THE ROLE OF PERCEPTUAL INFORMATION FOR EPISODIC MEMORY IN CHILDREN AND YOUNG ADULTS: ELECTROPHYSIOLOGICAL AND BEHAVIORAL CORRELATES OF RECOLLECTION AND FAMILIARITY

Vom Fachbereich Sozialwissenschaften
der Technischen Universität Kaiserslautern
zur Verleihung des akademischen Grades
Doktor der Naturwissenschaften (Dr. rer. nat.)
genehmigte

D i s s e r t a t i o n

vorgelegt von
André Haese

Tag der Disputation:	16.12.2020
Dekan:	Prof. Dr. Michael Fröhlich
Vorsitzende/r:	Prof. Dr. Thomas Schmidt
Gutachter/in:	1. Jun.-Prof. Dr. Daniela Czernochowski
	2. Prof. Dr. Thomas Lachmann

D 386

Januar 2021

Table of Contents

Acknowledgments

This dissertation was supported by a lot of people throughout its different stages. I would like to thank these colleagues and friends for their professional discussions, helpful criticism, and encouragement. First and foremost, I would like to thank my supervisor, Daniela Czernochowski. She continuously guided me through the maze of gyri and sulci of the human brain. In doing so, I learnt very much and I am positive that it greatly shaped my thinking and my work. Furthermore, there have been a lot of colleagues whom I owe my thanks as well – too many to name them all. These colleagues and friends assisted me with their invaluable insights on various topics. I would like to specifically thank the Scientific Writing Peer Critique Group of Shanley Allen who helped me overcome at least some of the Germanesque English in my writing, largely improving my writing style. I thank my "doctoral siblings" Ann-Kathrin Beck, Larissa Leist, Petra Ludowicy, and Max Wolkersdorfer for their companionship, advice and their ongoing appreciation. Further thanks go to Daniel Pinske and Steffen Herff for reminding me that there is always time for hobbies. Likewise, I thank Monique Verjans and Sofia Kermas for providing me with so much free time, patience and endurance, for their flexibility and their ever-lasting interest in and support of my PhD topic and my field of research. Finally, I wish to thank my family, Monika and Jürgen, Aleks, Tanja, Adrian and Levi (for reminding me of the applicability of all developmental psychology) for always and sincerely believing in me, comforting me, and helping me with the various obstacles that cannot be resolved in a peer-review process.

Summary

In this dissertation, I will present the studies conducted during my doctoral studies. In spite of a lot of research in the last decades, the complex cognitive processes underlying human memory are not fully unraveled. Furthermore, the development of neuroscientific methods like functional magnetic resonance imaging (fMRI) and event-related potentials (ERPs) have further build a foundation for new insights. Naturally, the utilization of these techniques led to further adaptation of both these techniques and the paradigms in which they have been employed. This can be observed in the research literature on episodic memory retrieval. Familiarity and recollection, have been found to be the chief factors at play during memory retrieval. The two processes have been thoroughly characterized in several studies and reviews (e.g., Mecklinger, 2000; Rugg & Curran, 2007; Yonelinas, 2002; Zimmer & Ecker, 2010), yet there are still open questions that have to be addressed by researchers in this field (c.f., Leynes, Bruett, Krizan, & Veloso, 2017; MacLeod & Donaldson, 2017).

In order to answer these questions, we conducted several studies during my doctoral studies. In Study 1, we developed a paradigm to investigated episodic memory using ERPs. In the study phase, pictorial stimuli were presented which at test were either perceptually identical, perceptually changed, or entirely new. Data collected from a sample of young adults revealed that the paradigm was suitable to elicit ERP correlates of both familiarity and recollection. As the newly developed paradigm yielded similar results as existing literature, we then applied this paradigm in two developmental populations, second-graders and fifth-graders. According to the ERPs, the younger children seemed to rely on recollection alone, whereas ERPs of older children suggested the use of familiarity for perceptually identical items and only after intentional encoding. In a follow-up study two years later, we used the results from both studies to only slightly refine the paradigm, again administering it to young adults. In this study, Study 3, we found that ERP correlates were much smaller than in the earlier studies, hence we used a data-driven approach to detect time windows of interest. In spite of the large body of research on episodic memory, these studies serve to demonstrate that episodic memory is a complex interplay of several contributing cognitive processes which need to assessed carefully in order to unravel the key factors at play during familiarity and recollection.

A brief introduction to human memory research

Access to human memory is such a common everyday task that we hardly consider the cognitive processes involved during the encoding and later retrieval of information. We know that humans have long been interested in the nature of human memory, as can be seen in philosophers like Plato and Aristotle discussing the nature of human memory in documents published two millennia ago. This interest has not subsided until today and in the 19th century, Ebbinghaus (1885) studied meaningless syllables in order to measure how many of these he would remember in the following days. His controlled and systematic measures as well as their documentation can be considered the foundation of modern memory research.

Today, memory is assumed to consist of three qualitatively different memory systems that have been described by Tulving (1985): Procedural memory, semantic memory, and episodic memory. Procedural memory contains all automated behavior patterns we need and use regularly like reading or switching on the indicator when driving a car. Semantic memory is assumed to contain all knowledge we accumulate in our life, for instance the names of animals, our vocabulary, or the meaning of scientific terms. Lastly, and most relevant for the topic of this thesis, Tulving postulated the existence of an episodic memory system, in which episodes of our life are stored, for example our last meal, our weekend activities, or surprising encounters when driving home from work.

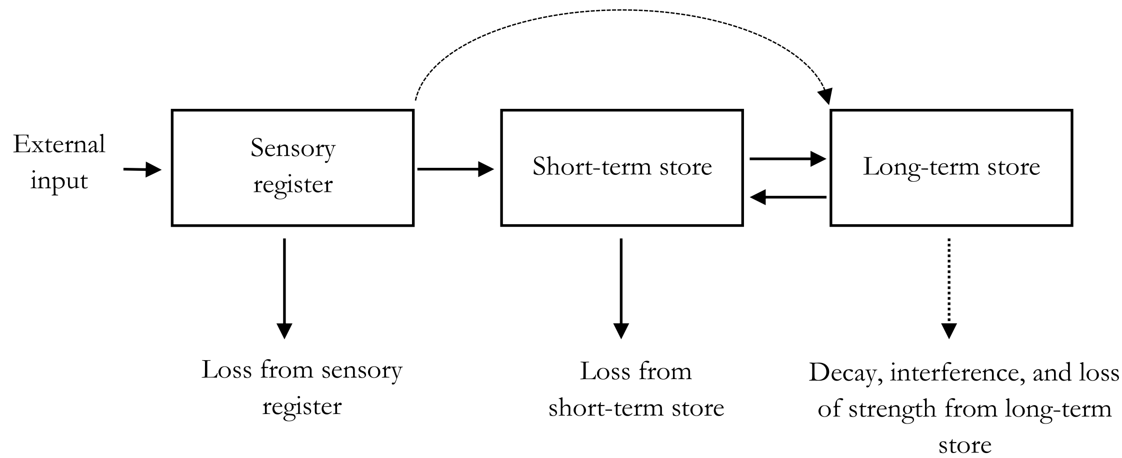

Figure 1. Multi-store memory model of Atkinson and Shiffrin (1968)

In order to describe episodic memory processes, Atkinson and Shiffrin (1968) proposed a multi-store model (Fig. 1), which separates episodic memory into the sensory register, the short-term store, and the long-term store. This separation is based on qualitative properties like the rate of decay, the duration information is contained, and the capacity of each system. Upon perceiving information, Atkinson and Shiffrin assume it is stored in the sensory register, a storage which contains information for about half a second. Within this very short time frame, participants store information for the first attentional selection processes, during which four to five items can be selected for further processing (Sperling, 1960). Those items selected from the sensory register then enter the short-term memory which plays an important role not only for storage (as the name might suggest), but also for the processing of this information. The processing of this memory subsystem has been thoroughly investigated, in particular by Baddeley and colleagues, who postulated and investigated the so-called working memory (for an overview, see Baddeley, Hitch, & Allen, 2018). Short-term memory has been found to contain about seven items that are rapidly forgotten unless maintained (Eysenck & Keane, 2007, p. 191f.). Lastly, the long-term store has the important role of storing all information gained throughout one's life. As implied by this overarching definition, its capacities have been a bit less easy to discern. For instance, it is possible that information not accessible at first becomes accessible after a certain cue is encountered which alleviates this retrieval. For example, we may have forgotten about a certain episode from our childhood, yet we may meet (and remember) a person from that episode. This meeting, or details given by this person, may serve as retrieval cues, giving access to memories not accessible beforehand. Consequently, most researchers either assume either a (sheer) limitless capacity and duration for the information stored or they argue that it is impossible to assess with current methods.

In the last decades, a plethora of research questions has led to a lot of insightful research on the matter of long-term memory encoding – the storage of information into memory – and retrieval – the access to stored memory traces (e.g., Atkinson & Juola, 1973; Malmberg, Raaijmakers, & Shiffrin, 2019). Here, I want to focus on episodic memory, as familiarity and recollection are considered the two chief processes at work during episodic memory retrieval. I will describe both in detail in the next section.

Two chief cognitive processes in episodic memory retrieval

In a traditional memory paradigm, participants study a list of words, pictures, or faces that are to remembered (in intentional encoding procedures; in incidental encoding procedures, participants are unaware of the test phase until they actually engage in retrieval; c.f. Block, 2009). Some studies ask participants to retrieve the contents of the study phase by asking them to freely recall this information. Other studies prompt participants with cues like the first letter of all words. Similarly, recognition paradigms not only offer cues at test but the items themselves, together with items not studied previously. As such, there are items presented previously (old items) and items not encountered in the preceding study phase (new items). These two item categories can in turn be categorized correctly or incorrectly. As such, there are four possible cases researchers can discern: hits, misses, correct rejections, and false alarms. Hits are items studied previously and correctly identified as old, whereas studied words or images not remembered are considered misses. Whenever an item is correctly identified as a new item, this category has been coined correct rejection, whereas new item falsely assumed to have been present during a preceding study phase are commonly called false alarms. Snodgrass and Corwin (1988) have extensively reviewed the pros and cons of different measurement approaches, so I will introduce the aspect of behavioral assessment only briefly in this thesis. As evident from the rationale above, hits are of high relevance for the assessment of an individual's memory performance as they comprise correctly recognized items. One might hence assume that a high hit rate, i.e. the relative frequency defined as hits divided by the amount of all old items, approximating 1 equals a high memory performance. Imagine, however, a participant always considering an item as "old", irrespective of its actual state. This perfect hit rate might suggest perfect memory on first glance, but of course they instead merely guessed an item was old for every prompt. Fortunately, this would be apparent in the false alarm rate, i.e. the relative frequency defined as false alarms divided by the amount of all old items, as this rate would similarly reach 1. Accordingly, a memory expert should exhibit a high hit rate along with a low false alarm rate. As convenient measure of both variables, the behavioral performance score Pr has been defined as the difference between hit rate and false alarm rate; a Pr of 1 equals a high memory performance whereas a Pr at level of (or close to) 0 means a person performed at chance level.

When it comes to this process of recognition, there are two seemingly contrary views. One view assumes that a single process of memory strength is sufficient to explain episodic memory retrieval whereas the other view assumes that two cognitive processes, *familiarity* and *recollection*, are employed in the service of retrieval. Of these two postulated processes, familiarity has been defined as a somewhat uncertain feeling of knowing that something that is seen or heard has been encountered before (e.g., Atkinson & Juola, 1973), whereas recollection has been defined as the conscious and intentional retrieval as a consequence of a recollective search process (Jacoby, 1991). For each item in an episodic memory test, participants may have the vague "feeling of knowing" that they saw something previously without contextual information. This is called familiarity as this process is assumed to rely on the familiarity an item elicits. Alternatively, participants may clearly "remember" a formerly studied word due to contextual cues they remember from the study episode along the item. In these instances, researchers assume that recollection has been employed in the service of episodic memory retrieval (the idea of "remembering" versus "knowing" has been used in the remember/know paradigms, c.f. Yonelinas, 2002). In addition to this qualitative difference in participant responses, quantitative measures corroborated the notion of two separable processes (Yonelinas, 2002). For instance, familiarity has been found to be faster than recollection as giving the participants a response deadline during a test led to differential effects on both processes. Also, the differentiation between recall and recognition performance may allow a separation of both processes if the recall process is considered to be a recollective search process: Recall is assumed to be attributable to recollection, whereas recognition can be understood as the interplay between both processes. Furthermore, recollection-based retrieval often gives access to qualitative information not available via familiarity (Yonelinas, 2002). It has been shown that participants are often capable of describing additional features from the study episode, for instance contextual details, thoughts or events that occurred during study (e.g., "I remember that 'bread' was part of the list because I clearly recall thinking I had to buy a loaf of bread on my way home"). It has been shown that this recall of associative information is related to the subjective feeling of remembering responses and has hence been attributed to recollection (e.g., Hockley & Consoli, 1999). Yet another approach has been to ask participants after each response about their subjective confidence during their retrieval task (e.g., Yonelinas, 1997), as recollection has been linked to high-certainty responses whereas familiarity was associated with varying degrees of confidence (Yonelinas, 2002).

As can be seen, there is a multitude of methods speaking in favor of several processes underlying episodic memory retrieval. One of these was the innovative process-dissociation technique developed by Jacoby (1991) which has been used to disentangle the two processes underlying retrieval – Jacoby originally called these two automatic and intentional retrieval which largely represent both familiarity and recollection respectively (c.f. Yonelinas, 2002). In Jacoby's study (Experiment 2). In this paradigm, participants were presented with 5-letter-words and 5-letter-anagrams that were to be read out aloud. Subsequently, they were presented with an auditory list of words that they were asked to remember for a later retrieval phase. In this retrieval phase, participants were instructed only to call those items "old" that had been presented auditorily; by contrast, the 5-letter-words and anagrams from before were to be rejected as "new" items. Accordingly, not all old items, but only a specific subgroup of items is to be categorized as "old". Due to the separation of item sets, this procedure has been coined "exclusion" task. In a typical "inclusion" task, however, participants give an "old" response to all items that have been encountered before without further discrimination. Thus, in an inclusion task, even the vague feeling of familiarity is sufficient to perform well in the task. By contrast, additional employment of strategic search processes is required for successful completion of the exclusion task. This innovative design allows automatic retrieval to be a source of memory error (Jacoby, 1991; cf. Jacoby, Kelley, Brown, & Jasechko, 1989), as automatic retrieval without strategic rejection would result in an error in source attribution and hence impair performance. In his third experiment, Jacoby (1991) used the difference of inclusion and exclusion task performance to estimate the contributions of automatic and intentional memory retrieval to memory performance, a technique adopted by other researchers for process-estimation methods (c.f. Yonelinas, 2002, also for the rationale behind these estimates). Over the last decades, several dual-process models have emerged as a consequence of the large body of evidence speaking in favor of two separate processes (e.g., Mandler, 1979, 1980; Tulving, 1985;

Tulving & Schacter, 1990; Yonelinas, 1994; 1997; for an extensive review on dual-process models, see Yonelinas, 2002).

By contrast, there are also single-process models of episodic memory which postulate a single retrieval process (for reviews on this matter, see Pratte & Rouder, 2011; Wixted, 2007; Yonelinas & Parks, 2007). According to these single-process models, observable differences between both processes could also be explained as different degrees of memory strength. Memory traces of high strength are considered to be the result of efficiently stored information, thus being retrieved faster and more easily, hence eliciting responses of high certainty. Information stored at subpar level, instead, would elicit a feeling of uncertainty and result in a less certain participant response. Thus, the degrees of certainty associated with familiarity and recollection in dual-process models could be explained with a single process. For the time being, both accounts have converged into hybrid models which entail aspects of both theoretical frameworks (for a recent overview on this matter, see Juola, Caballero-Sanz, Muñoz-García, Botella, & Suero, 2019). Advocates of both single process and dual process models agree that the assumption of familiarity and recollection can be considered a useful measurement tool of recognition memory as has been shown in the past decades (Yonelinas, 2002).

It is noteworthy that the assumptions of dual process and hybrid models have been supported by emerging neuroscientific evidence. The employment of neuroscientific methods gave access to new tools to further investigate the interplay between the two processes in episodic memory retrieval. With the discovery of neural correlates of familiarity and recollection in event-related potential (ERP; e.g., Curran, 2000) and in functional magnetic resonance tomography (fMRI; e.g., Diana, Yonelinas, & Ranganath, 2010) studies, new research tools became available to further evaluate episodic memory retrieval. In addition to behavioral performance and reaction times, the impact of experimental manipulations on the now-established measures of familiarity and recollection could be assessed. In the next section, I will give a brief introduction to the established neural correlates in the field of episodic memory which were investigated in the studies reported in this dissertation.

Neural correlates as key to understanding episodic memory retrieval

Neuroscientists assume that every cognitive process has a neural foundation, so perception, categorization, recognition as well as decision or motor actions should be associated with a neural correlate. These correlates ought to be observable via different neuroscientific measurement techniques that allow investigating neural structures based on ferromagnetic properties of human tissue (magnet resonance imaging; MRI) or functional activation patterns based on the metabolism of oxygen (fMRI). Compared to other neuroscientific methods, both MRI and fMRI excel in their spatial resolution, and hence are useful to investigate research addressing the question of exactly *where* in the brain the activity is prominent during a certain task or event. In the case of human memory, the main brain areas active during encoding, storage and retrieval are in the medio-temporal lobe consisting of the hippocampus, the parahippocampal gyrus, the entorhinal and the perirhinal gyrus (Eichenbaum, Yonelinas, & Ranganath, 2007). In addition, the prefrontal cortex has been found to be active during memory tasks as well (Simons & Spiers, 2003), which has been related to the increased demand of executive control, for instance for the utilization of previous knowledge (Brod, Werkle-Bergner, & Shing, 2013).

While advantageous for questions regarding the localization of cognitive processes in the human brain, fMRI studies are at disadvantage when an investigator wants to understand *when* a participant engages in a certain cognitive process due to its low temporal resolution. Given that episodic memory retrieval is the result of cascades of several underlying cognitive processes – e.g., attentional processes, familiarity, recollective search processes, maybe the resolve of response conflict, retrieval and/or error monitoring – a high temporal resolution is key to disentangle the interplay of these cognitive processes at work. Hence, electroencephalography (EEG) is a well-suited application for these questions, although at the cost of low spatial resolution.

EEG measures the electrical activity in the brain by placement of electrodes on the human scalp. The electrical activity is the voltage difference between each electrode and a reference electrode (often either one of two mastoids or the average of all electrodes). While the raw EEG signal, i.e. the sum activity of the brain during a certain period, is already a helpful instrument for neurological diagnostics, the investigation of cognitive processes often uses a different approach. After measuring the raw EEG, neuroscientists can calculate the averaged electrical activity after certain events, which are repeated throughout a single experiment and then compared to each other. It is assumed that after averaging, the peaks and troughs of the signal (i.e. the differences in electrical potential also called event-related potentials) represent the activity induced by the event alone, whereas random shifts ("noise") are diminished greatly. For instance, one might compare activity elicited by stimuli that a participant has been instructed to attend to with neural activity elicited by stimuli a participant has been instructed to ignore. The resulting difference wave would not represent activity related to the stimulus perception or any button press, but would ideally only differ in the attentional resources invested by the participant. This assumption that ERP averages of different conditions can by utilized to contrast conditions in which cognitive processes ought to be present or not is the main rationale behind most ERP studies. Of course, the matter of episodic EEG and ERP measurement is a more complex field, a comprehensive introduction to the ERP method is offered in the book of Steve Luck (2005).

In order to investigate episodic memory research, differences between correctly recognized old and new items is contrasted. During retrieval, it is assumed that new items encountered for the first time and correctly categorized as new items – hence called correct rejections – cannot consist of memory representations. Following a similar line of thought, old items correctly recognized as old – hits – are most likely to represent successful memory retrieval. The contrast of both hits and correct rejections is thus a valid tool to evaluate memory processes (a cautious interpretation is advisable when interpreting the absence of ERP effects, however, as will be demonstrated and discussed in the studies of this dissertation). Hence, ERP studies traditionally depict the effects as a net difference of correct responses (correct old minus correct new responses; but see also e.g., Curran & Dien, 2003, for analyses of misses in addition to correct responses due to the respective research questions; Czernochowski, Brinkmann, Mecklinger, & Johansson, 2004; Czernochowski, Mecklinger, Johansson, & Brinkmann, 2005), whereas behavioral studies using the abovementioned performance measure Pr instead focus on the difference correct and incorrect responses (hit rate minus false alarm rate). In order to clearly characterize old/new effects as well as the factors eliciting them, innovative experimental procedures have been developed to compare ERP averages of different conditions and paradigms.

For instance, the aforementioned issue whether retrieval consists of one or two processes could be re-evaluated with the help of both neuropsychological and pharmacological studies. In rats, hippocampal lesions have been found to selectively reduce recollection-based memory retrieval, but not familiarity-related retrieval (Sauvage, Fortin, Owens, Yonelinas, & Eichenbaum, 2008). Similarly, the administration of certain anesthetics has been found to lead to a differential reduction neural signatures reflecting familiarity and recollection (Nyhus & Curran, 2012; Veselis et al., 2009), whereas others only selectively reduced recollection (Curran, DeBuse, Woroch, & Hirshman, 2006). Interestingly, the two processes were found to be associated with different activation patterns for both processes in the prefrontal and the parietal cortex as well as the hippocampus (Yonelinas, Otten, Shaw, & Rugg, 2005). As indicated by these examples, emerging neuroscientific evidence showed the complexity of neural processes at play during retrieval.

