERP components elicited by standard and deviant tones in an oddball task. No age related difference in the topography of the P300 to deviant stimuli was found, indicating that differences in the topographical distribution of old/new effects are not caused by general age effects.

As expected, performance in the memory task increased with age in terms of memory accuracy and was coupled with shorter reaction times. At the same time, children responded in a more conservative way leading to a group difference in bias, i.e. children tended to respond 'old' only when they were really sure that they saw an old item. The ERP old/new effect for the children closely resembled the parietal component typically observed in adult ERP studies that has been associated with recollection. Adults' ERPs showed a more widespread topographical distribution with a midcentral maximum. This could reflect the fact that in addition to the recollection-based decisions as evident in the parietal old/new effect familiarity-based decisions were made. The beginning of a pronounced late right frontal effect that has been connected to post-retrieval evaluation (Düzel et al., 1999, Rugg & Wilding, 2000) is also evident in the 400-600 msec time window for the adults.

The combined ERP and behavioral data suggest that the age groups used different strategies for this memory task: the conservative bias and the parietal topography

suggest that children relied mainly on recollection. Adults' ERPs in combination with their less conservative response strategy suggest that familiarity was used to a larger extent by adults. This may have led to enhanced response uncertainty and the need for further evaluation even after the response was completed, as reflected in the adults' late right frontal effect. This tendency might have been emphasized by the feedback given after each trial that was originally included to keep up children's motivation to perform the task. The increase in performance with age can be conceived as a function of increasingly efficient recollection that is accompanied by the use of the faster process of familiarity in adults. This line of reasoning is supported by the adults' faster ERP latencies. Decrease in reaction times in adults could be related to the availability of the faster assessment of familiarity as well as to more efficient frontal modulation of the recollective reinstatement of item attributes.

The results reported here are in many respects consistent with previous studies comparing children's ERPs during item recognition memory tasks. Cycowicz et al. (2003) reported similar overall magnitude of the amplitude differences for the age groups studied. A broad negative deflection with a frontal distribution for both old and new items was also evident in the younger age groups in the Cycowicz et al. (2003) study, but considerably smaller than in the present study as the children in our study were considerably younger than the ones reported by Cycowicz et al. (2003). The broad negative deflection was also observed in the Marshall et al. (2002) study with 4-year-old children and described as a typical response to visual stimuli in children (Marshall et al., 2002). Friedman (1992) reported larger negative deflections for pictures than words in children, but not adolescents and adults. These were interpreted in terms of a less automatic association between pictures and their names in children and might reflect the fact that children tend to encode pictures schematically based on sensory features, whereas adults tend to encode more semantically or conceptually (Friedman, 1992). A similar negative deflection is typically reported in oddball tasks in children (Johnstone et al., 1996; Thomas & Nelson, 1996). An age-related decrease in N2 amplitude to standard stimuli has been implicated as an index of the gradual development of control with respect to attentional focus, i.e. to attend selectively to task relevant stimuli. According to this view, the frontal lobes act as selective filtering or inhibitory control mechanism (Johnstone et al., 1996).

In terms of ERP old/new effects, our data are also consistent with the item memory results of the previous study (Cycowicz et al., 2003). Since the main focus of the previous study was to look at the development of item and source memory, they did not directly compare the relative contributions of recollection and familiarity in the item recognition task. Cycowicz et al. (2003) reported parietal ERP old/new effects between 415-615 msec in all age groups, although the effect was long-lasting for the children. Thus for the children and adolescents the time window that was used tapped only the beginning of the old/new difference, potentially underestimating existing groups differences. In the present study, we examined children that were considerably younger and had considerably longer reaction times than adults. Another factor that might contribute to longer latencies is the nature of the task in the present study. It is considerably more difficult to compare the conceptual information of a picture with that of items studied as photos or words. In support of this view, mean reaction times for adults in the present study were 150-200 msec longer than those reported by Cycowicz et al. (2003).