As the studies in this dissertation used the ERP method to evaluate both retrieval processes, in the following section I will give a brief overview on the ERP components of episodic memory retrieval commonly used to characterize memory retrieval in ERP studies.

ERP components of memory retrieval

As described above, two cognitive processes have been associated with episodic memory retrieval: familiarity and recollection. Researchers have discovered two distinct neural signatures which have been used as an index of their respective employment in a task. For each of the two processes, old items have been found to elicit more positive amplitudes than new items in ERPs contrasting successful to unsuccessful memory retrieval (Yonelinas, 2002). For familiarity, these effects tend to emerge after 300 to 500 ms at midfrontal electrode sites, and a likewise positive deflection for correct items has been identified as a marker of recollection after 500 to 800 ms at parietal electrode sites (Curran, 1999; 2000; Wilding, 2000; Wilding, Doyle, & Rugg, 1995; for reviews, see Friedman & Johnson, 2000, and Johnson, 1995). The ERP component of familiarity has been named FN400, whereas the recollective counterpart is called Late Posterior Complex (LPC). First tentative attributions of these components to their respective cognitive processes have been corroborated in extended paradigms which allowed a careful evaluation of variable manipulations affecting either of both ERP components. In consequence, both ERP components can be considered established and well-characterized. For instance, due to prior knowledge of the time course of episodic memory retrieval, Rugg, Mark, et al. (1998) were able to attribute differences in the familiarity time window (300 to 500 ms) to dissociative effects on implicit and explicit memory by asking participants to encode items either deeply or shallowly (c.f. Craik & Lockhart, 1972). Rugg and colleagues analyzed both time windows, 300 to 500 ms and 500 to 800 ms, and found both ERP components of familiarity and recollection in their respective time windows.

Furthermore, studies have reported inconsistent results regarding the magnitude of the midfrontal FN400 in paradigms in which pictorial items were changed, for instance when the test item was presented in a different color. In some studies, this modification diminished (Ecker, Zimmer, & Groh-Bordin, 2007a; Tsivilis, Otten, & Rugg, 2001) or even eliminated (Curran & Doyle, 2011, Experiment 2; Groh-Bordin, Zimmer, & Mecklinger, 2005) the old/new effect, whereas in others, no differential effect on the magnitude of the old/new effect was observed (Curran, 2000; Curran & Cleary, 2003; Curran & Dien, 2003; Czernochowski et al., 2005; Ecker, Arend, Bergström, & Zimmer, 2009; Friedman, Cycowicz, & Bersick, 2005; Wiegand, Bader, & Mecklinger, 2010). Reviewing studies on the FN400, Zimmer and Ecker (2010) came to the conclusion that perceptual changes at retrieval affected the ERP component of familiarity if item characteristics were relevant for the task at hand. If, however, participants were instructed to consider changed items as "old" (i.e., an inclusion task) the ERP component was of similar magnitude. This finding is of high interest, as it suggests that familiarity is not simply a highly automatic bottom-up process, but seems to be affected by top-down processes like the prior knowledge about the relevance of perceptual features as well: "This is clearly a strategic top-down influence of retrieval orientation (Herron and Wilding, 2004; Wilding and Rugg, 1997) on familiarity processing. We therefore consider our original familiarity conception as too static and too strongly focused on bottom-up processing" (Zimmer & Ecker, 2010, p. 1074).

Similar discussions can be found for the ERP component of recollection which has been shown to emerge as a larger positivity for old versus new items when source memory has been retrieved successfully (Wilding, 1999, 2000). Due to this finding, the size of the ERP component of recollection has been proposed to reflect the quality of the memory trace – the more information a person can recollect, the larger is the ERP component. A smaller ERP component was observed after an item was attributed to the wrong source (Wilding, 1999); a larger component was elicidted when source information was retrieved (no source correct vs. one source correct vs. two sources correct; Wilding, 2000). Recent evidence by MacLeod and Donaldson (2017) challenges this assumption: They reported difficulties relating the magnitude of this ERP component to behavioral measures of memory (Pr; Snodgrass & Corwin, 1988) which suggests that the underlying processes may be more complex in nature than originally expected.

One possible explanation may be another ERP component found during episodic memory retrieval, the late parietal negativity (LPN). The LPN has been found under difficult retrieval task conditions and has been related to both further source-specifying retrieval and response conflict resolution (Mecklinger, Johansson, Parra, & Hanslmayr, 2007). It is assumed that when the old/new decision is difficult, participants employ further recollective search processes in order to recall contextual details which may be used to reduce or resolve response conflict (for a review, see Mecklinger, Rosburg, & Johansson, 2016). As the LPN itself is assumed to reflect recollective search processes when recollection alone is not sufficient for the task execution, it is only plausible that the LPN holds similar temporal and spatial traits as the LPC. It is found in the time window between 600 to 1900 ms as a parieto-occipital negativity for conditions under which recollection is difficult. Thus, there may be instances in which the positive amplitudes of the LPC are diminished by negative amplitudes of the LPN possibly reducing the parietal old/new effect assumed to reflect recollection. Taken together, these examples show that apparent inconsistencies are actually beneficial, as they allow a deeper understanding of the investigated processes. Not only do these ERP studies grant insight into the cognitive processes themselves, but additionally into the ERP components used to measure these processes; accordingly, ERP components successively become more fine-grained instruments for the assessment of their respective cognitions, which in turn allows a more clear-cut investigation of the cognitive processes.

The development of episodic memory and its neural correlates

The examples above also serve to show that episodic memory retrieval is a remarkably intricate matter with its underlying processes intertwining and partly concealing each other. One way to circumvent this may be the investigation of developmental populations. When children engage in memory search, it is plausible that they employ similar cognitive processes as adults or precursors thereof. Unlike adults, children tend to rely on less refined forms of perceptual, semantic, and episodic systems (Ofen & Shing, 2013). As a consequence, it is conceivable that children employ less, possibly confounding, cognitive processes cognitive processes during an experimental task than adults. Hence, understanding the developmental trajectories of episodic memory retrieval may not only grant insight into the fundamentals of children's episodic memory retrieval, but also broaden our understanding of adult episodic memory retrieval. Given that not only behavioral studies (see below) but also fMRI studies (Casey, Giedd, & Thomas, 2000) revealed a continued development of attention and memory throughout childhood and adolescence, it seems promising to investigate these developmental trajectories in order to understand how adult retrieval processes came to be.

Billingsley, Smith, and McAndrews (2002) asked children and adolescents aged 8 to 19 to specify for each response whether they "remembered" each test item or whether they merely "knew" that it was old, a paradigm known as the remember/know paradigm (Tulving, 1985). This showed that children give both responses after being trained in the paradigm, suggesting that children are able to introspectively differentiate between information with contextual detail (recollection) and information without it (familiarity). Furthermore, children not only seemed to employ both processes, they also gave more "know" than "remember" responses, suggesting that episodic information was less effectively retrieved by younger children (aged 8 to 10). This might possibly derive from less effective recollective search processes, as suggested by children's lower behavioral memory performance (Billingsley et al., 2002).

In order to elucidate this, further studies computed estimates for both processes based on receiver operating characteristic (ROC) curves derived from participants' confidence ratings (Ghetti & Angelini, 2008; for an application of this method in an adult population, see Yonelinas, 1997) or by using the process dissociation procedure of Jacoby (1991) described above (Koenig, Wimmer, & Hollins, 2015). In their study, Ghetti and Angelini (2008) presented pictures to children in shallow and deep encoding tasks (c.f. Craik & Lockhart, 1972) asking them rate their confidence alongside their answer. Estimates of familiarity and recollection revealed that both processes developed differentially. While recollection increased significantly between 8 to 10 years of age, estimates of familiarity increased between 6 to 8 years of age. Notably, ROC curves suggested both processes to be observable in children. Similarly, Koenig et al. (2015) used the process dissociation procedure of Jacoby (1991) described above and found comparable developmental trends.

In line with these parameter estimates, age-related differences were larger in source memory performance measures than in item memory measures (e.g., Cycowicz, Friedman, & Duff, 2003; Czernochowski et al., 2005; Gulya et al., 2002; for a multinomial modelling account comparing independent parameters for item and source discrimination, see also Cycowicz, Friedman, Snodgrass, & Duff, 2001). As detailed above, contextual information is assumed to reflect recollective retrieval, whereas the absence of contextual information is assumed to reflect familiarity. Hence source memory performance is considered to chiefly consist of recollection-based retrieval, whereas both familiarity and recollection may contribute to item memory recognition. Accordingly, a larger age difference for source vs. item memory may be explained as a delayed maturation of recollection-based versus familiarity-based retrieval. Taken together, behavioral evidence suggests that children can employ both familiarity and recollection, albeit not as flexibly as adults and certainly not with the same level of efficacy. Considering the established ERP correlates of episodic memory retrieval in adults, it thus seems conceivable to expect similar neural correlates in children.

Consistent with this notion, a parietal positivity for old versus new items – resembling adults' ERP correlate of recollection – was observed in children and adolescents aged 4[1] to 14 (Cycowicz & Friedman, 2003; Czernochowski, Mecklinger, & Johansson, 2009; Czernochowski et al., 2005; Marshall et al., 2002; Sprondel, Kipp, & Mecklinger, 2011). By contrast, no correlate of familiarity resembling the FN400 was reported for children. So in spite of behavioral evidence suggesting the employment of both retrieval processes, only recollection could be identified in ERPs of correct memory retrieval. An important key to this puzzle was offered by Mecklinger, Brunnemann, and Kipp (2011) who utilized the fact that the dual-process framework states that familiarity is considered a fast and automatic process whereas recollection usually is a slower and controlled cognitive process (Yonelinas, 2002). Using a response deadline, Mecklinger and colleagues compared participant performance of two conditions. In the condition without time limit, participants gave their memory response in a self-paced way; results revealed the established finding that a parietal old/new effect attributable to recollection was observable, yet no earlier frontal old/new effect could be observed. In the other condition, participants responded within a certain time limit and results of both children and adults did not display parietal effects, but instead a frontal positivity for old versus new items could be observed: This ERP correlate was attributed to familiarity in both adults and children.

Given the prior discrepancy between behavioral and neuroscientific evidence, the study of Mecklinger et al. (2011) was an important bridge for the gap in the literature. It seems that similar to adults' FN400 being susceptible to perceptual modifications between study and test under some task characteristics (Zimmer & Ecker, 2010; see the brief introduction above), children's frontal effects are similarly susceptible to task characteristics. As such, the understanding of familiarity-based retrieval necessitates a clearer picture of the processes at play, which can be assessed given this very susceptibility in the data. If we learn which experimental paradigms are successful in

[1] Note that in the study of Marshall, Drummey, Fox, and Newcombe (2002), latencies of old/new differences were higher in 4-year-olds than in adults.

eliciting or even fostering familiarity in children, we may learn which cognitive processes are involved in this cascade of subprocesses; in line with this, the FN400 has been suggested to reflect not familiarity per se, but instead processes that are elicited by those responsible for assessing familiarity (Tsivilis et al., 2001).

Development of a new ERP paradigm to research episodic memory retrieval

As can be seen in the previous pages, there has been a plethora of research on episodic memory retrieval, both using behavioral measures and neuroscientific approaches like fMRI and ERPs in refined research paradigms; and yet, open questions remain. After decades of research, guidelines for neuroscientific studies have emerged (e.g., Keil et al., 2014; Picton et al., 2000), allowing an easier comparison of different researchers using electrophysiological measures to address their questions. As a consequence, established findings are often extended by corroborating evidence, although sometimes the refinement and adaptation of existing paradigms leads to slight inconsistencies in the literature. These apparent contrasts of evidence are often helpful tools to further further our understanding of both the cognitive processes underlying a paradigm as well as the exact properties affecting the ERP correlates representing them. A good example is the P300, a component originally described by Sutton, Braren, Zubin, and John (1965) and investigated very thoroughly throughout the following 50 years (for a systematic investigation, see Polich, 2007; for examples from the domain of episodic memory retrieval, see Leynes et al., 2017; MacLeod & Donaldson, 2017; Mecklinger et al., 2016).

As detailed above, there are more factors at play during episodic memory retrieval. Accordingly, we developed a new paradigm that was different from previous studies in several regards. Firstly, we used both an incidental and an intentional encoding procedure assuming that the nature of the encoding task or the quality of the retrieved memory trace might affect whether participants can utilize familiarity and recollection. Secondly, we used three types of stimuli, two old and one new, in order to investigate not only correct old and new items, but also whether perceptual modifications affect the observable ERP components. Thirdly, we used a developmental population to evaluate if the intricacies between familiarity and recollection may be unveiled by uncovering the assumed correlates of familiarity and recollection. We assumed that perceptual modifications would be key in detecting differential ERP effects of familiarity in developmental populations. As has been shown by Zimmer and Ecker (2010), the FN400 indexing familiarity is affected by perceptual manipulations in exclusion tasks. More specifically, items perceptually modified would elicit a smaller familiarity-related frontal old/new effect at test than perceptually changed items – but only if the perceptual change was of relevance for the task (e.g., due to the exclusion task instruction). Similarly, the contrast of perceptually identical and changed items was assumed to affect ERPs of retrieval in children. As children's reading capabilities are more heterogeneous in comparison to adults, developmental differences in behavioral performance or electrophysiological indexes of episodic memory for words might be attributable to differences in reading skills. Furthermore, behavioral measures of memory performance indicate a typically lower performance for children than for adults. In order to rule out that low memory performance is responsible for the lack of familiarity-related ERP effects, we instead chose pictorial stimuli for the studies reported in this dissertation.

In the following sections, I will present three studies conducted during my PhD studies that were part of a research project funded by the German Research Foundation [grant number 188808856] in which the developmental trajectories of episodic memory retrieval as well as executive control were investigated in longitudinal studies. In these studies, participants engaged in a set of two tasks, one was a retrieval task described in the studies of the dissertation. The other task was a task-switching paradigm in which participants saw numbers consisting of either one or three digits that were either all ones or threes (i.e., "1", "3", "111", or "333"). At the beginning of each trial, there was a cue indicating whether participants had to count the digits or instead identify the presented digits (Czernochowski, 2014, 2015). In Study 1, we evaluated the adopted and modified stimuli and the viability of the paradigm in an adult sample (Haese & Czernochowski, 2015), in particular whether the perceptual modifications would elicit effects comparable to those found in similar paradigms in existing literature (e.g., stimuli with changes in color or shape, Ecker, Zimmer, et al., 2007a; changes in the outline color of a stimulus, Groh-Bordin, Zimmer, & Ecker, 2006; changes in color in images resembling Ishihara plate stimuli, Groh-Bordin et al., 2005). As the LPN has been shown to reflect recollection-related source-specifying retrieval processes (Mecklinger et al., 2007), an evaluation of pre-response time windows for a comparison between stimulus-locked and response-locked ERP averages was considered. In addition, the results of this study would allow us to check if the paradigm had to be adopted before administering it to a developmental sample, for instance if behavioral performance was too low or if ERP effects of memory retrieval were unobtainable with the paradigm. In Study 2, we administered the same paradigm to children in primary school to investigate if our hypothesis that perceptual modifications were key to eliciting ERP correlates of familiarity in children (Haese & Czernochowski, 2016); here, adults' data collected in Study 1 served as the control group for this evaluation. The results of both studies sparked our interest in understanding which paradigm changes were responsible for the results previously rarely reported in existing literature, so we slightly modified the paradigm. We removed a previous incidental encoding phase as no ERP effects of familiarity were observed after incidental encoding in children (see Study 2). This allowed us in turn to use more items in the paradigm as described in Study 3 (Haese & Czernochowski, under review). To our surprise, the ERP correlates observed were different to those observed in Studies 1 and 2, so we refined our statistical analysis and used principal component analysis to objectively determine the selection of time windows for ERP analyses. This matter and its implication will be discussed in detail in the corresponding section.

Study 1

Sometimes we have to intentionally focus on the details:

Incidental encoding and perceptual change decrease recognition memory performance and the ERP correlate of recollection[2]

Abstract

Prior studies suggest that memory retrieval is based on two independent processes: Recollection and familiarity. Here, we investigated the role of incidental and intentional encoding, and specifically whether perceptual changes between study and test affects behavioral and electrophysiological correlates of both retrieval processes. During retrieval, participants distinguished between identical and changed exemplars as well as novel distractors. Following incidental encoding, participants had difficulty identifying changed exemplars; item and feature recognition increased after intentional encoding, in particular for changed exemplars. Reflecting this increase in memory performance, the ERP correlate of recollection was larger after intentional encoding and for identical item repetitions, whereas the ERP correlate for familiarity was largely unaffected. Pre-response old/new effects corresponding to later aspects of recollection (700 – 1000 ms relative to stimulus onset) were larger in response- compared to stimulus-locked averages, but also of similar magnitude for identical and changed exemplars. These results corroborate previous findings suggesting that the electrophysiological signature of recollection is modulated as a function of memory performance. The role of task characteristics and material retrieved from memory for modulations in familiarity-based retrieval processes is discussed.

Introduction

When we go shopping for items we rarely use, we may find ourselves unable to remember which brand we bought last time. However, similar products are often found next to each other, so we need to retrieve specific features from memory to identify the product we chose last time – for instance the color of the bottle, the shape of it, or even the position in the shelf. According to numerous investigations, there are two independent processes supporting recognition memory retrieval in situations like that: Familiarity and recollection (Yonelinas, 2002). Familiarity-based retrieval supports the distinction between items encountered previously and new items, although details about the previous encounter are not retrieved along with the item itself. By contrast, recollection-based retrieval is an effortful and slower process, leading to highly confident memory

2 As a part of the cumulative dissertation, this section has been published in a peer-reviewed journal: Haese, A. and Czernochowski, D. (2015). Brain and Cognition (96). 1-11. Tables given in the Supplementary materials of the published article were removed from this thesis for the sake of brevity.

judgments often based on additional details retrieved. Both processes can be dissociated based on behavioral characteristics (e.g., separating responses on the basis of reaction times, subjective reports of remembering or knowing, or contextual features remembered; for a review, see Yonelinas, 2002). In addition, event-related potentials (ERPs) allow to examine neural correlates of both processes at the speed in which they unfold. Familiarity is associated with more positive amplitudes for old compared to new items at frontal electrode sites (about 300 – 500 ms; e.g., Rugg & Curran, 2007), whereas recollection is associated with a parietal positivity for old compared to new items (about 500 – 800 ms; e.g., Wilding, 2000).

When additional details associated with studied items (e.g., word plurality, presentation modality, source) are remembered, the ERP correlate of recollection has been found to be larger (Curran, 2000; Curran & Cleary, 2003; Trott, Friedman, Ritter, & Fabiani, 1997; Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Vilberg, Moosavi, & Rugg, 2006; Wilding, 1999, 2000; Wilding & Rugg, 1997). By contrast, for the ERP correlate of familiarity, a more heterogeneous pattern of results has been reported, putatively at least in part a result of the different methodological approaches employed to investigate ERP correlates of recognition memory. When item attributes are modified between study and test phases – for instance, items might be displayed in a different size, orientation, or color at test compared to their original format – these changed exemplars sometimes elicited a reduced (Ecker, Zimmer, et al., 2007a; Tsivilis et al., 2001) or no ERP correlate of familiarity (Curran & Doyle, 2011, Experiment 2; Groh-Bordin et al., 2005). However, in other studies changing stimulus features between study and test did not affect the frontal old/new effect (Curran, 2000; Curran & Cleary, 2003; Curran & Dien, 2003; Czernochowski et al., 2005; Ecker et al., 2009; Friedman et al., 2005; Wiegand et al., 2010). Zimmer and Ecker (2010) suggest that these inconsistencies can be explained by investigating subtle differences in stimulus attributes or task instructions: For instance, in some of the former studies, participants were asked to differentiate perceptually identical from perceptually changed items. In some of the latter studies, by contrast, perceptual features were not relevant for task execution, as perceptually changed and identical items both received an "old" response. Thus, when perceptual features are emphasized in a task, perceptual aspects of familiarity may become prominent; however, when perceptual features are less relevant for participants, familiarity may be based, to a larger extent, on conceptual features (e.g., more abstract semantic item content).

In addition to perceptually- and conceptually-driven task demands during retrieval (Zimmer & Ecker, 2010), the nature of encoding operations can also influence subsequent retrieval. Hence, the studies cited above can also be compared with respect to the tasks performed during the study phases: Previous memory studies used either (1) explicit instructions to focus on *specific* perceptual features during encoding which would become relevant during memory retrieval (e.g., Curran, 2000; Curran & Cleary, 2003; Ecker, Zimmer, et al., 2007a), (2) explicit instructions about a subsequent memory test, but not regarding a potential distinction between old items and similar lures (e.g., Ecker et al., 2009; Ecker, Zimmer, & Groh-Bordin, 2007b; Groh-Bordin et al., 2006) or (3) incidental encoding in which participants were not aware of any subsequent test phase (e.g., Groh-Bordin et al., 2005; Küper, Groh-Bordin, Zimmer, & Ecker, 2012; Tsivilis et al., 2001; Wiegand et al., 2010). In addition, participants in previous studies sometimes completed multiple study-test cycles, including a practice of the test format before the learning phase, and were either explicitly instructed (e.g., Czernochowski et al., 2005) or could *infer* which aspects of the stimuli were relevant following the first test trials without explicit instruction. This point applies especially to those studies in which only a single attribute is modified (for instance plurality, color, size, left/right orientation, presentation modality; e.g., Curran & Doyle, 2011; Nyhus & Curran, 2012; Ranganath & Paller, 1999). After the first test phase, participants are likely to strategically adapt their attentional focus towards relevant stimulus features during subsequent encoding trials. Hence in the present study, incidental (participants are not informed about a subsequent test phase) and intentional (participants know about a subsequent test phase and hence intentionally encode items) study-test blocks were directly compared in order to systematically assess retrieval with and without perceptually fine-tuned encoding processes. Notably, participants could not predict which feature dimensions (e.g., size, color, specimen of object shown, orientation) would change between study and test phases to ensure that participants could not focus on one specific item feature in the second, intentional, encoding phase[3]. Thus, we assessed (1) to what extent details of an object with rich perceptual features can be recognized in an unexpected recognition test and (2) whether performance further increases when stimuli are memorized intentionally[4].