Based on reaction times in the groups and visual inspection of the waveforms, the time windows for the ERP analyses in our study were chosen at 400-600 msec for adults and 700-900 msec for children.

The topography of the old/new effects also broadly corresponds to the one reported by Cycowicz et al. (2003). Both groups of children show a slightly left lateralized parietal topography, while adults show a more central maximum in this time window. While this difference is not reliable at the midline electrodes after normalization of the Cycowicz et al. (2003) data, it is reliable in the present study. One potential reason is that the two studies compared topographies for different electrode sites (8 midline electrodes vs. a 3x3 grid of 9 electrode sites). Finally, no early or late frontal old/new effects for the adult group were reported in the Cycowicz et al. (2003) study. One potential reason for this might be the use of a nose-tip reference that tends to underestimate effects at frontal electrodes (e.g. Nunez, 1981).

Frontal effects in adults, but not in children

In the present study, early (250-400 msec) frontal effects as well as late (700-1100 msec) right frontal effects were only found in the adult group, but not in children. Several reasons might be responsible for the lack of late frontal effects in children. First, it is conceivable that the longer response times and the delayed ERP components in the children contribute to the lack of late frontal effects since the recording epoch only lasts for 1500 msec. However, it is very unlikely that this is the main reason since no evidence for post-retrieval evaluation or strategic task modulation can be seen behaviorally. Second, since the late frontal component has been related to prefrontal modulation and evaluation of memory retrieval (Düzel et al., 1999; Rugg & Wilding, 2000), the lack of this effect in children might reflect the delayed maturation of the prefrontal cortex. Older children or adolescents may show evidence of some right frontal evaluation processes if given enough time between the trials, but for the younger children this procedure would make total recording time too long. In future studies this assumption could be tested when examining adolescents that are beginning to show evidence of strategic modulations behaviorally with a longer interval between the trials.

A related question concerns the lack of the early frontal effect in children. It has been connected with familiarity-based decision in adults and is onsetting about 100-200 msec earlier than the parietal component related to recollection (Curran, 2000; Curran & Cleary, 2003; Friedman & Johnson, 2000; Mecklinger, 2000, 2004), so prolonged latencies of ERP components in general do not explain the lack of early frontal modulations in children. The lack of both frontal effects might be closely related and presumably strategically driven in the present case: the use of familiarity-based decisions presumably requires more post-decision re-evaluation of relatively fast decisions. One reason why children do not show many familiarity-based decisions in the present study is that these may depend on the strategic modulations as evidenced by the late right frontal effect. Since recollection-based recognition judgments are made more confident than familiarity-based decisions (Tulving, 1985), children might lack the ability to accommodate response uncertainty by post-retrieval evaluations. As long as these strategic evaluation processes are not yet possible, familiarity-based

decisions might occur, but do not necessarily lead to correct responses. According to this view, these illusory familiarity effects should be present in false positive responses that were not part of the analyses of the old/new effect.

Another aspect of strategic modulation is the intention to retrieve previously studied material, i.e. retrieval mode (Rugg & Wilding, 2000). Ecker and colleagues (this volume) demonstrate that a perceptual mismatch between study and test even in task irrelevant features results in longer reaction times and differences in the ERP components for congruent and incongruent hits in explicit, but not implicit testing. The authors conclude that in an explicit retrieval mode a bound representation of all stimulus features is being accessed so that any mismatch of features could make a successful reactivation more difficult. It is conceivable that children's retrieval mode is less flexible in that the sensory mismatch between study and test items results not only in longer reaction times as seen in adults, but also in a lower recognition rate. Adults, in contrast, seem able to adjust their retrieval mode to the demands of this specific task, as evident in their flexible use of familiarity and recollection.

The question remains if the lack of early frontal modulation supports the hypothesis that mainly recollection was the basis of children's memories. Performance data suggest that both groups of children in the present study were more conservative in their responses than adults. It is conceivable that the more liberal response criterion in adults leads to more familiarity-based responses in the correct responses to old items (i.e. hits) in the adult group. In contrast, both groups of children tended to say yes only if quite sure. If this explanation is true, then children with a more lenient criterion should show a higher amount of familiarity-based responses. The ERP component reflecting these familiarity-based responses should be observable earlier than the parietal effect in children and presumably show a more frontally distributed topography. This assumption was tested in an additional analysis in which median-split groups of children with particular conservative bias (i.e. strict) and a less conservative bias (i.e. more lenient) were formed. Since the latencies, amplitudes and topography of the effect were similar for both groups of children, younger and older children were collapsed for this analysis. The subgroups with a lenient vs. strict response criterion differed reliably from each other (median = 0.365, mean $Br_{lenient}$ = 0.47, mean Br_{strict} = 0.26, $t(38) = 274.46$, $p < .0001$). The two groups of strict and lenient children did not show different ERP waveforms at frontal sites based on visual inspection. This post-hoc analysis does not support the view that the lack of frontal effects in children is directly related to the more conservative response bias. However, as the more lenient children in the median-split groups were still slightly more conservative than the adult group, this null-result needs to be interpreted with care and does not lead to the conclusion that children did not rely on familiarity for correct responses at all.

Another potential reason for the lack of midfrontal effect to hit responses in children can be derived from the task characteristics. Familiarity involves the assessment of global study-test similarity (Curran & Cleary, 2003). Recently, attempts to disentangle perceptual and conceptual contributions to familiarity have been made by manipulating levels of processing or comparing modality-specific processing in young adults (Toth, 1996) or using electrophysiological methods to dissociate semantic familiarity, recognition-related familiarity and perceptual fluency (Nessler, Mecklinger, & Penney, in press). Likely, both processes contribute to the feeling of

familiarity. In general, changes in perceptual characteristics lead to a reduction in familiarity, but not recollection, whereas both processes are sensitive to conceptual manipulations (Yonelinas, 2002). In the present study, global similarity between study and test items could predominantly be assessed on a conceptual level. Empirical evidence suggests that children rely more heavily on perceptual compared to conceptual features in episodic memory. This tendency is seen most clearly when the child is free to choose how to encode items (cf. Friedman, 1992). If children, unlike adults, do not rely on conceptual similarity but rather base their recognition decisions on perceptual similarity between study and test items, this would not be beneficial in the present task. In this case, the children would be forced to rely on recollection, which was successful in some cases - namely the hit trials included in the ERP averages. Since the task was difficult especially for the younger children, they did not succeed in recollecting many trials. Their low performance level even in item memory could in part be caused by this difficulty. If this is true, hits to items studied as photos should include more familiarity-based recognition judgments than hits to items studied as words. Unfortunately, not enough correct trials were available to test this prediction.

The parietal effect in children

Prior studies have demonstrated that the parietal old/new effect is correlated with the amount of recollection-based judgments in young adults (cf. Wilding, 2000). To confirm whether the parietal effect in children was associated solely with the correct identification of old items (i.e. hits), misses (i.e. old items that were given a 'new' response) were compared to correct responses in a post hoc analysis. As before, only subjects with a minimum of 10 trials per condition were included in the analysis ($n=22$ from both groups of children), thus adults' error trials could not be evaluated. For misses, a main effect of Condition [$F(2, 42)=6.06, p<.01$] and an interaction of Condition \times Lat [$F(4, 84)=4.59, p<.01$] was found in the 700-900msec time window. Comparisons for the three conditions revealed that hits differed reliably from correct rejections as well as from misses at parietal and central electrode sites (all $ps<.05$). Correct rejections and misses did not differ at any electrode site (all $ps>.15$). These analyses provide additional support to the notion that the parietal effect in children is associated with successful recollection, since it does not differentiate old items that were falsely rejected from correct rejections of new items.