Moreover, existing studies vary in the response requirements during retrieval: In some studies, "old" responses are given to both identical and changed items (e.g., Curran & Dien, 2003; Curran & Doyle, 2011; Ecker et al., 2009; Groh-Bordin et al., 2005; Küper et al., 2012; Ranganath & Paller,

---

3 Previous studies (e.g., Groh-Bordin et al., 2005; Küper et al., 2012) also kept participants from focusing on single item features. In these studies, participants were not asked to specifically memorize item features and were neither informed about feature changes. Also, they only had one test phase, so participants could not adapt their encoding strategy in any subsequent study phase. In contrast to most of the reviewed studies our paradigm investigated the difference between incidental and intentional encoding and thus had to rule out the potential confound of a total strategy shift: To maintain comparable cognitive processes during study in both phases, in our paradigm it was not obvious which perceptual features of an item would be changed; participants could not selectively attend a single (predictable) item feature and thus process items on an entirely different level (e.g., by verbalizing "flower, blue").

4 Note that previous studies compared retrieval after incidental and intentional encoding tasks in an oddball or related paradigms (e.g., see Cycowicz & Friedman, 1999, 2007; van Hooff, 2005). These papers focus on different theoretical and methodological aspects (e.g., targets are less frequent than standard stimuli and studied items are learned to criterion).

1999, general test blocks; Tsivilis et al., 2001). In others, "new" responses are given to both changed items and novel distractors (e.g., Curran, 2000; Curran & Cleary, 2003; Ecker, Zimmer, et al., 2007a, Experiment 2; Ranganath & Paller, 1999, specific test blocks). Furthermore, memory for perceptual features can be assessed by sequential prompting (first old/new discrimination, then identical/changed discrimination; e.g., Ecker et al., 2009; Ecker, Zimmer, et al., 2007a; Groh-Bordin et al., 2006; Wilding et al., 1995) or by offering participants all three options (i.e., same/different/new) at once (e.g., Bader, Mecklinger, Hoppstädter, & Meyer, 2010; Ecker, Zimmer, et al., 2007b; Nyhus & Curran, 2012). As changed items are not mapped to either identical or new items, this response format allows a more detailed classification of responses.

Finally, most ERP studies on memory retrieval focus on stimulus-locked averages (for exceptions, see de Chastelaine, Friedman, & Cycowicz, 2007; Johansson & Mecklinger, 2003). Time-locking the averages to the response onset, however, allows to evaluate processes more closely related to decision-making than to stimulus evaluation. The late parietal negativity (LPN) for old (versus new) items, for instance, has been found while or even after memory judgments were made regardless of old/new status of the item (Mecklinger et al., 2007; for a review, see Johansson & Mecklinger, 2003). This component has been associated with effortful search for and/or retrieval of an item's specific feature conjunction and, more generally, response conflict. Its magnitude putatively reflects the effort dedicated to recollective search and is sensitive to the amount of contextual information retrieved during source judgment (Friedman et al., 2005; Mecklinger et al., 2007; Rugg, Schloerscheidt, & Mark, 1998). Sharing temporal and topographical characteristics with the recollection-related ERP component, these two old/new effects can overlap with opposite polarity, attenuating each other. De Chastelaine et al. (2007) compared stimulus-locked and response-locked ERP waveforms and found no reliable difference of LPN magnitude between targets and non-targets, i.e. changed exemplars that had to be categorized as "new", in stimulus-locked averages. Analyzing response-locked averages, however, the old/new difference was larger for targets than for non-targets. The parietal negativity found for the non-targets was taken to reflect increased response inhibition. Hence, comparing stimulus- and response-locked averages helped to disentangle the cognitive processes during this time, as the LPN temporarily overlaps with later aspects of the ERP correlate of recollection (de Chastelaine et al., 2007).

Taken together, we expected behavioral recognition performance to improve after intentional (and perceptually fine-tuned) encoding for both general old/new and specific identical/changed discrimination. We expected participants to engage in both familiarity and recollection, as indexed by their respective ERP correlates. In line with behavioral improvement, after intentional encoding we expected the parietal old/new effect to be larger, especially for identical items (Ecker, Zimmer, et al., 2007a). With respect to familiarity, mixed findings are reported in the literature. We evaluated

Zimmer and Ecker's (2010) prediction that the ERP correlate for familiarity should be larger for identical items than for changed items due to the perceptual weight of our task (a pattern of results reported by Curran & Doyle, 2011, Experiment 2; Ecker, Zimmer, et al., 2007a; Groh-Bordin et al., 2005; Tsivilis et al., 2001). Lastly, we investigated the LPN resulting from perceptually identical, changed and new items, as both the different response format – three response options at the same time instead of a sequential (first old/new, then identical/changed) prompt – and the high relevance of features (i.e. source-specifying attributes) are likely to affect response inhibition and, thus, this ERP correlate. For a more detailed investigation of the cognitive processes underlying the respective time window, we compared stimulus-locked and response-locked averages, as demonstrated by earlier studies (de Chastelaine et al., 2007; Johansson & Mecklinger, 2003).

Method

Participants

Twenty-two right-handed undergraduate students, recruited on Heinrich-Heine-University campus, participated in our study, and reported to be free from neurological or psychiatric disorders. As compensation, they received course credit or monetary compensation. Data from four participants could not be analyzed due to failure to follow instruction (n = 1), insufficient amount of artifact-free EEG trials (n = 2), or low performance level (more than two standard deviations below group mean; n = 1). Thus, the final sample consisted of 18 participants (20 – 23 years, mean 21.4; 16 women).

Material

For our study, we selected pictures from the Rossion and Pourtois (2004) dataset. To avoid distinctiveness effects, we only included items common and contemporary in Germany. Since participants were asked to distinguish pictures from altered versions, we also excluded perceptually similar items (for instance bee and fly). We created alternate versions for 80 of these images by changing certain perceptual features of each stimulus or pairing items that show different exemplars of the same object (quantity, size, orientation, color, specimen of the presented object; see Fig. 2). Note that several items were changed in more than one dimension to increase discriminability. To increase our item pool, we also selected cliparts from CorelDRAW® X4 which met these criteria and were overall similar to the Rossion and Pourtois dataset. In total, we used 280 images, 80 of which were changed exemplars.

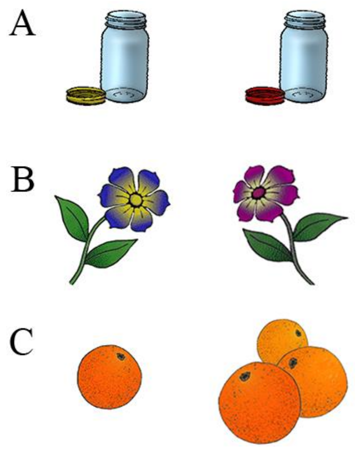

Figure 2. Sample Stimuli. These images illustrate the perceptual changes we used in this study (A: color; B: orientation and color; C: quantity and orientation). Note that we did not necessarily change only one dimension.

Procedure

The experiment was part of a multi-experiment session lasting approximately 2.5 to 3 hours. After signing the consent form, participants performed selected subtests of two test batteries, Test of Attentional Performance for younger children (Zimmermann, Gondan, & Fimm, 2004) and Wechsler-Intelligenztest für Erwachsene (German version of Wechsler Adult Intelligence Scale; von Aster, Neubauer, & Horn, 2006). They were prepared for EEG measurement and then completed two experiments (a task-switching paradigm with numerical stimuli and the memory paradigm reported here). The order of both experiments was counterbalanced across participants.

The memory paradigm consisted of four blocks: First, incidental encoding and a surprise recognition test, then intentional encoding and an expected recognition test. During the study phase, items were presented individually at the center of fixation. Participants were asked to decide whether each item was more commonly found indoors or outdoors (incidental study phase). In both test phases, three types of stimuli were presented: 40 novel distractors, 40 identical repetitions of studied items, and 40 perceptually changed repetitions of the studied items. Participants decided whether each item was "same", "different" or "new" (using index and middle finger of one hand for both "old" categories and the other index finger for responding "new"; the association of old and new categories to right and left hand were counterbalanced across participants). Immediately prior to the study phase, participants practiced the tasks with eight study items; immediately before the first retrieval phase (i.e., after incidental encoding), participants practiced the task with 12 test items (four "same", "different" and "new"). During the intentional study phase, participants were instructed to memorize the images while still performing the indoors-outdoors categorization task. In the second test phase, 40 identical items from the incidental phase were used again; 20 of these were presented again as identical exemplars, whereas the remaining 20 were replaced by changed exemplars, keeping the proportion of same and different items among these re-presented items constant.[5] During the study phases, all stimuli were presented for 1s to keep presentation times equal across stimuli; participants were informed that indoor-outdoor responses could be given after stimulus offset only. During the test phases, stimuli were presented until response onset. Whenever participants needed more than 5 seconds for a response, they were encouraged to answer more spontaneously. Between study and test blocks, rehearsal was minimized by engaging participants in conversation (two minutes between study and test phase, five minutes between incidental and intentional blocks). All pictures were preceded by a fixation cross, presented for 1000 ms.

5 In an initial step, we compared ERP correlates of familiarity and recollection after intentional encoding between the 20 items studied once (only during intentional encoding) and the 20 items studied twice (during incidental and intentional encoding). As they did not differ, we collapsed across these item types to increase the amount of trials.

Behavioral Analyses

In order to evaluate memory performance, we calculated corrected recognition scores (Hit rate – False Alarm rate; c.f. Snodgrass & Corwin, 1988) as a general index of old/new discrimination, i.e. regardless of whether an item was specified as same or different. In addition, we calculated the proportion of correct feature identifications among correct "old" responses, that is "same" responses to same items and "different" responses to different items. To compare performance in both measures between identical and perceptually changed items and after incidental and intentional study phases, we calculated a Repeated Measures ANOVA with the factors Phase (Incidental vs. Intentional Encoding) and Item Type (Same vs. Different). All behavioral and ERP analyses were computed with SPSS 22.0.0 ($\alpha = .05$).

EEG Recording and Data Preprocessing

We recorded EEG with active Ag/AgCl electrodes at 27 positions according to the extended 10-20 system: FP1, FP2, AF7, AF3, AFz, AF4, AF8, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, CP1, CP2, P7, P3, Pz, P4, P8, O1, O2 (reference FCz was restored after offline re-referencing to linked mastoids). Electrodes above and below the right eye and F9 and F10 measured EOG. We kept impedances below 25 kΩ and recorded data at a sampling rate of 500 Hz (A-D converted with 16 bit resolution). Offline, we applied a Butterworth band-pass filter (0.1 Hz – 30 Hz, 24 dB/oct) and corrected ocular movement by applying an ICA-based correction (as implemented in the Vision Analyzer 2.0.3; BrainProducts GmbH, Gilching, Germany). Finally, we employed a semi-automatic procedure to detect and reject trials still containing uncorrected artifacts (e.g., muscular activity). Artifacts were automatically detected with the following criteria: (1) The gradient of EEG amplitudes in any electrode exceeded 20 µV/ms, (2) the difference between maximum and minimum exceeded 75 µV during an interval of 200 ms, and (3) activity fell below 0.5 µV during an interval of 100 ms. These events were evaluated based on visual inspection. The spherical spline interpolation of Perrin, Pernier, Bertrand, and Echallier (1989) was applied to interpolate electrodes (up to 3 per participant) that could not be corrected otherwise. In order to investigate effects of successful memory retrieval, we analyzed correct responses in each test phase. Epochs lasted from -100 ms prior to stimulus onset until 3000 ms. Data were baseline corrected using the first 100 ms. We compared feature hits (i.e., "same" responses to same and "different" responses to different item repetitions) as well as correct rejections. Responses given after 3000 ms were excluded from ERP analysis (approximately 3 % of all trials). Mean trial numbers and ranges for each condition are given in Table 1.

Table 1. Mean trial numbers of the analyzed conditions.

Response category	Retrieval after incidental encoding		Retrieval after intentional encoding	
	mean	range	mean	range
Correct Rejection (item type new, response "new")	33.1	26 – 39	31.3	22 – 37
Feature Hits same (item type same, response "same")	28.7	21 – 40	30.7	23 – 37
Feature Hits different (item type different, response "different"	20.7	12 – 31	28.3	18 – 36

ERP Analyses

For comparison of ERP differences following both incidental and intentional encoding we chose a grid of 3 x 3 electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) and computed Repeated Measures ANOVAs with the factors Laterality (Left vs. Midline vs. Right), Anterior-Posterior (Frontal vs. Central vs. Parietal) and Item Type (Feature Hits Same vs. Feature Hits Different vs. Correct Rejections). To directly compare same and perceptually changed items and phase effects, we performed a corresponding Repeated Measures ANOVA with the factors Phase (Incidental vs. Intentional Encoding), Item Type (Same vs. Different), and the factors Laterality and Anterior-Posterior for each time window. The first analysis tested for general old/new effects, whereas the second one further specified these effects by contrasting Incidental versus Intentional Encoding and Same versus Different. To dissociate frontal and parietal ERP effects associated with familiarity and recollection, respectively, we conducted subsidiary analyses at frontal, central, and parietal electrode sites. Only main effects or interactions with the factor Item Type are reported for the sake of brevity.

To prevent any bias for any of the three response categories, new items comprised one third of all items in the test phases. As performance in the second test phase was expected to increase relative to the first, these distractors may be particularly salient in the second test phase. To avoid any potential confound of salience in the ERP waveforms, we used correct rejections from the first phase for all ERP analyses (for a similar approach, see Czernochowski et al., 2009)[6]. Feature hits

6 As expected, behavioral performance was higher after intentional than after incidental encoding. Similar to Cycowicz and Friedman (2007), who reported a larger P3 at parietal electrodes when a deviant tone was memorized, we found more positive amplitudes for the ERP averages of new items after intentional compared to incidental encoding at parietal electrodes in a time window from 300 – 700 ms, $F(1,17) = 15.04$, $p < .01$, $\eta_p^2 = .47$. This, in turn, would attenuate old/new effects. To avoid this potential confound, we compared

for same and different items were each compared to correct rejections in planned contrasts. For all analyses we chose two time windows, 300 – 500 ms and 500 – 700 ms, corresponding to familiarity and recollection old/new effects, respectively. In addition, we evaluated LPN-related effects (stimulus-locked) in the time window 700 – 1000 ms and the corresponding time-window for response-locked averages, -600 – -300 ms relative to the response onset. Greenhouse-Geisser correction (Jennings & Wood, 1976) was applied where necessary. Uncorrected degrees of freedom are reported along with ε-values and with corrected *p*-values for these instances.

Results

Behavioral Data

We found higher old/new performance for same (.90) relative to different (.78) items, $F(1,17) = 38.44$, $p < .001$, $\eta^2_p = .69$, and after intentional (.87) versus incidental (.82) encoding, $F(1,17) = 9.97$, $p < .01$, $\eta^2_p = .37$. As illustrated in Figure 3, this effect tended to be larger for different items: $F(1,17) = 4.08$, $p = .06$, $\eta^2_p = .19$. In a second step, we evaluated the proportion of correctly identified features. After incidental encoding, 77 % of correct old responses were correctly identified as perceptually same or different (i.e., feature hits), whereas after intentional encoding this percentage increased to 89 %, $F(1,17) = 53.05$, $p < .001$, $\eta^2_p = .78$. Features were more often correctly recognized for same (88% feature hits) than for different items (78% feature hits), $F(1,17) = 18.39$, $p < .001$, $\eta^2_p = .52$; this effect was larger after incidental encoding: $F(1,17) = 6.28$, $p < .05$, $\eta^2_p = .27$. Taken together, both general old/new discrimination and specific same/different discrimination improved after intentional encoding and for perceptually identical stimuli. The effect of intentional encoding was larger for different items, in particular with respect to feature identification.

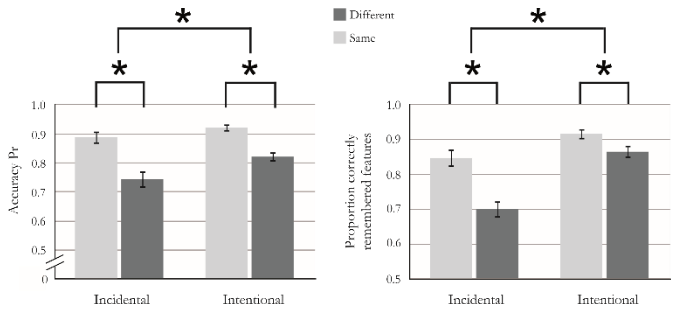

Figure 3. Behavioral indices of old/new (left) and same/different (right) discrimination. Behavioral performance after incidental and intentional encoding for identical (light gray) and changed (dark gray) exemplars. Memory performance was better after intentional encoding and for identical exemplars; in particular, after intentional encoding retrieval of features was higher for different exemplars. Note that Pr values of 0 and feature recognition scores of .5 reflect guessing. Error bars represent standard errors of the mean, asterisks indicate significant post-hoc comparisons.

averages of old items with correct rejections from the first phase, where new items were less distinct due to the lower behavioral performance.

ERP results

Figure 4 illustrates topographically widespread old/new effects across all time windows: Same items were associated with more positive amplitudes than different items, and elicited somewhat larger old/new effects than different items after intentional compared to incidental encoding. Old/new effects were largest at midline and right electrode sites (see Tables 2 – 5).

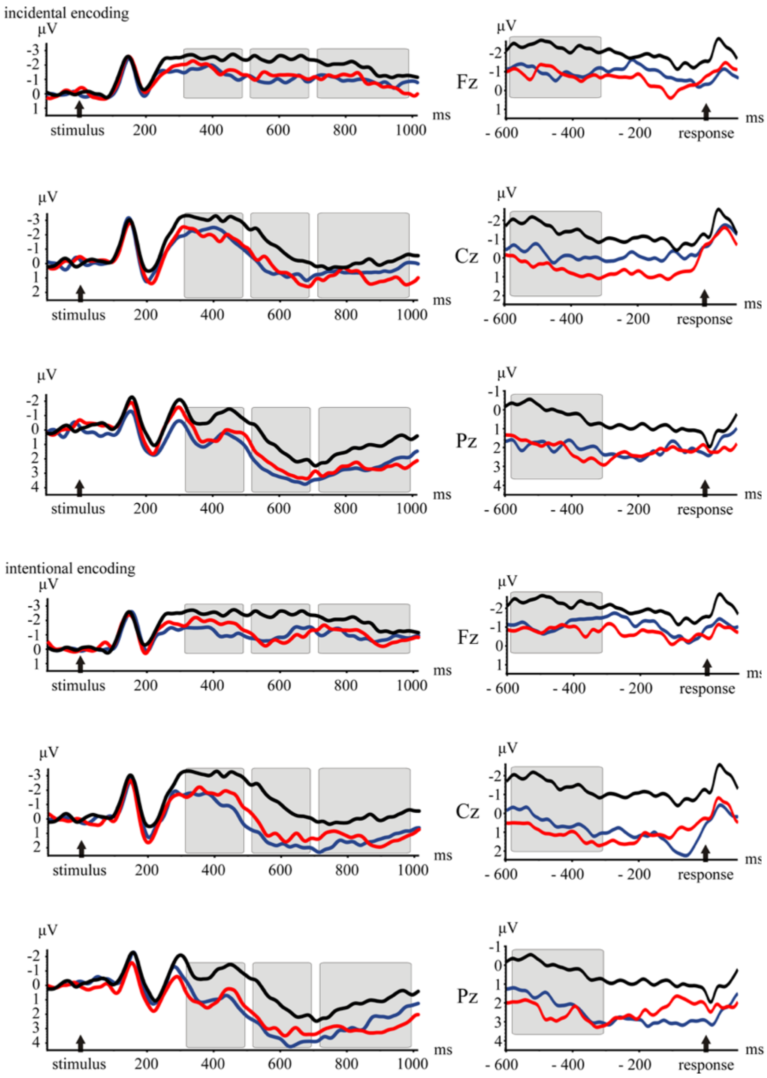

Figure 4. ERP old/new effects following incidental and intentional encoding, for stimulus- (left) and response-locked (right) averages. ERP waveforms after incidental (top) and intentional (bottom) encoding of feature hits for same (blue) and different (red) items, and for correct rejections (after incidental encoding; black line). Note the difference in scaling for the y-axes. About 250 ms after stimulus onset, ERPs associated with old items elicited more positive amplitudes across the analyzed electrode sites. In response-locked averages (corresponding to the 700 – 1000 ms time window based on mean RTs), old/new effects were larger. Gray boxes mark the time windows used for analyses.

Familiarity-related effects (300 – 500 ms; Table 2)

After incidental encoding, same and different feature hits elicited more positive amplitudes than correct rejections, $F(2,34) = 16.09$, $p < .001$, $\eta^2_p = .39$. Follow-up analyses showed that this effect was largest at fronto-central (same) and central (different) electrode sites. After intentional encoding, same and different feature hits also elicited more positive amplitudes than correct rejections, $F(2,34) = 15.68$, $p < .001$, $\eta^2_p = .48$. Follow-up analyses showed that this effect was largest at central electrode sites for both item types (frontal: $\eta^2_p = .26$; central: $\eta^2_p = .34$; parietal: $\eta^2_p = .21$). Comparing the effects of Phase and Item Type directly, we found no reliable difference between same and different items, $p > .20$, but intentional encoding tended to elicit more positive ERP amplitudes than incidental encoding ($p = .07$; Table 6).

Table 2. Overview of ERP results between 300 and 500 ms

effect (df_1,df_2)	incidental			intentional		
	ε	F	η^2_p	ε	F	η^2_p
Item type (2,34)		16.09***	.39		15.68***	.48
same vs. CR (1,17)		15.93***	.48		21.49***	.56
different vs. CR (1,17)		20.32***	.54		16.77***	.50
Item type X AP (4,68)		—			—	
frontal (2,34)		5.81**	.26		6.55**	.28
same vs. CR (1,17)		9.68**	.36		10.53**	.38
different vs. CR (1,17)		6.42*	.27		5.50*	.25
central (2,34)		8.81***	.34		15.75***	.48
same vs. CR (1,17)		12.23**	.42		21.28***	.56
different vs. CR (1,17)		22.29***	.57		15.51**	.48
parietal (2,34)		4.64*	.21		8.22**	.33
same vs. CR (1,17)		7.68*	.31		13.27**	.44
different vs. CR (1,17)		5.68*	.25		8.31*	.33
Item type X LAT (4,68)		—			2.58* [a]	.13
Item type X LAT (4,68)		—			—	
Item type X LAT X AP (8,136)		—			—	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; [a] Pz > P3 > P4

Recollection-related effects (500 – 700 ms; Table 3)

After incidental encoding, same and different feature hits elicited more positive amplitudes than correct rejections, $F(2,34) = 13.89$, $p < .001$, $\eta^2_p = .45$. Subsidiary analyses showed that this effect was slightly larger at central electrode sites for both same and different items than at frontal and parietal electrode sites (frontal: $\eta^2_p = .31$; central: $\eta^2_p = .42$; parietal: $\eta^2_p = .31$). After intentional encoding, same and different feature hits also elicited more positive amplitudes than correct rejections, $F(2,34) = 18.09$, $p < .001$, $\eta^2_p = .52$. Further analysis showed that this effect was pronounced at centro-parietal electrode sites (frontal: $\eta^2_p = .30$; central: $\eta^2_p = .54$; parietal: $\eta^2_p = .41$); different items were associated with more positive amplitudes at central than at frontal and parietal electrode sites (frontal: $\eta^2_p = .36$; central: $\eta^2_p = .53$; parietal: $\eta^2_p = .29$). While we found smaller effects at left electrode sites for different items (left: $\eta^2_p = .37$; midline: $\eta^2_p = .54$; right: $\eta^2_p = .49$), same items showed no lateralization. Comparing phase and item type effects, we found that same items were associated with more positive amplitudes than different items, $F(2,34) = 6.54$, $p < .05$, $\eta^2_p = .28$. An interaction Phase X Anterior-Posterior indicated that at central electrode sites, intentional encoding elicited more positive amplitudes than incidental encoding, $F(4,68) = 3.36$, $p < .05$, $\eta^2_p = .17$ (see Table 6).

Table 3. Overview of ERP results between 500 and 700 ms

effect (df_1,df_2)	incidental			intentional		
	ε	*F*	η^2_p	ε	*F*	η^2_p
Item type (2,34)		13.89***	.45		18.09***	.52
same vs. CR (1,17)		17.79***	.51		26.01***	.61
different vs. CR (1,17)		15.88***	.48		16.78***	.50
Item type X AP (4,68)		—			—	
frontal (2,34)	.63	7.70**	.31		7.40**	.30
same vs. CR (1,17)		8.41**	.33		7.99*	.32
different vs. CR (1,17)		8.79**	.34		9.72**	.36
central (2,34)		12.20***	.42		19.58***	.54
same vs. CR (1,17)		16.21***	.49		26.00***	.61
different vs. CR (1,17)		12.51**	.42		19.47***	.53
parietal (2,34)		7.60**	.31		11.97***	.41
same vs. CR (1,17)		10.75**	.39		24.51***	.59
different vs. CR (1,17)		8.73**	.34		6.87*	.29
Item type X LAT (4,68)		—			2.58* [a]	.13
Item type X LAT X AP (8,136)		—			—	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; [a] midline > left = right

Stimulus-locked LPN effects (700 – 1000 ms; Table 4)

Stimulus-locked, we found reliable old/new effects after incidental encoding for same and different items, $F(2,34) = 4.78$, $p < .05$, $\eta^2_p = .22$. Further analyses revealed that these old/new effects were only reliable at central electrode sites, $F(2,34) = 4.41$, $p < .05$, $\eta^2_p = .21$. After intentional encoding, we found old/new effects for same and different items, $F(2,34) = 5.46$, $p < .01$, $\eta^2_p = .24$. Subsidiary analyses showed that these effects were only reliable at central, $F(2,34) = 7.28$, $p < .01$, $\eta^2_p = .30$, and parietal electrode sites, $F(2,34) = 4.38$, $p < .05$, $\eta^2_p = .21$, and only at midline and right, but not at left electrode sites, $F(4,68) = 3.33$, $p < .05$, $\eta^2_p = .16$. Comparing phase and item type, we found no reliable differences (all *p*s > .28).

Table 4. Overview of ERP results between 700 and 1000 ms

effect (df_1,df_2)	incidental			intentional		
	ε	*F*	η^2_p	ε	*F*	η^2_p
Item type (2,34)		4.78*	.22		5.46**	.24
same vs. CR (1,17)		7.82*	.32		8.63**	.34
different vs. CR (1,17)		4.96*	.23		6.72*	.28
Item type X AP (4,68)		—			—	
frontal (2,34)		—			—	
central (2,34)		4.41*	.21		7.28**	.30
same vs. CR (1,17)		7.17*	.30		12.51**	.42
different vs. CR (1,17)		4.76*	.22		7.78*	.31
Item type X LAT (4,68)		2.73* [a]	.14		—	
parietal (2,34)		—			4.38*	.21
same vs. CR (1,17)		—			7.18*	.30
different vs. CR (1,17)		—			5.70*	.25
Item type X LAT (4,68)		—			3.10* [b]	.15
Item type X LAT (4,68)		—			3.33* [c]	.16
Item type X LAT X AP (8,136)	.48	2.28*	.12		—	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; [a] C4 > Cz, C3 n.s.; [b] P4 > Pz, P3 n.s.; [c] midline = right, left n.s.

Response-locked LPN-related effects (-600 – -300; Table 5)

Response-locked, we also found reliable old/new effects after incidental encoding, $F(2,34) = 11.21$, $p < .001$, $\eta^2_p = .40$. Further analyses revealed effects for both item types to be topographically widespread and slightly larger at central electrode sites (frontal: $\eta^2_p = .27$; central: $\eta^2_p = .42$; parietal: $\eta^2_p = .26$). After intentional encoding, we found reliable old/new effects, $F(2,34) = 10.19$, $p < .01$, $\eta^2_p = .38$, at central, $F(2,34) = 11.90$, $p < .001$, $\eta^2_p = .41$, and parietal electrode sites, $F(2,34) = 8.23$, $p < .01$, $\eta^2_p = .33$. Comparing phase and item type, we also found no reliable differences (all *p*s > .10).

Table 5. Overview of response-locked ERP results between -600 and -300 ms

effect (df_1,df_2)	incidental			intentional		
	ε	F	η^2_p	ε	F	η^2_p
Item type (2,34)		11.21***	.40	.76	10.19**	.38
same vs. CR (1,17)		15.89***	.48		17.60***	.51
different vs. CR (1,17)		13.86**	.45		11.55**	.40
Item type X AP (4,68)		—			—	
frontal (2,34)		6.14**	.27		—	
same vs. CR (1,17)		9.89**	.37		—	
different vs. CR (1,17)		6.09*	.26		—	
central (2,34)		12.40***	.42		11.90***	.41
same vs. CR (1,17)		13.12**	.44		16.27***	.49
different vs. CR (1,17)		15.94***	.48		14.37**	.46
Item type X LAT (4,68)		5.28*** [a]	.24		2.79* [b]	.14
parietal (2,34)		6.00**	.26	.70	8.23**	.33
same vs. CR (1,17)		8.57**	.34		20.25***	.54
different vs. CR (1,17)		8.75**	.34		9.12**	.35
Item type X LAT (4,68)		—			4.78** [c]	.22
Item type X LAT X AP (8,136)	.53	2.75*	.14		—	

Note. * $p < .05$, ** $p < .01$, *** $p < .001$; [a] C4 > Cz = C3; [b] C4 = Cz > C3; [c] midline > right > left

Table 6. Overview of differences between same and different items in all time windows

effect (df_1,df_2)	300 – 500			500 – 700			700 – 1000			-600 – -300 (response-locked)		
	ε	F	η^2_p	ε	F	η^2_p	ε	F	η^2_p	ε	F	η^2_p
Phase (1,17)		—			—			—			—	
Item type (1,17)		—			6.54*	.28		—			—	
LAT (2,34)	.58	8.79**	.34	.56	10.28**	.38	.54	11.19**	.40	.58	9.64**	.36
AP (2,34)		15.37***	.48		—			5.26*	.24		5.62**	.25
AP X Phase (2,34)		—			3.36*	.17		—			—	
AP X Item type (2,34)		—			—			—			—	
Frontal												
LAT (2,34)					3.84*	.18						
Central												
Phase (1,17)					5.34*	.24						
Item type (1,17)					4.77*	.22						
Parietal												
Item type (1,17)					8.72**	.34						

Note. * $p < .05$, ** $p < .01$, *** $p < .001$

Discussion

The present study evaluated ERP correlates of familiarity and recollection following incidental and intentional encoding. During the test phase, participants were asked to indicate whether perceptual features were repeated between study and test phases (i.e. same exemplars), whether perceptual features had changed between study and test phases (i.e. different exemplars) or whether items were presented for the first time (i.e. new foil items). Specifically, we addressed (1) to what extent perceptual details are retrieved at an unexpected memory test and (2) whether advance knowledge about the relevance of perceptual details modulates ERP correlates of familiarity and recollection between the test phases. In addition, we evaluated (3) decision-related memory processes (i.e. LPN) as reflected in stimulus- as well as response-locked averages. The present results suggest that (1) following incidental encoding, participants have difficulty identifying changed exemplars (2) only the ERP correlate of recollection was larger following intentional compared to incidental encoding and (3) response-related ERPs were similar for changed and identical exemplars; old/new effects were (a) larger in pre-response than in stimulus-locked averages and (b) larger in terms of effect sizes after intentional versus incidental encoding. These results will be discussed in turn below.

For both identical and changed exemplars, overall memory performance was larger after intentional encoding; notably, feature identification of changed exemplars clearly improved (from .70 to .87). In line with these results, earlier studies reported generally increased memory performance after intentional encoding (Block, 2009; Hyde & Jenkins, 1973), and improved memory performance when an item is presented identically in the test phase (e.g., for pictures: Czernochowski et al., 2005; Ecker, Zimmer, et al., 2007b; Küper et al., 2012; for words: Goldinger, 1996; Hintzman, 2002; Senkfor & Van Petten, 1998; Snodgrass, Hirshman, & Fan, 1996; Wiegand et al., 2010; Wilding et al., 1995; for novel melodies: Lange and Czernochowski, 2013). It is likely that a larger (i.e., 100%) overlap of perceptual features for identical compared to changed items supports retrieval of identical exemplars to a larger extent than retrieval of changed items (c.f., Snodgrass et al., 1996). To the best of our knowledge, our study is the first to report that intentional encoding can lead to a higher performance specifically for perceptually changed items, whereas the performance for identically presented items remained comparable in this study. This is likely due to a fine-tuned attentional focus to perceptual details in the intentional study phase, whereas during incidental encoding participants presumably processed items on a more conceptual level only[7]. Together, this pattern of results suggests that participants rely predominantly on abstract

7 It seems conceivable that participants encoded items deeper after intentional than incidental encoding. However, only four participants explicitly reported trying to group the items or to relate them to each other. By

conceptual object representations unless they know that perceptual features are relevant, by either explicit task instructions or task experience. These abstract representations support old/new distinction, but for feature identification additional perceptual cues need to be present, as was the case for identical item repetitions in the present paradigm. When explicitly asked to memorize items, these additional perceptual features are encoded and can be retrieved to support the specific discrimination of identical and changed items. Note that the task order also could have influenced this effect: During the retrieval phase after incidental encoding, participants learned which kind of perceptual changes we used in our paradigm (i.e., that items could change in size, orientation, etc.). While participants were unable to predict which aspects would be changed in the upcoming retrieval phase, it is possible that they adjusted their attentional focus to the kinds of perceptual details that would turn out to be relevant.

Consider that any memory test (or even mentioning the word "memory" is likely to cause at least some participants to encode at least a few items; thus the task order could not be reversed as a countermeasure for practice or fatigue effects. Note that all participants demonstrated that they understood the instructions during the practice phases (they used all response categories). In addition, the experiment only took 35 to 45 minutes in total (including three breaks) and the very high performance after intentional encoding (the second block) speaks against the possibility of fatigue effects. We would not consider the change of perceptual focus from incidental to intentional encoding as a practice effect, but one of the key manipulations of the paradigm.

With respect to the ERP correlates of familiarity and recollection, consistent with previous studies using pictorial stimuli (e.g., Czernochowski et al., 2005; Ecker, Zimmer, et al., 2007a, 2007b; Galli & Otten, 2011; Mecklinger, 2006; Opitz, 2010a), in the present investigation the two correlates were less dissociable in terms of timing and topography compared to prior studies using verbal stimuli (e.g., Curran, 1999; Curran & Dien, 2003; Trott et al., 1997). It is likely that pictorial stimuli are processed more easily and hence faster than words due to their lower abstractness; this idea is in line with the high behavioral memory performance for pictures (picture superiority effect; e.g., Paivio, Rogers, & Smythe, 1968; for an overview, see Hockley, 2008).

The ERP correlate for recollection was larger for identical than for changed items, and larger after intentional than incidental encoding at centro-parietal electrode sites. Both effects have been reported in earlier studies: Larger parietal old/new effects have been found when associative or

---

contrast, 14 participants named no particular encoding strategy that would indicate an entirely different encoding strategy (instead, 7 only stated that they tried to "memorize" without further explanation), suggesting that the encoding strategies in both phases did not substantially differ from each other (i.e., intentional encoding was similar to incidental encoding with the exception of the intent to remember).

contextual information is retrieved (Curran & Doyle, 2011; Donaldson & Rugg, 1998; Van Petten, Luka, Rubin, & Ryan, 2002; Wilding, 2000; Wilding & Rugg, 1997; for a similar result, see Nyhus & Curran, 2012). Additionally, an increase in the magnitude of this correlate has been associated with higher memory performance (e.g., Czernochowski et al., 2009; L. H. Evans, Herron, & Wilding, 2012; Friedman, de Chastelaine, Nessler, & Malcolm, 2010; Opitz, 2010a; Van Petten et al., 2002; Van Strien, Hagenbeek, Stam, Rombouts, & Barkhof, 2005). In sum, we observed modulations of the ERP component of recollection that can be explained by higher memory performance and the additional retrieval of perceptual details. Here, it demonstrates that participants engaged in recollection for identical as well as changed exemplars and after both incidental and intentional encoding.

With respect to the effects on the ERP correlate of familiarity, we found neither differences in the ERPs elicited for identical and changed exemplars, nor differences in those following incidental and intentional encoding. This challenges the notion that only the relevance of perceptual features – i.e. a task that promotes attention to perceptual stimulus attributes (like an exclusion task) versus a task in which these attributes are not relevant (like an inclusion task) – determines whether the ERP correlate of familiarity is attenuated or not (Zimmer & Ecker, 2010). The pattern of results observed here suggests that other factors should be considered as well: Given the perceptual focus (after intentional encoding), we expected a reduction in the familiarity-related ERP component for changed items, but found no reliable difference between identical and changed items. Unfortunately, only few studies used a threefold-response format and report ERP curves for both identical and changed items, although this approach allows to examine cognitive processes of retrieving item memory and contextual information at the same time. In one of the few studies that prompted participants with three response alternatives simultaneously (Ecker, Zimmer, et al., 2007b, intrinsic condition), a reduced frontal old/new effect was reported for changed (as opposed to identical) items. However, this study reported two major differences compared to the present investigation: First, they observed no ERP correlate of recollection, whereas we found correlates of both processes. Accordingly, their old responses are likely to largely reflect predominantly familiarity-based retrieval – whereas here, ERPs for identical and changed items likely reflect both processes. Thus, their study might have been more sensitive to detect perceptual modulations of familiarity's ERP correlate. Second, most changed exemplars in the present study consisted of perceptually similar pictures: It is conceivable that a large perceptual overlap still allows the assessment of familiarity based on the (remaining) identical perceptual features, possibly leading to an attenuation of the ERP correlate. Notably (in line with Ecker, Zimmer, et al., 2007b), inspecting the ERP curves and topographies (Figs. 4 and 5) demonstrates that the magnitude of the ERP correlate for familiarity is smaller for changed, compared to identical, exemplars. Taken together, we found evidence that changed exemplars do not necessarily reduce the magnitude of the frontal correlate of familiarity, even though our task promoted a perceptual focus. It is conceivable that (in addition to the perceptual weight during retrieval) either (1) the overlap of perceptual features between changed and identical items or (2) the relative contribution of familiarity to retrieval has a critical impact on the size of the frontal old/new effect. Thus, future studies investigating this issue should (a) directly contrast pictures with different degrees of perceptual similarity between identical and changed items and (b) utilize paradigms that promote familiarity as retrieval process, for example by selectively impairing recollection-based retrieval (Nyhus & Curran, 2012) or by presenting stimuli across different contexts (Opitz, 2010a).

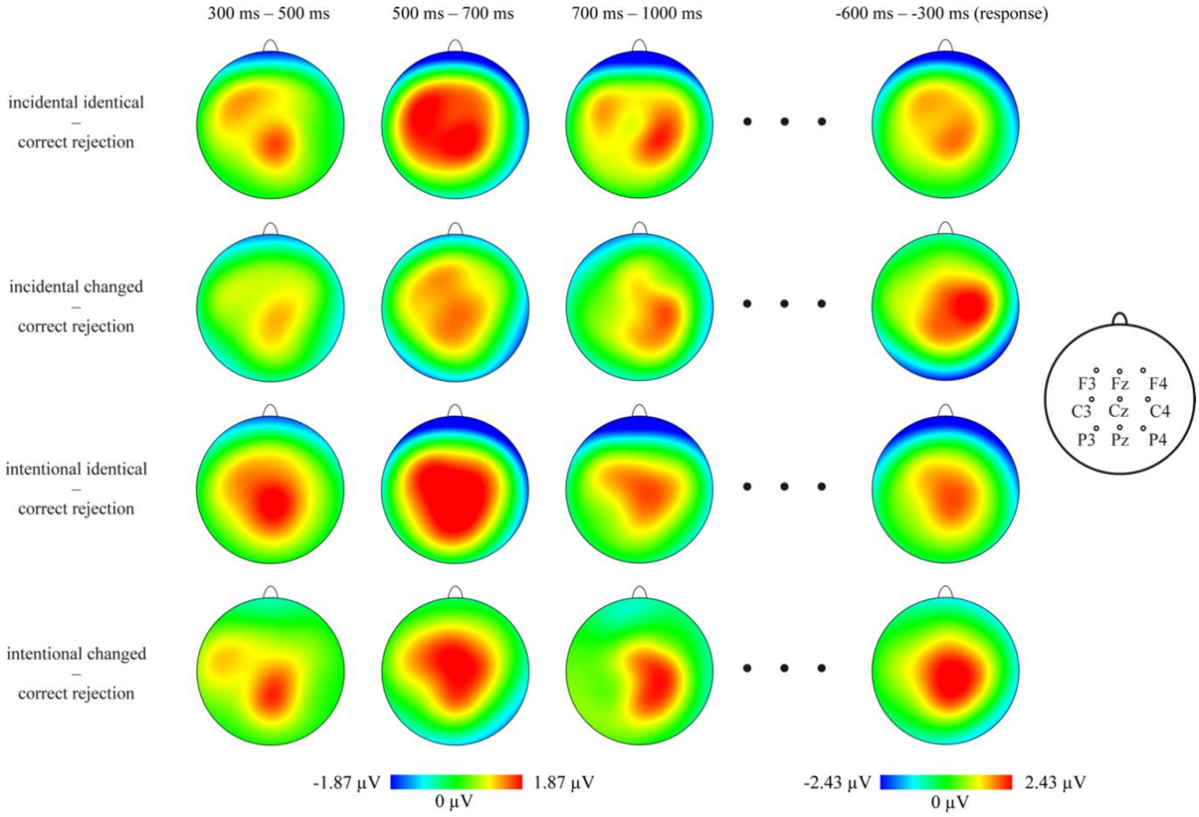

Figure 5. Topographies of old/new effects. These topographies illustrate the spatial distribution of old/new differences (correct old responses minus correct rejections after incidental encoding) for each condition (feature hits) and time window, 300 – 500 ms, 500 – 700 ms, 700 – 1000 ms, and -600 – -300 ms (pre-response).