In young adults, typically the size of the old/new effect is related to performance level, since better performance usually is based on a higher amount of recollection-based memories (cf. Wilding, 2000). Comparing the old/new effect between good vs. poor performers across both groups of children (based on a median-split to ensure equal group sizes) pointed to a difference in the magnitude of the old/new effect in the two groups. In a next step, this effect was quantified as individual peak amplitude at PZ and correlated with performance level for both groups of children. In contrast to expectations, larger peak amplitudes were connected to lower Pr values ($r = -.48, p<.01$).

This negative correlation does not lead to the conclusion that the parietal old/new effect in children reflects something other than memory processes since it is presumably confounded by maturational factors. Unlike comparing subsets of adult

samples, there are a number of problems when correlating the amplitude of an old/new effect at a given electrode with any index of performance in a developmental study. First, even within the groups of children, there are many maturational changes (e.g. increasing brain volume, synaptic connectivity and increasing myelination) related with age. These maturational changes lead to the reduction of overall amplitudes as well as to an increased memory performance. The negative correlation might be caused by brain maturity: if children with a better performance also have a more mature brain that generates smaller (i.e. more adult-like) amplitudes, the old/new difference for these children would be smaller as well.

Another possible confound of the correlation between magnitude of the old/new effect at PZ and performance level is the difference in the topography of the old/new effect described above. Since the old/new effect peaked at different electrode sites in the groups, PZ was chosen as the electrode for the analysis of peak magnitude because it was the electrode site where all groups had a reliable old/new effect. This might have caused an underestimation of the old/new effect for some children. This assumption was tested by comparing the topography of the old/new effect separately for good and poor performers. First, subgroups were formed using a median split on the basis of Pr values. Good and poor performers in both groups of children reliably differed in performance accuracy (young children: median=0.42, mean_good=0.51, mean_low=0.30, $t(18)=180.67$, $p<.0001$. Older children: median=0.55, mean_good=0.63, mean_low=0.40, $t(18)=239.19$, $p<.0001$). Next the topography and the magnitude of treatment effects was calculated for good and poor performers. Since the subgroups only contain 10 subjects and thus the statistical power is low, only unscaled data were considered in this post hoc analysis.

Figure 5 reveals that the topographies of the complete groups may not be representative for these subsets of good and poor performers. On the basis of the topographical distribution, three patterns can be seen: young children with low performance show a bilateral to right parietal topography, whereas young children with better performance and older children with lower performance show a left parietal topographical distribution. The topography in the group of older children with good performance resembles the adults' topography more closely.

The complete group of 6-8 year olds showed a widespread parietal activation with a maximum at P3 ($\varpi^2=0.60$) that was still quite strong at PZ ($\varpi^2=0.40$) and P4 ($\varpi^2=0.36$). In contrast, for those children with low performance the old/new effect was pronounced at right parietal electrode sites ($\varpi^2=0.58$ for P3 as well as P4, $\varpi^2=0.46$ at PZ). A similar right-lateralized parietal old/new effect was reported in 4-year-olds by Marshall and colleagues (2002). Note that the amplitudes in this group are clearly larger than for the better performing children of the same age group, which might be connected with less maturation. An alternative explanation could be the use of non-verbal strategies, i.e. not relating the items with their name. This nonconceptual strategy would be expected to lead to particularly poor performance. To test this prediction, future studies could assess naming latencies for the young children. If good performance is related to shorter naming latency, this could speak in favour of a strategic effect. On the other hand, children in this age range quite often know strategies for memory tasks, but fail to use them spontaneously (Bjorklund & Douglas, 1997; DeMarie & Ferron, 2003).