With respect to later aspects of retrieval, we found the LPN and later aspects of recollection to attenuate each other in stimulus-locked averages: the overlap of the positive (late recollection) and negative (LPN) ERPs attenuated the parietal old/new effect in the late time window (700 – 1000 ms). After intentional encoding, we found a parietal old/new effect, but due to the overlap with the LPN it was still smaller than in the previous time window (compare Tables 3 & 4). The LPN is associated with response inhibition, which might occur due to the response selection same vs. different, and with the retrieval of source-specifying features (i.e., the retrieval of stimulus features in order to correctly categorize an old item as identical or changed). Notably, the magnitude of the LPN reflects the effort participants invest in their retrieval (c.f., Mecklinger et al., 2007), so we can conclude that participants did not (or did not have to) engage more effort for retrieving item features for (a) changed compared to identical pictures or (b) incidental compared to intentional encoding.

By contrast to the stimulus-locked pattern of results, we observed a reliable parietal old/new effect after both incidental and intentional encoding when evaluating the response-locked averages; in these, the LPN affected the ongoing ERP correlate of recollection to a smaller extent. Remarkably, we found neither an effect of encoding instruction nor of perceptual changes on either stimulus-locked or response-locked analyses, so we can conclude that the later aspects of recollection (i.e., 700 ms onwards) were not affected by the perceptual match or by the instruction to memorize items.

Previously, there have only been two studies that investigated stimulus-locked and response-locked averages. However, they focused on post-response time windows (Johansson & Mecklinger, 2003) or had a different retrieval task (de Chastelaine et al., 2007), making a comparison to our pattern of results difficult. Thus, although the different methodological focus of these studies allows us no direct comparison of results, together these three examples demonstrate the advantages of combining stimulus- and response-locked analyses. In the present investigation, our stimulus-locked and response-locked averages suggest a high similarity in processing (Fig. 4); by contrast, both analyses lead to different results (compare parietal old/new effects in Tables 4 & 5), so the response-locked analysis dissociated recollection-related effects and the LPN better. Critically, neither perceptual change (Item type) nor the instruction to intentionally encode items (Phase) influenced the ERP correlate of recollection in these later time windows. In her review, Henke (2010) suggested to dissociate rapid and slower subprocesses of recollection. Although tentative, the present data suggest that rapid recollection (i.e., observed in the time window 500 – 700 ms) is affected by both perceptual change and the amount of information retrieved, whereas slower recollection (i.e., observed in the time window 700 – 1000 ms) appears unaffected by either factor. Generally, the comparison of stimulus- and response-locked averages may prove to be a helpful tool when investigating time windows subject to stimulus- as well as decision-related cognitive processes.

Conclusion

The instruction to memorize items intentionally improved memory performance in particular for perceptual features, suggesting that participants relied predominantly on abstract conceptual processing during incidental encoding. Feature identification was particularly low for changed exemplars, which could not (to the same extent) be utilized as a retrieval cue for source-specifying information. The present results replicate and extend prior findings with respect to the ERP correlate of recollection, which was larger after intentional (versus incidental) encoding and for identical (versus changed) items. By contrast, the magnitude of the old/new positivity related to later aspects of recollection was comparable irrespective of perceptual change or instruction to memorize; these old/new effects were larger for response- (versus stimulus-)locked averages, suggesting that decision-related processes play a major role during this time period. Evaluating both types of ERP averages may prove fruitful to dissociate overlapping cognitive processes in future studies, in particular for relatively late aspects of stimulus processing. Prior findings have been less consistent with respect to the ERP correlate of familiarity, which remained largely unaffected by perceptual change and intentional encoding. The present study corroborates the notion that the (sub-)processes associated with familiarity-based retrieval may be more sensitive to subtle variations in task characteristics and material retrieved from memory.

Evaluation for the subsequent developmental study

In line with our expectations, ERP correlates of both familiarity and recollection could be obtained by means of this paradigm. The comparison of incidental and intentional encoding as well as the comparison of identical versus changed item modifications gave access to a differential evaluation of both ERP components. Notably, the LPN indexed the engagement of further source-specifying retrieval as it diminished the magnitude of the LPC reflecting recollection – a consequence of shared temporospatial properties of both components and their opposing polarities. This phenomenon which will be revisited in Study 3 where this pattern of findings was replicated, necessitating a data-driven approach to discern ERPs of old and new items. The data of Study 1 allow the conclusion that the paradigm is a viable tool for eliciting episodic memory retrieval in adults. Accordingly, the cognitive processes underlying retrieval ought to be observable in a developmental sample as well.

Previous behavioral studies indicated usage of familiarity and recollection in children as young as 6 with a particular increase in adoption of familiarity between children aged 6 and 8 (Ghetti & Angelini, 2008; but see also Koenig et al., 2015). In the study of Mecklinger and colleagues (2011), a paradigm was used in which children aged 8 to 10 had to respond within 1050 ms, rendering recollection hardly usable. Children were assumed to hence only rely on familiarity-based retrieval in the memory task, which was corroborated by the frontal old/new effects assumed to reflect familiarity. As this design has proven effective, we selected similar developmental populations aged 6 to 10 years. As far-reaching changes in executive functioning have been proposed as a result of school entry (Brod, Bunge, & Shing, 2017), we decided to investigate episodic memory in children in the second and fifth grade rather than solely based on chronological age. Previous evidence allows the assumption that ERPs of recollection would be observable in ERPs of younger and older children in primary school as a parietal positivity for old versus new items (e.g., Cycowicz & Friedman, 2003; Cycowicz et al., 2003; Czernochowski et al., 2005). In contrast to previous studies, we assumed that our task would also elicit a reliable ERP correlate of familiarity in children due to a) the intentional encoding procedure after a first incidental study-test cycle and b) its pictorial stimuli. Zimmer and Ecker (2010) demonstrated that perceptual modifications affect the FN400 reflecting familiarity in adults under exclusion conditions, so we assumed that the exclusion task of our paradigm would likely give rise to an FN400 in children for perceptually identical items. A perceptual change was assumed to attenuate the FN400. As the study of Mecklinger et al. (2011) succeeded in eliciting FN400-like effects in this age group, we assumed to the paradigm would elicit similar effects in this age group. With respect to younger children, it was unclear if the paradigm would also promote familiarity-related processes in younger children, but based on the rationale above it was assumed that the likelihood of such effects would be increased in comparison to previous investigations. Taken together, the results of Study 1 confirmed our hypothesis that the paradigm was suited for the investigation of episodic memory retrieval in adults and suggested a similar viability in children due to its paradigm characteristics.

Study 2

Task characteristics are critical for the use of familiarity:

An ERP study on episodic memory development in middle childhood[8]

Abstract

Children have often been assumed to rely on familiarity in episodic memory retrieval based on low source memory performance. However, the frontal familiarity-related event-related potential (ERP) correlate is typically absent in children, in contrast to a prominent parietal old/new effect reflecting recollection. Here, we presented identical and perceptually changed pictures after incidental and intentional encoding to assess whether (a) identical perceptual item features or (b) a high memory performance promoted by intentional encoding would elicit an ERP correlate associated with familiarity in 7-year-olds (N = 20) and 10-year-olds (N = 20). Despite generally high memory performance we observed frontal old/new effects in older children only, selectively for perceptually identical items after intentional encoding. By contrast, parietal old/new effects were observed in both groups. Furthermore, late parietal old/new effects were much smaller for changed items, suggesting that older children employed additional recollective search processes to differentiate between identical and changed items.

Introduction

Imagine that you are searching for a misplaced key. What strategies might you employ to help you remember where you last saw it? You might choose to search in all the usual places such as the entrance to your home or inside your handbag. Imagine further that when you ask your child to help you in the search, they immediately remember that you left it on a shelf in the bathroom. Why did you fail in your search while your child succeeded? One possibility is that you and your daughter utilized different strategies to help in the memory search. For example, it is possible that you did not think about this possibility because you hardly ever take your keys into this room. In this case, you utilized previously held conceptual information in your memory search. Although this normally supports successful memory retrieval, your child's less conceptually guided search led to a quicker solution. This example illustrates that when children engage in memory retrieval, they likely use different strategies than adults – strategies that may sometimes even lead to a better outcome than the conceptual strategy of adults.

---

[8] This section has been published in a peer-reviewed journal: Haese, A. and Czernochowski, D. (2016). Cognitive Development (40). 82-100. Tables and supplemental data referring to data of the adult sample is given in Study 1 and hence not included in this dissertation.

Although there has been a growing interest in episodic memory retrieval in children in recent years (e.g., Cycowicz, 2000), there are still inconsistencies in the literature. As detailed below, behavioral data suggest that children mainly rely on familiarity (Cycowicz, 2000). By contrast, most event-related potential (ERP) studies found evidence for recollection but not for familiarity-based retrieval in children (Czernochowski et al., 2005; Friedman et al., 2010). To reconcile these apparently contradicting findings, it is necessary to pay close attention to the methods used in the respective lines of research. For instance, the paradigms commonly used in adult ERP research might not be effective in eliciting familiarity-based retrieval in children, as the cognitive processes supporting familiarity might differ between children and adults. The aim of the present study was to address this open issue by using a new paradigm designed to promote familiarity-based retrieval in children.

In adults, the contribution to retrieval of two processes, familiarity and recollection, has been studied extensively (Yonelinas, 2002). When people base their memory judgment on their global feeling of having previously encountered an event, they have employed familiarity in their retrieval, when they engage in a controlled memory search that leads to the retrieval of contextual details, they have used recollection (Yonelinas, 2002). Recollection processes generally reflect more effortful and slower retrieval compared to familiarity-based processes, and further, result in higher response confidence. These two types of retrieval processes can be distinguished by multiple outcome measures like fast versus slow reaction times, the correct versus incorrect retrieval of contextual details, or introspective reports of "knowing" something is old versus "remembering" contextual details (Tulving, 1985; for a review, see Yonelinas, 2002).

Previous literature has indicated that recollection and familiarity processes follow different developmental trajectories and that there are age-related differences in children's ability to recruit these two processes (Ghetti & Angelini, 2008). For example, several studies found that age-related differences are larger when source memory measures are used compared to when item memory is tested, suggesting a slower development of recollection compared to familiarity (Cycowicz, 2000; Cycowicz et al., 2003; Cycowicz et al., 2001; Czernochowski et al., 2005; Gulya et al., 2002; for paradigms with preschool children, see also Riggins, Rollins, & Graham, 2013). Cycowicz and colleagues (2001) investigated this by comparing the results of two different test phases. In the item recognition block, participants decided whether a black test picture was "old" or "new". Thus, contextual information was not necessary for successful task execution. In the source recognition block, participants instead decided whether a picture was "old-red", "old-green", or "new", so the old categories were further separated according to the contextual information. Accordingly, contextual information was essential for the task. Memory representations of children seemed to be less detailed as they exhibited more errors when it came to the retrieval of an item's context than adults. This was taken as evidence that children rely on familiarity, not recollection, as it has been shown that successful retrieval via recollection allows the recognition of contextual information. Since then, more studies have been conducted, sketching a more complex pattern of behavioral results: While recollection appears to develop until adolescence, familiarity seems to have a different developmental trajectory. Based on confidence ratings, signal detection models of familiarity and recollection estimate a relatively stable use of familiarity between the ages of five and eleven years, whereas estimates of recollection double or even triple in the same age range (Ghetti & Angelini, 2008). Other studies report similar results with little or no developmental differences with respect to familiarity in children beyond five years of age (e.g., Billingsley et al., 2002; Brainerd, Holliday, & Reyna, 2004; for an overview, see Rollins & Riggins, 2015). In a nutshell, behavioral evidence suggests that children rely on both familiarity and recollection. Based on errors in source memory paradigms, recollection appears to have a longer developmental trajectory than familiarity.

A very different pattern of results is shown in studies of familiarity and recollection using event-related potentials (ERPs). In adults, recollection and familiarity have been dissociated using the temporo-spatial characteristics of ERPs in numerous investigations (Curran, 2000; Friedman & Johnson, 2000; Rugg, Mark, et al., 1998, for an overview, see Opitz & Cornell, 2006). In episodic memory paradigms, differences between ERPs of correctly recognized "old" and "new" items (old/new effects) are compared to describe memory-related effects in neurophysiological data. For adults, recollection has been associated with a parietal positivity for old versus new items between approximately 500 and 700 ms (e.g., Wilding, 2000). Similarly, a parietal ERP correlate of recollection was consistently observed in children (10-year-olds, Cycowicz et al., 2003; 12-year-olds, Czernochowski et al., 2009; 8-year-olds and 11-year-olds, Czernochowski et al., 2005; 8-year-olds and 14-year-olds, Sprondel et al., 2011). By contrast, familiarity has been associated with a frontal positivity for old versus new items in earlier time windows (e.g., Curran, 2000; for a review, see Rugg & Curran, 2007) in adults. Based on the behavioral findings cited above, a corresponding ERP correlate of familiarity should be expected in children as well. However, no such correlate was observed in children (e.g., Czernochowski et al., 2005).

So if children rely on familiarity and if early frontal old/new effects reflect familiarity in adults, why have no studies reported a frontal positivity for children as well? This has been a gap in the literature for several years, until Mecklinger et al. (2011) offered one potential explanation with a new paradigm. They asked participants to respond fast (response deadline: 750 ms for adults; 1050 ms for children aged 8 to 10), as familiarity-based retrieval is usually faster than recollection-based recognition (Yonelinas, 2002; but see also Besson, et al., 2015; Montaldi & Mayes, 2010). As a result, the response deadline paradigm eliminated recollection as a viable route to memory retrieval, as reflected by the lack of parietal old/new effects in adults and children. Interestingly, when the ERP correlate of recollection was no longer present, a frontal old/new effect could be observed in children's ERP averages, taken to reflect familiarity. This procedure has been successful in eliciting familiarity-based retrieval by eliminating the alternative route to retrieval. Note that this is one of the few developmental ERP studies in which participants were only required to distinguish between old and new items. Hence, all old items were presented with the same perceptual features during study and test. Maybe in previous ERP studies children relied on recollection because the paradigm promoted recollection-based retrieval processes due to the requirement to retrieve contextual details – rendering familiarity-related old/new effects less prominent. Still, during the same paradigms, ERP correlates of familiarity-based retrieval were observed in young adults, suggesting age differences in the factors promoting familiarity- versus recollection-based retrieval strategies. Alternatively, children might simply prefer recollection if feasible.

Previous studies focused on investigating episodic memory retrieval as a whole, but it seems that for the particular investigation of ERPs associated with familiarity the task has to be adapted. In this study, we addressed a few methodological factors, which might have interfered with the previous observation of this correlate in children (see also Czernochowski et al., 2005): (1) age differences in memory performance (2) response format, and (3) age-related differences in the employment of a perceptual or conceptual focus during study. In the following paragraphs, we explain each of these factors in more detail.

With respect to memory performance, children typically perform worse than adults in episodic memory tasks (e.g., Cycowicz, 2000; Czernochowski et al., 2005). Children sometimes produce a large number of false alarms (i.e., "old" responses to new items), so a potentially large portion of their "old" responses may be based on guessing whether an item was old or new. Accordingly, ERPs associated with hits (i.e., "old" response to an old item) may well reflect both successful memory retrieval and cases where children just guessed. If we assume that children in previous studies might have been more prone to guessing, this might have attenuated old/new effects reflecting both familiarity and recollection. In a previous study, Azimian-Faridani and Wilding (2006) argue that the ERP correlate of familiarity might be too small compared to the ERP correlate of recollection to index differences between critical conditions (see also Curran, 2004). So while guessing induced by a high task difficulty may mask the effect of both retrieval processes – familiarity and recollection –, it may well have a stronger masking effect on the less robust ERP correlate of familiarity. It should be highlighted that there are also paradigms in which children produced fewer false alarms than adults (Czernochowski et al., 2005; Paz-Alonso, Ghetti, Donohue, Goodman, & Bunge, 2008; Rollins & Riggins, 2013), which can be the result of a more cautious response tendency, or potentially age-related differences in prior semantic knowledge (for a review, see Brod et al., 2013). In sum, guessing behavior is likely to differ between paradigms, and sometimes also between age groups. As it is difficult to estimate beforehand, it is best to minimize this potentially confounding factor by aiming to achieve a high memory performance across age groups. Thus, we propose that ERP correlates of familiarity and recollection need to be associated with similar and sufficiently high levels of memory accuracy in children and adults in order to validly compare retrieval processes between age groups. To ensure this, we used colorful pictures of familiar objects and animals as stimuli and kept instructions as well as response requirements as simple as possible.

With respect to response format, most ERP studies that investigated episodic memory in children specifically assessed source memory. Hence during study, items were presented with a contextual detail, e.g. a red or green outline color. At test a "neutral" format was used (for instance black outlines, e.g. Cycowicz et al., 2003) in either an inclusion or exclusion task. In an inclusion task, participants are asked to focus on whether or not items have been presented before – thus old items are judged to be "old" and successful task completion does not require access to contextual details (e.g., Cycowicz et al., 2003, item test; Czernochowski et al., 2004; Sprondel, Kipp, & Mecklinger, 2013, general test). In an exclusion task, retrieval of contextual details is necessary for a correct response – old items are only judged to be "old" when they belong to the target category (Cycowicz et al., 2003, source test; Czernochowski et al., 2005; Sprondel et al., 2013, specific test). Hence, non-target items are classified as either "old" or "new", according to task. Note that an exclusion task does not permit to differentiate between correctly rejected non-targets and those falsely identified as distractors (misses). Often inclusion and exclusion task requirements are changed several times between blocks of retrieval, adding additional demands with respect to response monitoring and the inhibition of an "old" response for a non-target item. Thus, we propose that introducing executive control demands during a memory retrieval task can underestimate children's source memory ability, as lower memory performance for non-targets might be due to underdeveloped executive control abilities rather than a memory deficit per se. In our paradigm we addressed this issue by offering three concurrent response options to our participants. Participants were asked whether an item was identical, changed, or new with respect to the study phase. This allowed us to compare ERP old/new effects separately for each item type. At the same time, this procedure does not introduce additional demands with respect to executive functions, which could distort our findings regarding memory judgments.

With respect to age differences in the spontaneous focus of attention, children and adults have been shown to focus on different aspects when viewing pictures of meaningful objects. While children process items on a perceptual level, adults tend to process items on a more conceptual level (Sloutsky & Fisher, 2004) unless perceptual details are task-relevant (Haese & Czernochowski, 2015). This might further contribute to age differences in the use of familiarity in previous investigations. In adults familiarity has been suggested to reflect a global study-test similarity, i.e. the overall "echo" of brain activation in response to a previously studied stimulus (Hintzman, 2001). If children assess familiarity predominantly on a more perceptual level, consistent with their spontaneous focus of attention, they might require a perceptual overlap between study and test in order to assess an item's study-test similarity. This issue might be addressed by comparing items with a complete perceptual overlap and those with changed perceptual item features. We would like to highlight that the perceptual item features we changed were designed to avoid salience effects, and at the same time prevented participants from focusing on single item aspects in the second encoding phase. For effects on differential item changes, please refer to ERP studies conducted with adults (e.g., Ecker et al., 2009; Ecker & Zimmer, 2009; Ecker, Zimmer, et al., 2007a, 2007b; Ecker, Zimmer, Groh-Bordin, & Mecklinger, 2007; Tsivilis et al., 2001). One important caveat is that adults can flexibly adapt their focus of attention to relevant item features (Haese & Czernochowski, 2015). Thus, we propose that explicit instructions to attend certain features during encoding or systematic variations in the stimuli employed will often allow participants to anticipate which stimulus features are relevant for later retrieval. Hence, adults are likely to adapt their attentional focus after anticipating task demands, whereas children are less likely to employ such strategic modulations of selective attention to single item features. As a consequence, age differences in memory performance are expected to increase due to these strategic modulations. How can we make sure that the attentional focus does not gradually change towards processing of single item features (e.g. by verbalizing the color along with each object)? In our study, participants did not anticipate any retrieval demands before the first test phase, and could not predict which feature would be relevant for any given item during the second phase. Hence, we eliminated this potential confound that arises when adults, but not children, adapt their encoding strategies.

Summary and Hypotheses

To summarize, we modified key aspects of the standard recognition paradigm to investigate familiarity-related old/new effects in children. Previous studies (Cycowicz et al., 2003; Czernochowski et al., 2005; Sprondel, Kipp, & Mecklinger, 2012; Sprondel et al., 2013) changed contextual details of items and asked participants in the test phase to remember the contexts from the previous study episode. Here, for half of the items, intrinsic item features (i.e., parts of the stimulus per se, Ecker, Zimmer, et al., 2007a) were changed between study and test to evaluate the role of perceptual overlap for familiarity-based retrieval in children. We changed items on different dimensions (e.g., color, size, or specimen) to ensure that participants did not just focus on single object attributes. This way, participants could not predict which feature would be changed later. The concurrent encoding task encouraged participants to encode objects semantically during both phases of memory encoding. Furthermore, we used two study-test blocks. In the first run, participants were unaware of the subsequent memory retrieval phase (incidental encoding), whereas in the second run, they were asked to intentionally memorize the items while performing the same task.

We designed a task that should be easy for children to ensure high memory performance across groups. Accordingly, we expected few, if any, behavioral differences in memory performance. Furthermore, performance should be higher after intentional encoding than after incidental encoding, indicating memory representations that are easier to access as a result of the intent to remember. With respect to ERPs, the pattern of results should be more complex. The ERP correlate of recollection, a late parietal old/new effect, should be observable across all age groups, potentially with later peak latencies in younger children. Our hypotheses regarding the ERP correlate of familiarity in children were more exploratory in nature. In line with previous evidence, we did not expect an ERP correlate of familiarity for all old items. We evaluated whether frontal old/new effects can be observed in children when the test item is presented identically – similar to Mecklinger and colleagues (2011). In adults, familiarity and recollection have often been investigated in the time windows between 300 and 700 ms. There are only few ERP studies on episodic memory in children and some of those selected later time windows to evaluate ERP correlates of retrieval in children compared to adults. To account for this inconsistency between previous studies, we also evaluate later aspects of recollection, reflected in the time window beyond 700 ms.

Method

Participants

Twenty-five second-graders (three left-handed) and 24 fifth-graders (two left-handed), recruited in local communities and schools participated in our study. They received 20 EUR and a small present as compensation. Data from five second-graders and four fifth-graders could not be analyzed due to (a) an insufficient amount of artifact-free EEG trials (two second-graders), (b) low performance level (more than two standard deviations below each group mean; two second-graders and three fifth-graders), and (c) incomplete data (one second-grader, one fifth-grader). Thus, the final samples consisted of 20 second-graders (aged 7 – 8 years, mean 7;8 years, 8 girls) and 20 fifth-graders (aged 9 – 11 years; mean 10;6 years, 10 girls). According to parents' reports, none of the children suffered from neurological or psychiatric disorders. We compared these two groups of children to a group of undergraduate students who were assessed with the same paradigm (Haese & Czernochowski, 2015).

Material

We used pictures from the dataset of Rossion and Pourtois (2004), but only included items familiar to children in the second and fifth grade. For the test phase, we either changed perceptual features of each stimulus or paired two items that showed different exemplars of the same object. After modification, items could have changed in size, orientation, or color, or depict a different specimen of the object. Since perceptual changes were a key manipulation of this paradigm, we also made sure no similar objects were included, like images for "bee" and "fly". In our paradigm, items were changed on more than one feature dimension to prevent participants from predicting which particular feature dimension would be relevant in the subsequent test phase. Thus participants were required to encode items as a whole, and could not simply focus on a single item feature during encoding, e.g. "blue button". In addition, we selected cliparts from CorelDRAW® X4 which met the same criteria and were overall similar to the Rossion and Pourtois dataset (please refer to Fig. 2 for examples of stimulus modifications).

Procedure

The experiment was part of a multi-experiment session lasting approximately 2.5 to 3 hours. On the day of EEG testing, participants completed two experiments in counterbalanced order (a task-switching paradigm, Czernochowski, 2015, and the memory paradigm reported here; 1.5 to 2 hours including breaks). The memory paradigm consisted of two blocks, incidental encoding and an unexpected recognition test, and intentional encoding and another recognition test. Throughout the study phase participants were asked to decide whether each item was more commonly found indoors or outdoors. In both test phases, we presented 120 items. Of these, 40 were novel distractors, 40 were identical repetitions of studied items, and 40 items were perceptually changed. Participants decided whether each item was "same", "different", or "new" (using index and middle finger of one hand for both "old" categories and the other index finger for responding "new"; the association of old and new categories to right and left hand were counterbalanced across participants). Immediately prior to each task, participants practiced both tasks with eight study items and 12 test items. During the intentional study phase, participants were instructed to memorize the images while still performing the indoors-outdoors categorization task. The intentional test phase was identical to the previous test phase, with one exception: We took 40 items that had been presented as identical items in the incidental phase and used these again. Of these, half were presented identically and half were replaced by changed exemplars. Thus, the test phase again consisted of 40 identical items (20 from the incidental phase), 40 changed items (20 from the intentional phase), and 40 new items. All responses were self-paced—if participants needed more than 5 seconds for a response, participants were encouraged to answer more spontaneously. During the breaks (two minutes between each study and test phase, five minutes between incidental and intentional study blocks) rehearsal was minimized by engaging participants in conversation. All pictures were individually presented at the center of fixation (1000 ms), and were preceded by a fixation cross (1000 ms).

Behavioral Analyses

To assess memory performance for the general old/new discrimination, we calculated Pr scores (Hit rate – False Alarm rate; c.f. Snodgrass & Corwin, 1988). For this general index of memory performance, a participant response was categorized as hit when identical items were categorized as either identical or changed (and vice versa for changed items). Likewise, a participant response was categorized as false alarm when new items were categorized as identical or changed. To assess feature memory, we compared the proportion of correct feature identifications across groups (response "identical" to identical items relative to the number of old items categorized as "identical" or "changed" and vice versa). In addition, we analyzed reaction times. For all behavioral analyses, we computed mixed-model ANOVAs with the factors Age (younger children/older children/young adults), Item type (identical/changed/new), and Phase (incidental/intentional). All behavioral and ERP analyses were computed with SPSS 22 (α = .05).

EEG Recording and Data Preprocessing

We recorded EEG with active Ag/AgCl electrodes at 27 positions according to the extended 10-20 system: FP1, FP2, AF7, AF3, AFz, AF4, AF8, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, CP1, CP2, P7, P3, Pz, P4, P8, O1, O2 (reference FCz was restored after offline re-referencing to linked mastoids). Electrodes above and below the right eye and F9 and F10 measured EOG, we kept impedances below 25 kΩ (500 Hz sampling rate; A-D converted with 16 bit resolution; offline Butterworth band-pass filter of 0.1 Hz – 30 Hz, 24 dB/oct). We corrected ocular movements by applying an ICA-based correction (as implemented in the Vision Analyzer 2.0.3; BrainProducts GmbH, Gilching, Germany) and used a semi-automatic procedure to detect artifacts like muscular activity. The automatic algorithm detected trials meeting at least one of the following criteria: (1) gradient of the EEG amplitude exceeded 20 µV/ms at any electrode site, (2) within 200 ms, the voltage increased or decreased more than 75 µV, or (3) for 100 ms, activity fell below 0.5 µV. The spherical spline interpolation of Perrin et al. (1989) was applied to interpolate electrodes (up to 3 per participant) that could not be corrected otherwise. To investigate effects of successful memory retrieval, we analyzed correct responses in each test phase. Epochs lasted from -100 ms prior to stimulus onset until 3000 ms (the first 100 ms served as baseline). We compared feature hits for both same items ("same" responses to identical items) and different items ("different" responses to changed items) to correct rejections (planned contrasts). We excluded exceedingly slow responses (> 4000 ms in children) from ERP analyses (approximately 5 % of all trials). Mean trial numbers and ranges for each condition are given in Table 7.

Table 7. Mean trial numbers for analyzed item types

	Younger children		Older children	
	Incidental encoding	Intentional encoding	Incidental encoding	Intentional encoding
Response category	mean (range)	mean (range)	mean (range)	mean (range)
Correct rejection	23.6 (7 – 35)	24.6 (12 – 32)	30.4 (14 – 36)	29.3 (14 – 37)
Feature hits identical	17.8 (7 – 26)	23.6 (14 – 36)	25.0 (15 – 39)	29.0 (18 – 38)
Feature hits changed	14.8 (7 – 28)	21.9 (12 – 30)	22.5 (11 – 31)	25.9 (8 – 34)

ERP Analyses

Here, we compared ERP differences during memory retrieval after both incidental and intentional encoding. Visual inspection of the waveforms suggested only small laterality effects in children, but ERP effects were clearly more posterior in children than in adults (see Study 1). Hence, we averaged across midline and lateral electrode sites to increase statistical power and computed mixed-model ANOVAs with the factors Anterior-Posterior (Frontal vs. Central vs. Parietal vs. Occipital) and Item Type (Feature Hits Identical vs. Feature Hits Changed vs. Correct rejections) on four regions of interest — F' (F3, Fz, F4), C' (C3, Cz, C4), P' (P3, Pz, P4), O' (O1, O2). Reliable effects of Item Type were followed up with planned contrasts (identical vs. Correct Rejection and changed vs. Correct Rejection). We evaluated the time windows 300 – 500 ms and 500 – 700 ms, corresponding to familiarity and recollection old/new effects, respectively. In order to examine later aspects of retrieval, we also evaluated old/new effects in the time window 700 – 1000 ms. Throughout the paper, old/new effects specify differences between old items and new items (for both identical and changed items). For a more extensive comparison the anterior-posterior distribution of effects (familiarity and recollection are associated with more frontal and parietal effects, respectively), we performed subsidiary analyses at frontal, central, parietal, and occipital electrode sites. For the sake of brevity, we only report effects related to the factor Item Type.

To prevent response bias for any of the three response categories, one third of all items presented during the test phases were new. As performance in the intentional test was expected to increase relative to the incidental test, these distractors may be particularly salient in the second test phase. In line with previous research on oddball effects (Cycowicz & Friedman, 2007; Czernochowski et al., 2009; Wetzel, Widmann, Berti, & Schroger, 2006), we observed more positive amplitudes for ERP averages of new items after intentional, compared to incidental, encoding in the time window between 300 and 700 ms in older children and adults, $F(1,19) = 7.63$, $p < .05$, $\eta_p^2 = .29$ and $F(1,17) = 15.04$, $p < .01$, $\eta_p^2 = .47$, respectively. As this saliency-related positivity for new items and the recollection-related positivity for old items share spatio-temporal characteristics, this overlap is likely to considerably attenuate recollection-related old/new effects investigated here. To avoid a potential confound of salience in the ERP waveforms, we used correct rejections from the incidental phase for all ERP analyses (for a similar approach, see Czernochowski et al., 2009; Haese & Czernochowski, 2015). Greenhouse-Geisser correction (Jennings & Wood, 1976) was applied where necessary. Uncorrected degrees of freedom are reported along with ε-values and with corrected *p*-values for these instances.

Results

Memory performance

We found better old/new discrimination after intentional encoding, $F(1,55) = 13.48$, $p < .001$, $\eta_p^2 = .20$, and for identical items, $F(1,55) = 189.30$, $p < .001$, $\eta_p^2 = .78$. For the more specific feature discrimination, we found that performance was better both after intentional encoding, $F(1,55) = 81.29$, $p < .001$, $\eta_p^2 = .60$, and for identical items, $F(1,55) = 8.20$, $p = .006$, $\eta_p^2 = .13$ (see Fig. 6). General old/new discrimination only tended to differ across age groups ($p = .090$), and there was no age difference in feature discrimination (p = .989). However, an interaction Age X Item Type indicated differences in feature memory performance, $F(2,55) = 3.34$, $p = .043$, $\eta_p^2 = .11$. Both groups of children showed similar

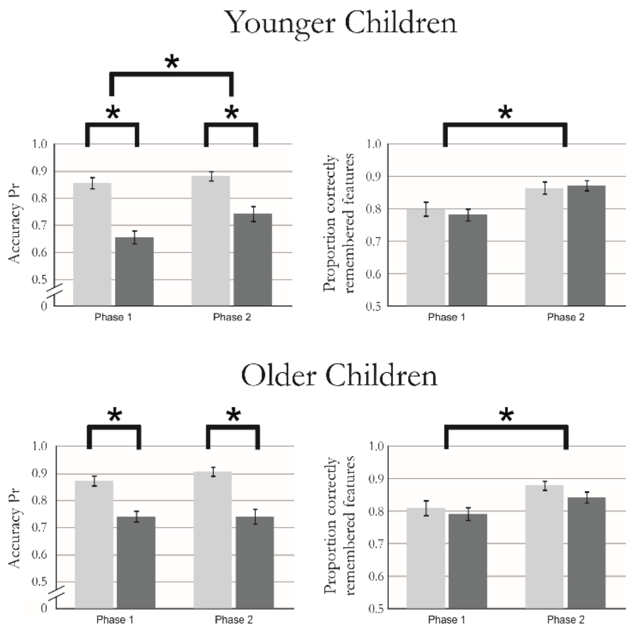

Figure 6. Memory performance for general old/new (left) and specific identical/changed (right) discrimination. Behavioral recognition probability after incidental and intentional encoding for identical (light gray) and changed (dark gray) exemplars. Item recognition was higher for identical items, feature recognition was higher after intentional encoding, but behavioral findings were largely comparable for both age groups. Pr values of 0 and feature recognition scores of .5 reflect guessing. Error bars represent standard errors of the mean, asterisks indicate significant post-hoc comparisons.

feature recognition performance for identical and changed items (both *p*s > .31), whereas adults correctly identified more identical than changed items, $F(1,17) = 18.39$, $p < .001$, $\eta_p^2 = .52$.

Reaction times

Across all age groups (see Table 8), reaction times were faster in the second (intentional) test phase, $F(1,55) = 12.20$, $p < .001$, $\eta_p^2 = .18$, and for both identical and new (relative to changed) items, $F(2,110) = 48.77$, $p < .001$, $\eta_p^2 = .47$, qualified by an interaction of these two factors, $F(2,110) = 6.04$, $p = .003$, $\eta_p^2 = .10$. With respect to age, we found that young adults were faster than both younger and older children and at the same time, older children were faster than younger children, $F(1,55) = 55.32$, $p < .001$, $\eta_p^2 = .67$, qualified by interactions with Phase, $F(2,55) = 3.39$, $p = .041$, $\eta_p^2 = .11$, and Item type, $F(4,110) = 2.80$, $p = .029$, $\eta_p^2 = .09$. Follow-up analyses revealed that only the two groups of children (younger children: $p < .05$; older children: $p < .01$), but not adults ($p = .91$) responded generally faster after the second intentional encoding. While changed items generally led to longer reaction times than identical and new items, this difference was larger for both groups of children (younger children: $\eta_p^2 = .60$; older children: $\eta_p^2 = .61$) than for adults ($\eta_p^2 = .53$).

The employment of two rather than one retrieval processes should be associated with more heterogeneity in reaction times. Thus, we also calculated the intra-individual coefficient of variation (ICV, defined as standard deviation divided by mean; for a similar approach, see Stuss, Murphy, Binns, & Alexander, 2003) and computed the mixed-model ANOVA used on reaction time data with these ICV values. Both groups of children exhibited more variable reaction times than young adults, $F(1,55) = 17.19$, $p < .001$, $\eta_p^2 = .39$; also, identical and new items were associated with a larger variability than changed items, $F(2,110) = 20.00$, $p < .001$, $\eta_p^2 = .27$. As illustrated in Table 8, ICVs in younger children and adults are descriptively comparable, and variability only tended to differ between incidental and intentional encoding ($p = .088$). By contrast, ICVs of older children selectively increased after intentional encoding for identical – but not changed or new – items, $t(19) = 2.95$, $p < .01$. In sum, all age groups responded faster to new and identical items relative to changed items. While children were generally faster after intentional encoding, adults were only faster for new items. Furthermore, reaction times of children were more variable than reaction times of adults; generally, changed items caused more variability in reaction times than identical or new items. We found no reliable difference of response variability between test phases after incidental or intentional encoding (Figure 7).

Table 8. Mean reaction times and intra-individual coefficients of variations for analyzed item types

	Younger children		Older children		Young adults	
	Incidental	Intentional	Incidental	Intentional	Incidental	Intentional
Response category	mean (ICV) [SD]	mean (ICV) [SD]	mean (ICV) [SD]	mean (ICV) [SD]	mean (ICV) [SD]	mean (ICV) [SD]
Correct Rejection (item type new, response "new")	1657 ms (0.41) [675]	1611 ms (0.41) [649]	1441 ms (0.38) [545]	1431 ms (0.39) [558]	1190 ms (0.32) [384]	1265 ms (0.30) [383]
Feature Hits identical (item type identical, response "same")	1776 ms (0.39) [678]	1672 ms (0.39) [656]	1531 ms (0.31) [481]	1469 ms (0.37) [552]	1138 ms (0.29) [338]	1130 ms (0.30) [338]
Feature Hits changed (item type changed, response "different")	1983 ms (0.34) [665]	1849 ms (0.33) [614]	1743 ms (0.31) [551]	1596 ms (0.32) [517]	1403 ms (0.26) [369]	1345 ms (0.29) [395]

ERP old/new effects

In the following analyses, ERP averages for identical and changed items reflect feature hits (i.e., identical items correctly remembered as identical and changed items correctly remembered as changed). Correct rejections were items correctly rejected after incidental encoding. Throughout the analyses, feature hits will be referred to as old items, correct rejections as new ones. An insufficient number of artifact-free trials prevented a direct comparison between items presented once or three times after intentional encoding. As there was no main effect indicating a difference between both conditions, we collapsed across these item types to increase the amount of trials. Consistent with prior findings, overall ERP amplitudes differed between age groups (for a review, see Picton & Taylor, 2007), but throughout all age groups, old/new effects emerged at about 250 ms. In adults, a widespread positivity for old items was observed (see Study 1). To reduce redundancy, please refer to Tables 2 and 3 for an overview of statistical effects. Some participants provided less than 10 trials for one (younger children, N = 3; older children, N = 1) or three conditions (younger children, N = 1). We ran an additional analysis to check for differences in the pattern of results but the results were virtually unchanged. At the end of each ERP result section we will briefly summarize the specific differences in the result pattern of the full sample compared to the sample with at least 10 trials per condition.

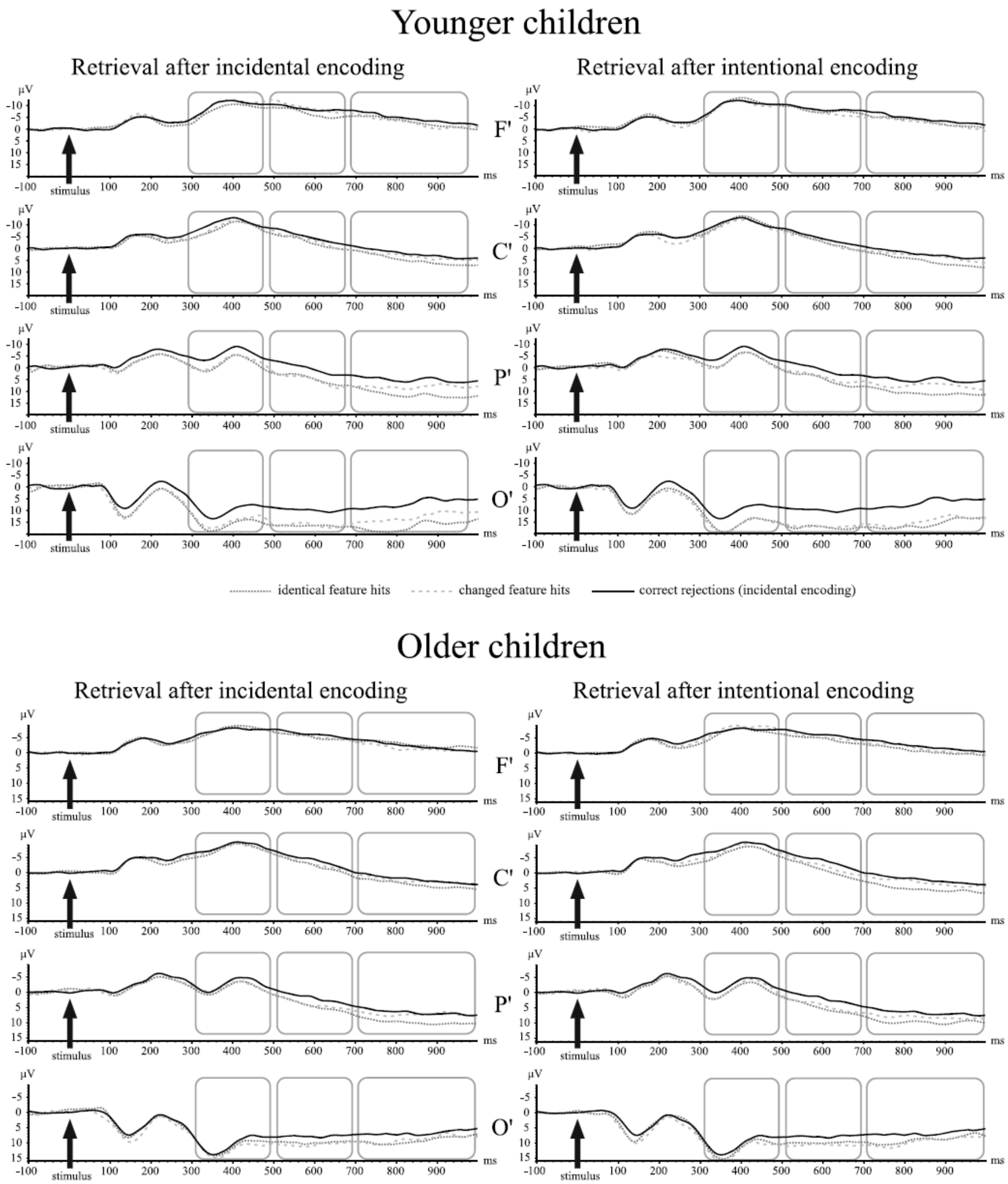

Figure 7. ERP old/new effects following incidental and intentional encoding. ERP waveforms after incidental (left) and intentional (right) encoding reflecting identical (dotted) and changed (dashed) feature hits in comparison to correct rejections (after incidental encoding; black line). Note the difference in scaling for both groups of children and, in particular, the much larger old/new differences at parietal and occipital electrode sites.

First time window (300 – 500 ms; see Table 9)

In younger children, both identical and changed items were associated with more positive amplitudes than new items after both incidental and intentional encoding, largest at parietal and occipital electrode sites. In older children, only identical items (i.e., not changed items) were associated with more positive amplitudes than new items, and only after intentional encoding (largest at central, but also extending to frontal electrode sites). We conducted a follow-up analysis to confirm this finding in an ANOVA with the factors Phase (incidental/intentional) and Item type (identical/changed) for this group. At frontal electrode sites, we observed a reliable interaction of both factors, $F(1,19) = 4.92$, $p < .05$, $\eta_p^2 = .21$. For comparison, in young adults both identical and changed items were associated with more positive amplitudes than new items across electrode sites, after incidental and intentional encoding (largest at frontal and central electrode sites). When we limited the analyses to participants with at least 10 trials per condition, an additional effect for changed items in the overall ANOVA for older children after intentional encoding. However, this overall effect was no longer reliable in any of the subsidiary analyses, hence we do not believe it adds substantially to our data.