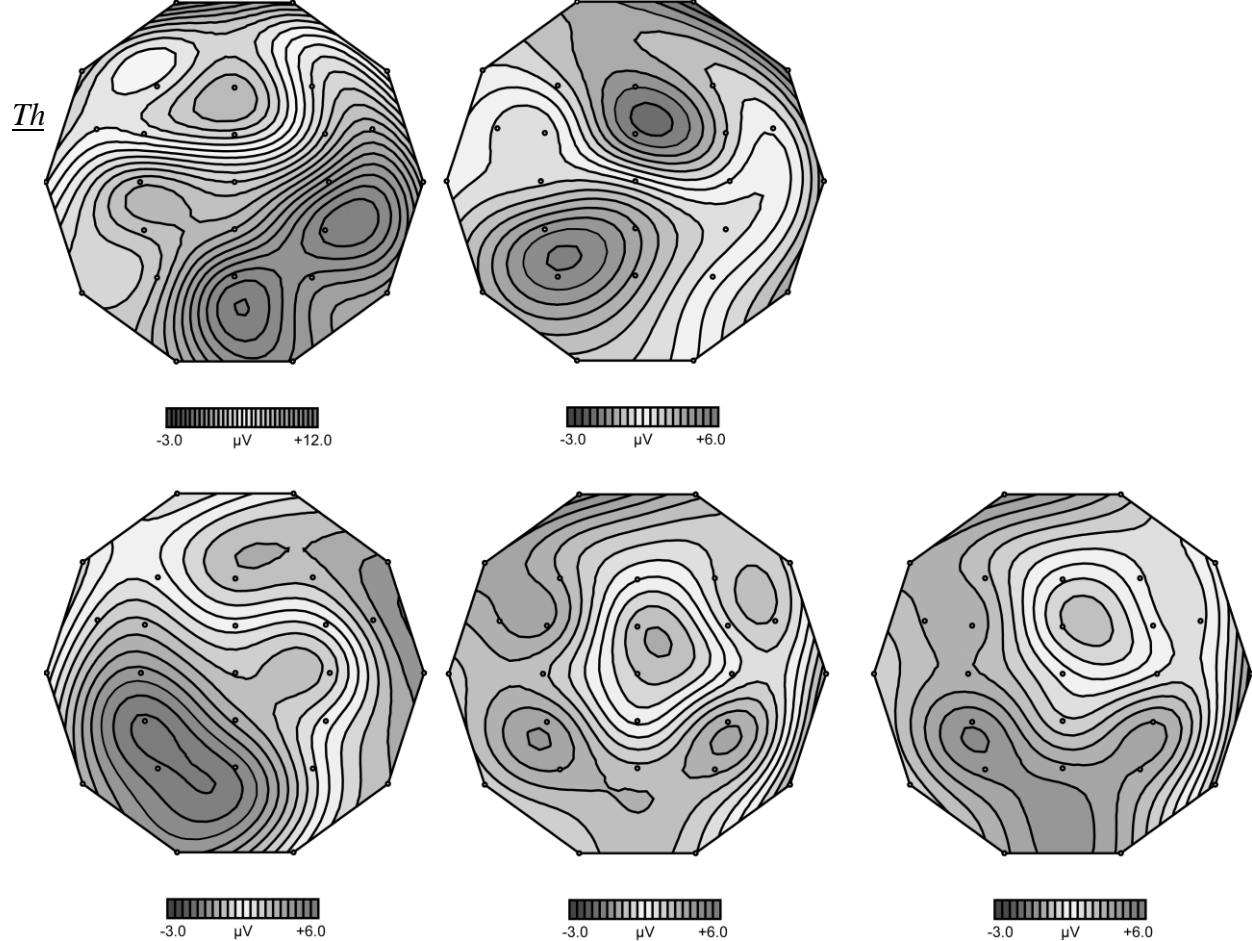


Figure 5. Contrasting poor (left) and good performers (middle) in the children. Young children (top row) and older children (bottom row) as a function of performance level during the 700-900 msec time window. Older children with high performance levels are also shown in an additional earlier time window (600-800 msec, right). Note the difference in scaling to indicate the topographical distributions and the maximal effects (i.e. largest amplitudes for poor performing young children).