Second time window (500 – 700 ms; see Table 9)

In younger children, both identical and changed items were associated with more positive amplitudes than new items after both incidental and intentional encoding (largest at parietal and occipital electrode sites). In older children, both identical and changed items were associated with more positive amplitudes than new items, after both incidental and after intentional encoding (largest at parietal and occipital electrode sites). After intentional encoding, old/new effects were found across all electrode sites (with the exception of frontal electrode sites for changed items). Note that in young adults, both identical and changed items were associated with more positive amplitudes than new items across electrode sites after incidental and intentional encoding. When we limited the analyses to participants with at least 10 trials per condition, changed items no longer elicited a reliable parietal old/new effect after intentional encoding; most likely, this was due to the smaller magnitude of this old/new effect in the reduced sample.

Third time window (700 – 1000 ms; see Table 10)

In younger children, both identical and changed items were associated with more positive amplitudes than new items, after both incidental and intentional encoding (largest at parietal and occipital electrode sites). Note that at the four levels of the factor Anterior-Posterior electrode location, changed items elicited old/new effects only at parieto-occipital (incidental encoding) and at occipital electrode sites (intentional encoding). In older children, both identical and changed items were associated with more positive amplitudes than new items after intentional encoding; after incidental encoding, only identical (but not changed) items elicited reliably more positive amplitudes than new items. Similar to younger children, the old/new effects had different distributions across the electrodes. While identical items elicited old/new effects across several electrode sites (incidental encoding: central, parietal, & occipital; intentional encoding: central & parietal), changed items only elicited old/new effects at parietal electrodes and only after intentional encoding. For comparison, in young adults identical and changed items were associated with more positive amplitudes than new items after both incidental and intentional encoding. These effects were only observed at central (incidental encoding) and centro-parietal (intentional encoding) electrode sites. Limiting the analyses to participants with at least 10 trials per condition led to the same pattern of results.

Table 9. Overview of ERP results for the familiarity- (300 – 500 ms) and recollection-related (500 – 700) old/new effects

effect (df_1,df_2)	300 – 500 ms						500 – 700 ms					
	incidental			intentional			incidental			intentional		
	ε	F	η^2_p	ε	F	η^2_p	ε	F	η^2_p	ε	F	η^2_p
Younger children												
Item type (2,38)		6.85**	.27		9.31***	.33		10.73***	.36		13.03***	.41
identical vs. CR (1,19)		9.11**	.32		6.33*	.25		14.74**	.44		15.41***	.44
changed vs. CR (1,19)		8.78**	.32		22.51***	.54		15.81***	.45		17.22***	.48
Item type X AP (6,114)		—		.38	6.67**	.26	.40	3.29*	.15	.35	5.60**	.23
F' (2,38)		—			—			—			—	
identical vs. CR (1,19)		—			—			—			—	
changed vs. CR (1,19)		—			—			—			—	
C' (2,38)		—			—			—			—	
identical vs. CR (1,19)		—			—			—			—	
changed vs. CR (1,19)		—			—			—			—	
P' (2,38)		6.56**	.26		5.22**	.22		9.38***	.33		6.44**	.25
identical vs. CR (1,19)		9.32**	.33		4.60*	.20		12.78**	.40		9.24**	.33
changed vs. CR (1,19)		10.38**	.35		9.49**	.33		15.38***	.45		5.97*	.24
O' (2,38)		6.71**	.26		6.71**	.26		9.05***	.32		9.05***	.32
identical vs. CR (1,19)		8.98**	.32		8.98**	.32		12.53**	.40		12.53**	.40
changed vs. CR (1,19)		8.47**	.31		8.47**	.31		10.04**	.35		10.04**	.35
Older children												
Item type (2,38)		—			3.87*	.17		7.08**	.27		12.51***	.40
identical vs. CR (1,19)		—			7.39*	.28		15.72***	.45		24.87***	.57
changed vs. CR (1,19)		—			—			7.87*	.29		12.57**	.40
Item type X AP (6,114)		—			—			—			—	
F' (2,38)		—			3.70*	.16		—			4.00*	.17
identical vs. CR (1,19)		—			—			—			6.58*	.26
changed vs. CR (1,19)		—			—			—			—	
C' (2,38)		—			4.49*	.19		—			9.80***	.34
identical vs. CR (1,19)		—			12.62**	.40		—			18.03***	.49
changed vs. CR (1,19)		—			—			—			6.09*	.24
P' (2,38)		—			—			5.90**	.24		8.25**	.30
identical vs. CR (1,19)		—			—			11.50**	.38		15.72***	.45
changed vs. CR (1,19)		—			—			6.12*	.24		9.59**	.34
O' (2,38)		—			—			6.58**	.26		6.58**	.26
identical vs. CR (1,19)		—			—			8.36**	.31		8.34**	.31

changed vs. CR (1,19)		—			—			9.12**	.32		9.12**	.32
Group effects												
AP X Group (3,114)		—			—			—			—	
Item Type X Group (2,76)		3.53*	.09		—			4.84*	.11		5.86**	.13
AP X Item Type X Group (6,228)		—			3.70*	.09		—			3.61*	.09

Note. * p < .05, ** p < .01, *** p < .001, CR = Correct Rejection.

Table 10. Overview of ERP results for the later time window (700 – 1000 ms)

effect (df_1,df_2)	Younger children						Older children					
	incidental			intentional			incidental			intentional		
	ε	*F*	η^2_p	ε	*F*	η^2_p	ε	*F*	η^2_p	ε	*F*	η^2_p
Item type (2,38)		14.81***	.44		13.69***	.42		5.27**	.22		9.48***	.33
identical vs. CR (1,19)		19.96***	.51		22.14***	.54		12.62**	.40		17.26***	.48
changed vs. CR (1,19)		11.89**	.39		10.73**	.36		—			9.29**	.33
Item type X AP (6,114)	.47	4.73**	.20	.36	7.32**	.28	.40	4.00*	.17		—	
F' (2,38)		—			—			—			—	
identical vs. CR (1,19)		—			—			—			—	
changed vs. CR (1,19)		—			—			—			—	
C' (2,38)		—			6.06**	.24		3.63*	.16		12.89***	.40
identical vs. CR (1,19)		—			11.50**	.38		5.69*	.23		33.46***	.64
changed vs. CR (1,19)		—			—			—			—	
P' (2,38)		13.34***	.41		8.94***	.32		7.25**	.28		5.93**	.24
identical vs. CR (1,19)		26.45***	.58		16.33***	.46		13.51**	.42		10.63**	.36
changed vs. CR (1,19)		5.40*	.22		—			—			5.06*	.21
O' (2,38)		14.07***	.43		14.07***	.43	.76	3.87*	.17	.76	3.87*	.17
identical vs. CR (1,19)		22.22***	.54		22.22***	.54		14.91**	.44		14.91**	.44
changed vs. CR (1,19)		7.90*	.29		7.90*	.29		—			—	
Group effects												
AP X Group (3,114)		—			4.21*	.10						
Item Type X Group (2,76)		5.05*	.12		—							
AP X Item Type X Group (6,228)		—			3.72*	.09						

*Note. * p < .05, ** p < .01, *** p < .001*, CR = Correct Rejection.

Discussion

Although familiarity and recollection have been investigated thoroughly in young adults, it still remains open how children engage in memory retrieval. While behavioral studies suggested a contribution of both familiarity and recollection, nearly all ERP studies so far only reported observing an ERP correlate associated with recollection. We argued that this might have been due to certain task characteristics in the few ERP studies conducted with children. Here, we developed a paradigm with adapted characteristics to test this notion.

Summary

This study focused on the role of familiarity for children in episodic retrieval paradigms. Most previous ERP studies reported only parietal old/new ERP effects suggesting children relied on recollection, whereas behavioral results instead indicated that children might rely mainly on familiarity. We assume that the paradigm used might play a key role in the observation of frontal, familiarity-related, old/new effects, so we developed a task that was relatively easy for children in order to achieve a memory performance that was comparable to adults. Hence, EEG averages of correctly recognized old items reflected a comparable level of successful memory retrieval across all age groups. In addition, all participants responded to whether an item was perceptually identical, perceptually changed, or new at the same time. This ensured that the corresponding ERP response did not vary based on the onset of the ERP correlates and was, therefore, comparable across conditions. This approach is preferable to complex inclusion and exclusion paradigms, which might have contributed to age differences in memory performance and in ERP correlates of recognition memory. Further, we used separate incidental and intentional encoding tasks to determine the nature of familiarity-related ERP responses after both types of encoding. Prior research has shown that the ERP correlate of familiarity is observed in adults after incidental and intentional encoding (Curran, 2000; Groh-Bordin et al., 2006; Groh-Bordin et al., 2005; Haese & Czernochowski, 2015). By contrast, so far only one study observed a putative ERP correlate of familiarity in children (Mecklinger et al., 2011). In the following paragraphs, we discuss the behavioral and ERP findings in turn and then highlight differences in the topographical distribution of old/new effects and the role of brain maturation in memory retrieval.

Behavioral Findings

Across age groups, the paradigm elicited a high memory performance. Hence, only small age differences in item memory performance were observed, thus eliminating the potential problem of guessing tendencies and low memory performance for interpreting age differences in ERPs. Both younger and older children exhibited better item memory performance for identical than for changed items, but older children did not benefit further from the instruction to intentionally encode the pictures. The pattern of results was slightly different for feature recognition performance. Here, both groups of children exhibited higher performance after intentional encoding compared to incidental encoding, irrespective of perceptual changes. It should be mentioned that our paradigm does not allow for more detailed insights as to how participants achieved feature hits. It is entirely possible that they had access to a detailed memory trace, which allowed them to directly evaluate the perceptual study-test similarity of each item. Alternatively, it is also possible that they relied on a "recall-to-reject" strategy (recalling the exact study episode in order to distinguish identical from changed exemplars) at least for some items. The processes contributing to this response category cannot be further separated on an individual basis in our design, and need to be further evaluated in future investigations. Reaction time analyses revealed a general age-related reduction in reaction times (replicating previous studies; e.g., Sprondel et al., 2011), and across all age groups slower response times for changed compared to identical items. After intentional encoding, both groups of children responded faster, indicating more efficient processing. We discuss these behavioral effects in the context of the ERP findings below.

ERP Findings

With respect to the ERP correlates of recognition memory in the time windows 300 – 500 ms and 500 – 700 ms, we found that younger children exhibited parieto-occipital old/new effects during both time windows. Interestingly, similar topographies (Figure 8) suggest that they relied on the same cognitive processes during both retrieval phases, although the higher behavioral performance after intentional encoding demonstrates that they followed the instruction and encoded items more efficiently. While the topography of these effects (a parietal positivity for old items) closely resembles the ERP correlate of recollection, the strikingly early onset is inconsistent with this interpretation. Considering the similar reaction times in both groups of children, it is unlikely that the ERP correlate of recollection has a much earlier onset in younger children compared to older children or adults. Instead, it seems more plausible to assume that younger children relied on additional resources to retrieve details from memory. Their behavioral memory performance was relatively high despite the lack of or less efficient employment of familiarity. In previous memory studies, early parietal old/new differences have been observed, presumably reflecting processes supporting recollection. For instance, Sprondel and colleagues (2011) suggest that the variety of perceptual features that participants might attend to serve as cues for the subsequent recollective process. Alternatively, this early parietal positivity has been associated with higher-order visual processing and implicit memory processes (K. M. Evans & Federmeier, 2005; Friedman et al., 2010; Van Strien, Glimmerveen, Martens, & De Bruin, 2009). Similarly, results from a prospective memory paradigm suggest that in young adults, an early positivity (largest at Cz) reflects increased attention to specific (task-relevant) stimulus aspects (Czernochowski, Horn, & Bayen, 2012). Taken together, we argue that the parietal positivity observed for old items in younger children could be interpreted as an early attentional modulation towards perceptual features for the discrimination between identical and changed items, which in turn supports recollective search.

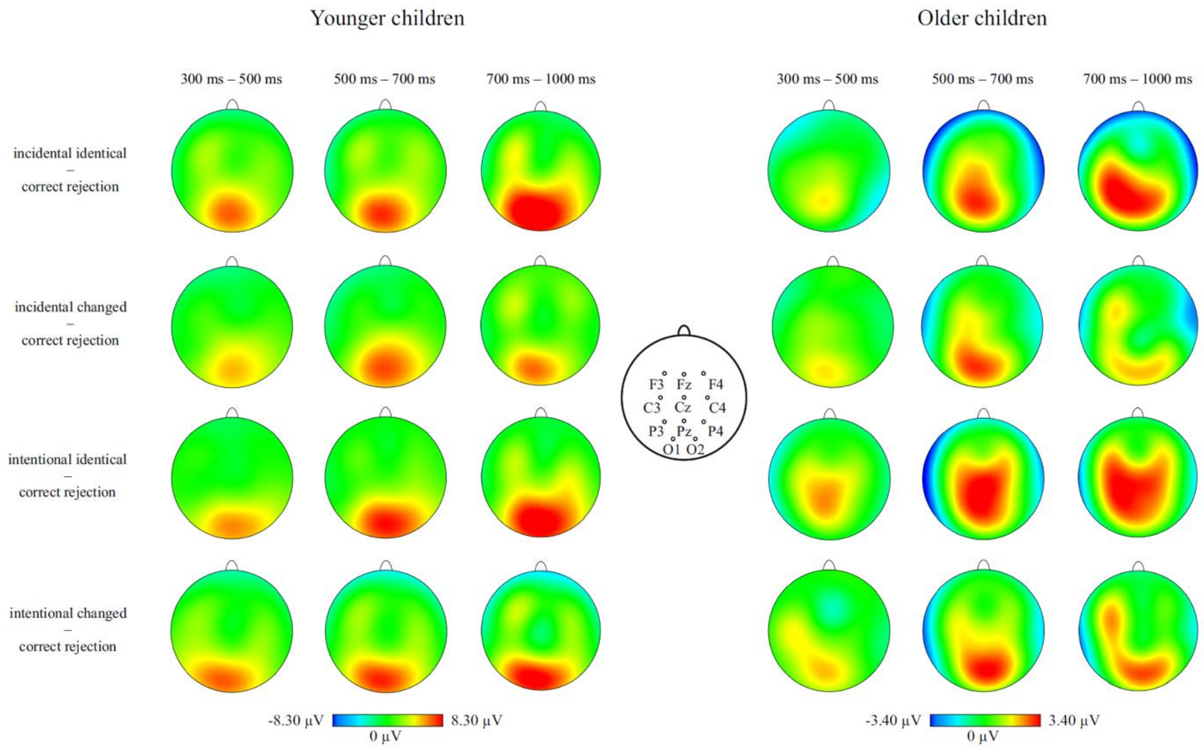

Figure 8. Left: Topographies of old/new effects in younger children. These topographies show the spatial distribution of old/new effects – i.e. correct old responses minus correct rejections (after incidental encoding) – in younger children in the analyzed time windows. Effects are predominantly observed at parieto-occipital electrode sites. Right: Topographies of old/new effects in older children. Effects are largest at centro-parietal electrode sites and, after intentional encoding, further extend to frontal electrode sites for identical items.

Further evidence supporting this interpretation can be found by comparing adults and children with respect to their pattern of memory performance between the first and second run. For adults, feature memory performance was higher after intentional than after incidental encoding. It is likely that they shifted from a conceptual focus after incidental encoding to a more perceptual focus of attention towards item features (Haese & Czernochowski, 2015). By contrast, we observed no reliable difference of younger children's feature memory performance between incidental and intentional encoding, indicating a more perceptual approach to the task (as has been found previously in children, see Sloutsky & Fisher, 2004). Accordingly, we conclude that children did not shift their attention to perceptual features strategically, because their spontaneous approach was already sufficient. Instead, they relied on the same attentional processes in both phases. The notion of an early attentional modulation in children is in line with the review of Cabeza, Ciaramelli, and Moscovitch (2012), who compared several theoretical accounts for an activation in the ventral parietal cortex in adults. They concluded that fMRI activity in the parietal cortex is associated with a high level of bottom-up attention, either by external cues – attention is captured by a salient item – or by internal cues, when attention is captured by salient *cognitive states* (e.g. highly confident responses). In addition, Ofen and Shing (2013) suggested that for memory retrieval, children rely on rudimentary forms of perceptual, semantic, and episodic systems. Thus, they would additionally require the support of the posterior and perirhinal cortex in order to complete these tasks, which in turn might result in the parietal positivity for old items we observed. In contrast to the earlier parietal old/new effect, the later parietal old/new effect is most likely attributable to recollection, consistent with prior findings (e.g., Czernochowski et al., 2004; Czernochowski et al., 2005; Sprondel et al., 2011; Van Strien et al., 2009).

Older children exhibited a more complex pattern of results. After incidental encoding, there were no old/new effects in the early time window, suggesting that older children did not rely on familiarity to evaluate the old/new status of an item. After intentional encoding, however, they exhibited a frontal old/new effect (comparable to Mecklinger et al., 2011), but only during retrieval of identical items. In the later time window, we observed old/new effects for both item types at (centro-)parieto-occipital electrode sites, reflecting recollection, consistent with prior findings (e.g., Czernochowski et al., 2004; Czernochowski et al., 2009; Czernochowski et al., 2005; Friedman et al., 2010; Mecklinger et al., 2011; Van Strien et al., 2009). After intentional encoding, we observed a frontal positivity for old items that was only reliable for identical items, most likely the continuation of the familiarity-related effects in the previous time window (Figure 9). While it seems plausible to assume that more experience with the task should be associated with a more consistent use of retrieval strategies, inspection of older children's ICVs (see Table 8) revealed that only identical items elicited larger ICVs after intentional encoding. Hence, this selectively larger variability supports the conclusion that older children engaged in additional processes after intentional encoding. In combination with the observation of a familiarity-related old/new effect in ERP averages for this condition only, this higher variability suggests that at least some children attempted to employ new strategies after intentional encoding for identical items, for instance evaluating the item's perceptual study-test similarity (i.e., perceptual familiarity). It should be noted that familiarity reflects a cascade of sub-processes (Tsivilis et al., 2001), which is not fully understood in adults either (Zimmer & Ecker, 2010). For instance, while earlier aspects of familiarity can lead to a fast old/new

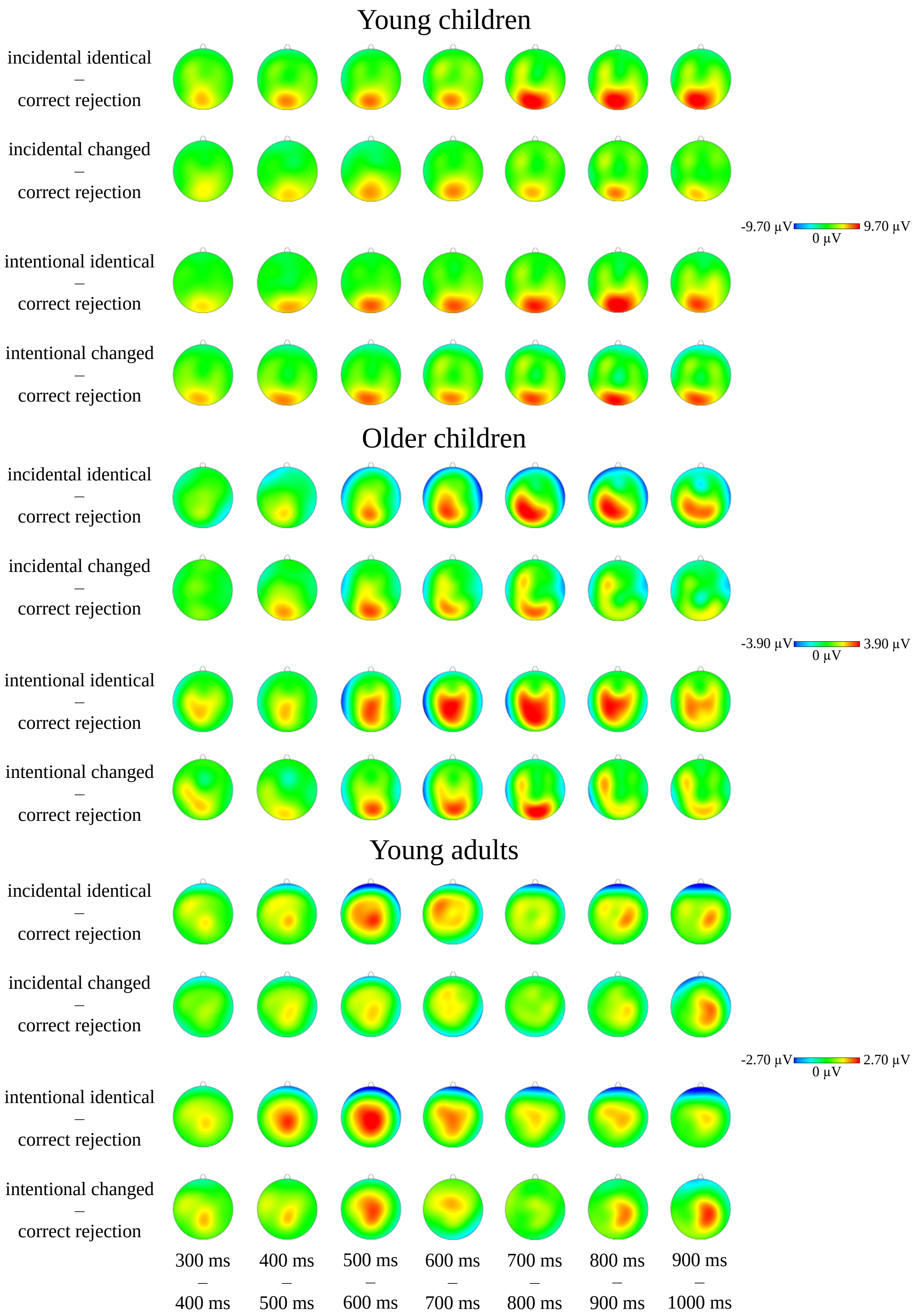

Figure 9. Topographical time course of old/new effects across age groups. This figure depicts the topography of old/new effects during the analyzed time windows (in time segments of 100 ms each) in the three age groups investigated; note the scale differences across age groups. In younger children, parieto-occipital effects are predominantly observed in all conditions, whereas in older children effects are largest at centro-parietal electrode sites. In comparison, adults show a widespread activation for old items that is, generally, much more frontal than in both groups of children.

decision, there is evidence suggesting that some processes attributed to familiarity may continue, parallel to the slower recollection. If recollection is not successful, participants might then again rely on the (still ongoing) familiarity-related retrieval, resulting in familiarity-related, yet slower old/new judgments (for evidence suggesting that early and later familiarity-related processes can be separated, see Besson et al., 2015; Montaldi & Mayes, 2010).