Interestingly, the 6-8 year olds performing better show a left parietal focus of the old/new effect in the given time window ($\omega^2=0.56$ at P3 and $\omega^2=0.08$ at P4). A similar pattern holds for those 10-12 year olds performing worse ($\omega^2=0.59$ at P3 and C4, $\omega^2=0.55$ at PZ, $\omega^2=0.15$ at P4). This corresponds to the topographical distribution typically found in the recollection component in adults (Curran, 2000; Curran & Cleary, 2003; Friedman & Johnson, 2000; Mecklinger, 2000, 2004).

On the other hand, for those 10-12 year olds with the good performance the topography is more widespread. Treatment magnitude is largest at F3 ($\omega^2=0.66$) with medium effects at P3 ($\omega^2=0.33$) and C3 ($\omega^2=0.32$). Considering the fact that better performance might also be reflected by shorter reaction times and shorter ERP latencies, the time window chosen for the complete group (700-900 msec) might reflect only the later parts of the old/new effect in these cases. The topography in a slightly earlier time window (600-800 msec) closely resembles that of the other groups in the later time window (compare Figure 5). In addition to the activity seen in the younger group, treatment magnitudes in the earlier time window reveal that the effect is still largest at F3 ($\omega^2=0.55$), although nearly equal in size at left parietal electrodes

($\omega^2=0.49$ at P3 and $\omega^2=0.43$ at C3). This might reflect an intermediate phase of better performing older children who begin to use familiarity, although this happens considerably later than in adults because the perceptual information is dissimilar.

To summarize, no positive correlation between the individual peak magnitude of the parietal effect at PZ and performance accuracy was found. This seems to be related with maturational factors. Although the topography of the old/new-effect does not vary between the groups of children, it does vary as a function of performance level within both groups of children. In particular the right parietal distribution in the youngest groups seems to be related to poor performance. Whether this effect is related to a lack of verbal mediation remains to be investigated. In contrast, young good performers as well as older poor performers show a left parietal topography of the old/new effect. Older children with a good performance level seem to differ from the others in terms of ERP component latencies, and show a similar left parietally distributed old/new effect about 100 msec earlier than the other children and an additional old/new difference at F3. The topography of the old/new effect thus seems to be a sensitive indicator of underlying processes and strategies that might contribute along with maturational factors to good or poor performance in children.

Conclusion and open issues

The results of the present study clearly speak for different strategic modulations of recognition memory processes in adults and children. Assuming that recollection is based on higher levels of certainty (Tulving, 1985), the conservative response bias in children may suggest that the children only respond 'old' when recollection was successful. On the contrary, adults are more flexible and by this are able to accommodate decisions even without recollection, based on a fast assessment of familiarity. Our ERP effects are consistent with this view: in children, the infrequent hit responses that are based on recollection elicit a large parietal old/new effect. Adults can rely on both familiarity and recollection since they are able to incorporate post-retrieval evaluations into their decisions.

It remains unclear why children are not recollecting more items. Less monitoring and control of memory retrieval due to still immature frontal lobe structures could be responsible for a failure of the reinstatement of the relevant features. Alternatively, the binding process might have not been successful during encoding leading to impoverished memory representations for many items.

The change of perceptual characteristics from study to test seems to disturb children's performance levels more than adults'. A plausible interpretation for this difficulty is that children may retrieve memory representations in a less conceptual way than adults (Friedman, 1992). This perceptual strategy would have made it impossible for them to use familiarity-based memories successfully and thus made the present task particularly difficult for the children. It needs to be examined in future studies if young children rely more on familiarity with other testing conditions and if their ERP correlate of familiarity is similar to that found in adults. Another issue remains open as well: it seems that older children who perform well do show some frontal old/new effects, albeit considerably later than adults.

In order to have a more clear-cut picture of the differential developmental trajectories of familiarity and recollection, it is important to compare tasks in which those two processes can be distinguished behaviorally, for instance in an exclusion task where familiarity and recollection elicit different responses.

Acknowledgements: The authors wish to thank Patric Meyer and an anonymous reviewer for helpful comments and Martina Zink for assistance in data collection. We further would like to thank all participants in this study, especially the children and their parents.

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