Why do children change their strategy after intentional encoding, as evident in the ICVs and ERP pattern? A change in strategy may either be due to intentional encoding per se, or alternatively, due to the practice with retrieving items in the previous retrieval phase. As the order of incidental and intentional encoding cannot be counterbalanced – after a memory retrieval task, participants are likely to encode items irrespective of the actual task – the current paradigm does not allow to distinguish between these two possibilities. An alternative account that might explain the change between the incidental and intentional encoding is that during intentional encoding condition, one third of old items were presented again (i.e., four times in total; the fourth presentation was either identical or changed: A-A-A-A or A-A-A-B). Behaviorally, items presented three times were more likely to be recognized than items presented once, but ERPs for both item categories were indistinguishable. Although this suggests that both conditions did not differ reliably, this particular research question needs to be addressed by a paradigm specifically tailored for this question. So far, it remains open whether the identical repetition of a subset of stimuli also contributed to the old/new effects observed in older children in the present paradigm.

Taken together, our study provides evidence that not only a response deadline (Mecklinger et al., 2011), but also other task characteristics and perceptual attributes determine whether an ERP correlate of familiarity can be observed in children during middle childhood (i.e., aged 8-10, Mecklinger et al., 2011; aged 9-11, this study). Note that in both studies items that elicited familiarity-based retrieval in children were identical item repetitions with a complete perceptual overlap between study and test. Thus, perceptual overlap might be a considered a necessary, but not sufficient pre-requisite for familiarity-based retrieval, as it was neither observed without a response deadline nor for the incidental encoding condition in the present investigation. This is in line with previous research suggesting that children at the age of eight years match perceptual stimulus aspects to memory contents at adult level (Sprondel et al., 2011) and that familiarity develops between the ages of six and eight years (Ghetti & Angelini, 2008). Moreover, older children have been reported to make less phonological and more semantic intrusion errors than younger children, indicating a development from a more perceptual (bottom-up) to a more conceptual (top-down) processing (5-year-olds and 8-year-olds, Dewhurst & Robinson, 2004; 8-to-11-year-olds, Maril et al., 2011; see also Sloutsky & Fisher, 2004 for pre-school children).

In the later time window (700 – 1000 ms), we observed a continuation of the ERP correlate of recollection from the previous time window for both groups of children. In adults, a late posterior negativity (LPN; Johansson & Mecklinger, 2003), associated with response inhibition and recollective search for perceptual features (Johansson & Mecklinger, 2003), overlapped with this positive old/new effect, as indicated by the lack of reliable old/new effects in this epoch (Haese & Czernochowski, 2015). We found no LPN of comparable extent in children, but in this time window identical and changed items were associated with different topographies (see Figures 8 and 9), particularly in older children. Interestingly, we observed that changed – but not identical – items elicited no late old/new effects after incidental encoding in older children, which might be regarded as a related phenomenon (i.e., a negativity diminishing the positivity reflecting recollection). Similar to the adults' LPN, it could reflect the additional recollection of source-specifying features under conditions of uncertainty (Johansson & Mecklinger, 2003). By contrast, after intentional encoding reliable ERP old/new effects were observed for changed items (although smaller than for identical ones). Notably, the pattern of behavioral data supports this tentative interpretation. If older children employ additional source-specifying recollective search processes for changed items, this should be evident in reaction times – and indeed, they exhibited longer reaction times for changed than for identical items. For younger children, a similar pattern of results suggests a related mechanism. Reaction times to changed items were longer than for identical items and the old/new effects in this time window for changed items are smaller. By contrast, old/new effects were of comparable magnitude in the earlier, recollection-related, time window. However, our paradigm does not allow to further disentangle the cognitive processes underlying this phenomenon, and further studies are needed to replicate this effect. Assessing the developmental trajectory of the LPN might enhance our understanding of the associated cognitive processes across the lifespan, as the LPN and its underlying processes are not entirely understood in adults, either (Johansson & Mecklinger, 2003). As the LPN has been shown to be larger for uncertain responses, one approach would be to assess metacognitive judgments associated with responses. A recent study suggested that children have the necessary metacognitive skills to evaluate and verbalize their confidence in learning (Destan, Hembacher, Ghetti, & Roebers, 2014), so it would be promising to investigate ERPs associated with different levels of response confidence. If children exhibit a higher confidence in their own judgment as a result of additional (source-specifying) retrieval, this metacognitive evaluation might be reflected in a similar negativity in the time window following the ERP correlate of recollection as in adults.

The role of brain maturation and open issues

When comparing the topographies in our age groups (Figure 9), the distribution of old/new effects is very different. Younger children exhibited a positivity for old items selectively at parietal and occipital electrode sites, whereas adults show a much more widespread positivity. Interestingly, older children exhibited old/new effects that were not as widespread as in adults, but still extended further to central and frontal electrode sites than effects in younger children, reflecting the discussed neurological maturation continuing into adolescence (e.g., Casey et al., 2000; Ghetti & Bunge, 2012). Crucially, the prefrontal cortex allows for a more coordinated memory retrieval. For instance, it might be an important support for determining whether an item is considered as "old" – for instance for the discrimination between pre-experimental and induced familiarity of any memory paradigm (Bridger, Bader, & Mecklinger, 2014; Ghetti & Angelini, 2008).

In developmental investigations, it should be noted that the neural architecture of children (e.g., their hippocampus) is not just a smaller version of the functional architecture of the mature nervous system in adults. For instance, in the study by Ghetti and colleagues (2010), activity in the mediotemporal cortex predicted subsequent item recognition, but not subsequent context recognition (i.e., the recognition of an item's color). By contrast, in adolescents and adults, activation in the hippocampus and posterior parahippocampal gyrus predicted successful color recognition, but not general item recognition. This suggests that during adolescence, the brain acquires additional capacities (i.e. a maturing prefrontal cortex) that can be utilized to support memory tasks – as evident in an age-related increase of the functional connectivity between the mediotemporal cortex and the dorsolateral prefrontal cortex (Ofen, Chai, Schuil, Whitfield-Gabrieli, & Gabrieli, 2012). It is conceivable that these additional processing resources allow the brain to specialize the existing regions employed in these tasks. In a similar vein, the memory representations of semantic and episodic memory seem to overlap in children, but no longer in adults (Ofen & Shing, 2013). According to Ofen and Shing, episodic and semantic memory systems might not be as specialized in children as in adults – children rely on rudimentary forms of perceptual, semantic, and episodic memory systems instead. Hence, younger brains are likely to compensate for the immaturity of the frontal lobe by recruiting other cortical areas than adults. Related findings have been found in memory studies with infant monkeys (Bachevalier & Mishkin, 1984) and in response inhibition paradigms conducted with children (e.g., Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002).

Conclusion

The focus of the present study was to assess ERP correlates of familiarity-based retrieval in children, which has previously only been reported by a single study using a response-deadline to eliminate the alternative route to episodic memory retrieval (Mecklinger et al., 2011). While no ERP correlates of familiarity-based retrieval were observed in younger children, older children relied on familiarity under certain conditions only. Replicating and extending previous work, we observed ERP correlates of familiarity for identical item presentations after intentional encoding in older children. By contrast, no reliable old/new ERP effects were observed for changed items and after incidental encoding in any group, likely reflecting a larger heterogeneity in processing. It is possible that some older children mainly rely on recollection, like younger children, whereas others already evaluate an item's familiarity, like adults. Analyzing this heterogeneity in future studies might provide an answer why children seem to rely on familiarity only under some task characteristics.

In our paradigm, children and adults exhibited comparable memory performance in spite of differences in the underlying ERP correlates, presumably due to differences in brain maturation. Comparing topographies of ERP old/new effects, it is evident that successful episodic memory retrieval is associated with different neural computations in each age group during the same task. It is conceivable that children are able to compensate for a less fine-tuned memory system (c.f. DeMaster, Pathman, & Ghetti, 2013) by recruiting additional processes like an early attentional modulation towards item features in younger children and later source-specifying retrieval in older children.

Adaptation of the paradigm based on the results of Study 1 and 2

The results of Study 2 showed that similar to Mecklinger et al. (2011) we succeeded in eliciting both frontal ERP old/new effects indexing familiarity and parietal ERP old/new effects reflecting recollection for children aged 9 to 11, but not for younger children. As illustrated in Figure 9, these effects were only reliable after intentional encoding and only for identical item repetitions, in accordance with our hypothesis that perceptual modulations would affect the ERP component of familiarity and in line with similar evidence in adults (Zimmer & Ecker, 2010).

A key role of the intentional encoding phase is also suggested by analyses conducted on the encoding processes of Study 2 (Köster, Haese, & Czernochowski, 2017). EEG oscillatory analyses revealed an increase in alpha suppression related to age, suggesting an enhancement of semantic processing with increasing age and in line with findings that schooling improves cognitive control (Brod et al., 2017; for a review on the role of semantic knowledge on memory, see Brod et al., 2013). In addition, an increase in frontal theta was observable in all age groups during intentional encoding, whereas posterior theta differed notably. Only younger children showed no increase of posterior theta between both encoding phases which gives rise to the explanation that they could, due to premature encoding processing, not recruit more resources, in contrast to adults and older children. That might explain why younger children were also unable to successfully engage in familiarity-related retrieval at test. As a consequence, it seems, children had to predominantly rely on recollection and an adapted attentional allocation to improve their memory performance as discussed in Study 2. This notion is in line with the finding that encoding processes as well as functional connectivity between brain areas improves in these age groups (c.f. Ofen et al., 2012; Ofen & Shing, 2013).

As can be seen from Study 2, the incidental encoding condition was not sufficient to elicit both familiarity and recollection in the developmental samples. While we learnt that an intentional encoding condition led to reliable early frontal ERP old/new effects reflecting familiarity, the data do not allow a clear-cut statement on why this was the case. Two explanations seem plausible, however: First, the instruction to intentionally memorize pictures gives rise to familiarity-related retrieval in children after a certain age. This suggests that older children, by mere instruction or encouragement, are capable of engaging in semantic encoding similar to adults (c.f. Köster et al., 2017). Second, the experience of the prior incidental study-test cycle granted children knowledge on the nature of possible stimulus changes, so that they could use this knowledge to in turn encode items on a different level in the second, intentional, encoding phase, consequently allowing them access to familiarity-related retrieval. Interestingly, this would mean that somewhen between second and fifth grade, children learn how to adapt their own encoding mechanisms similar to adults so that familiarity as a retrieval process becomes available. It should be noted that the dissociation of observing early frontal old/new effects during one phase, but not the other, is of key importance. This dissociation allows the assumption that children can employ familiarity as a retrieval process but only do so if prompted or given experience in similar tasks. Investigation of this open issue might bear implications for learning of school-aged children and their cognitive development in general.

In order to assess the clear nature of this phase difference in Study 2, we hence adapted the paradigm by removing the incidental encoding condition. Obviously, the sequence of phases could not be reverted as a participant engaging in intentional encoding is likely to adopt similar strategies when encountering the same (or a similar) task and hence might not encode items on an incidental level anymore. The pictorial items that became available due to the discarding of the incidental encoding phase were instead used to increase the stimulus pool to counteract the somewhat larger heterogeneity in children's data compared to adults' data. In doing so we not only hoped to gain more insight into familiarity-related retrieval, but also into further cognitive processes at play during retrieval (e.g., source-specifying retrieval indicated by the LPN or attentional processes indicated by the oddball-resembling parietal positivity). After administering this adapted paradigm to an adult sample, as control group, we found that ERP old/new effects largely differed from the dataset obtained in Study 1. As a consequence, a data-driven approach (Study 3) was used to adapt the time windows used in the analyses for the assessment of ERPs. It is noteworthy that the strict selection of equal time windows across samples may lead to wrong conclusion that a cognitive process is not employed even though it is merely delayed, as reported for delayed executive processes in older adults (e.g., Czernochowski, 2014), or employed at a later time as observed in developmental samples (e.g., Cycowicz et al., 2003; de Chastelaine et al., 2007). In the past, an adjustment of time windows based on visual inspection has proven a viable approach, but in cases in which the ERP averages are less easy to discern, such as here, a data-driven solution may be preferable. The rationale behind this approach is discussed in the following section along with the implications derived from a comparison of Studies 1 and 3.

Study 3

Using temporo-spatial principal component analysis as tool to dissociate latent ERP components of episodic memory retrieval[9]

Abstract

This methodological report details how principal component analysis (PCA) can be used as a valuable tool to dissociate latent ERP components, even when considerable temporal and spatial overlap makes it difficult to discern ERP effects in standard time windows. We illustrate our methodological approach in a data set from a recognition memory paradigm, in which event-related potential (ERP) correlates of familiarity, recollection and the late parietal negativity (LPN) were partially overlapping. By adapting standard time windows based on the results of a temporo-spatial PCA, small yet reliable ERP correlates reflecting familiarity and recollection for identical items and late recollection for changed items were identified, complementing the result pattern observed in behavioral performance. Due to similar temporo-spatial characteristics and opposing polarities in late parietal ERP correlates associated with memory retrieval, component overlap is often observed in this field of research. Hence, the complex interplay of several processes underlying higher cognitive functions such as memory retrieval may interfere with standard ERP assessment. In such instances, PCA can provide promising ways to objectively assess time window selection for subsequent ERP analyses.

Introduction

In an effort to understand human decision making, event-related potentials (ERPs) often complement behavioral data by revealing the mechanisms underlying overt responses. These cognitive processes are associated with modulations of the EEG signal, characterized by specific temporal and spatial properties. These established characteristics are essential as they allow inferences with respect to new paradigms and refined research questions. Latency shifts or the magnitude of ERP components give further insight into the interplay of the specific cognitive processes in a given paradigm. Even though multiple latent cognitive processes underlie each experimental trial in an experiment, specific cognitive sub-processes are isolated by contrasting conditions that ideally vary only in one respect. Since the skull acts as a spatial filter and cognitive processes are functionally interdependent, ERP correlates on the scalp are typically overlapping. Accordingly, "it is extremely

[9] As a part of the cumulative dissertation, this section has been submitted to a peer-reviewed journal (Haese and Czernochowski, under review).

difficult to isolate the latent components so that they can be measured independently, and this is the single biggest roadblock to designing and interpreting ERP experiments. Consequently, one of the keys to successful ERP research is to distinguish between the observable peaks of the waveform and the unobservable latent components" (Luck, 2005, p. 51). To isolate such latent components resulting from overlapping cognitive processes, it becomes necessary to identify subtle differences in the temporal course and topography of each latent component, in other words to find out when and where they do not completely overlap.

These latent components represent ERP correlates for cognitive processes, and are derived from EEG data according to guidelines established in the field of ERP research (Picton et al., 2000; see also Keil et al., 2014) with few degrees of freedom. Accordingly, one might assume that the precise location and exact temporal onset of any ERP correlate is easy to predict. However, task characteristics often affect the onset and/or the magnitude of an ERP correlate (e.g., Zimmer & Ecker, 2010), in particular for higher cognitive processes based on initial perceptual stimulus assessment and attentional prioritization according to task relevance. For instance, attentional allocation towards a stimulus has been shown to affect both the latency and the amplitude of the P300 (Katayama & Polich, 1998; c.f. Sutton et al., 1965 and, for a comprehensive review, Polich, 2007). This difference in attentional allocation between items may induce variability for later, i.e. higher and top-down driven, cognitive processes. But even a change to more or less complex stimuli (e.g. pictures vs. words) may affect the latency of some component cognitive processes, and hence the net result of electrophysiological responses observable at the scalp. Accordingly, the temporal onset of ERP correlates differs considerably across paradigms, specifically for components with a relatively long latency, reflecting higher order cognitive processes. Hence, latent ERP components may become difficult to disentangle due to temporal and/or spatial overlap or relatively small ERP effect sizes. This may be particularly relevant for special populations, e.g. patients, aging populations and children, in which longer response latencies are typically found. It is unclear which cognitive processes in particular are slowed relative to young adults. In these instances, related prior empirical evidence or theoretical considerations may be not sufficient to determine appropriate time windows or electrode locations to be used for a given data set. In these cases, it may prove worthwhile to rely on additional tools for an objective, data-driven analysis.

Principal component analysis as tool to separate ERP components

Principal component analysis (PCA) extracts linear combinations of variables from ERP averages to detect patterns of covariance in the data. These patterns of covariance can be regarded as correlates of cognitive processes – ideally with a single PCA factor representing a single processing step – and are thus closely related to ERP correlates. As such, the PCA is a useful tool for a data-driven detection of "features that might otherwise escape visual inspection" (Dien & Frishkoff, 2004, p. 189). These features can be very small differences between conditions, components with shared temporo-spatial characteristics, or even overlapping components with opposite polarities that cancel each other out.

As episodic memory retrieval is a compound of several underlying cognitive processes (e.g., Tsivilis et al., 2001), we use one of our own datasets to demonstrate that latent ERP components are often difficult to disentangle. Next, we illustrate how the temporo-spatial PCA (Donchin, 1966; Donchin & Heffley, 1979; Ruchkin, Villegas, & John, 1964; see also Dien and Frishkoff, 2004, and Dien, 2012) can serve to objectively identify time-windows of interest. The dataset is in essence a replication of a previous investigation (Study 1) which will also be re-analyzed here to demonstrate that the PCA-based approach is consistent across similar data. We chose to use a temporo-spatial PCA, using the temporal properties of the obtained factors in order to pinpoint time windows of interest; we used the spatial characteristics to validate the correspondence of these PCA factors to the established ERP components. As the temporo-spatial PCA describes the topographical distribution of cortical activity for each PCA factor, we further used the spatial information in order to cross-validate the assumed cognitive processes based on existing literature.

Previous studies (e.g., Curran et al., 2006; Curran & Dien, 2003; Curran & Friedman, 2004; Kayser, Tenke, Gates, & Bruder, 2007) demonstrate the viability of PCA-based approaches in the domain of episodic memory, conceivably because of the multitude of interdependent cognitive processes involved concurrently in this domain. For instance, Curran and colleagues (2006) selectively impaired recollection-based retrieval by administering Midazolam. In line with their hypothesis, Midazolam reduced the magnitude of a PCA factor attributed to recollection, a finding replicated and extended by Nyhus and Curran (2012). Curran and Friedman (2004) presented rotated grayscale images to their participants over the course of several days and participants were instructed to base their memory judgment on the intuitive feeling (i.e., familiarity) or by attempting to successfully recall contextual information (i.e., recollective search). Again, two PCA factors could be found resembling the established ERP components of familiarity and recollection. The application of the PCA method allowed to segregate a spatiotemporal overlap between these two factors. These studies corroborated the temporal and spatial characteristics of the established ERP components of familiarity (frontocentral, 300 to 500 ms) and recollection (parietal, 500 to 800 ms) by using PCA. Hence, this approach supports the detection of the time course of these two ERP components in a data-driven fashion.

Latent components during episodic memory retrieval

Numerous previous investigations (e.g., Mandler, 1980; Tulving, 1985; Tulving & Schacter, 1990; for a review, see Yonelinas, 2002) have demonstrated that recognition memory is supported by two cognitive processes: familiarity and recollection. During memory retrieval, correctly recognized items are characterized by positive deflections compared to items correctly classified as new, and the associated latent ERP components for both processes have been dissociated based on their timing and location (for a review, see Friedman & Johnson, 2000). Familiarity, a sense of having encountered information before, is observed at frontal electrode sites about 300 to 500 ms after stimulus presentation (e.g., Rugg & Curran, 2007), and often considered as an automatic process. In their review, Zimmer and Ecker (2010) suggest that the magnitude of the frontal ERP old/new differences may be affected by the amount of perceptual details – but only if retrieving these details is essential for successful task performance. For instance, when perceptually changed item repetitions are to be categorized as "old" along with identical item repetitions in a so-called inclusion task, both conditions elicit comparable early old/new ERP effects as index for familiarity-based memory retrieval. By contrast, when perceptually changed item repetitions are to be categorized as "new" in an exclusion task, a smaller ERP component of familiarity is observed for this condition. Recollection reflects the results of a more effortful search process, giving access to detailed contextual information like perceptual features or the source of a specific item. The corresponding ERP component is predominantly observed at parietal electrode sites, often accompanied by a more widespread activation between 500 to 800 ms after stimulus presentation (as reviewed by Curran, 2000; Curran & Cleary, 2003; Mecklinger, 2006). Notably, its magnitude has been found to increase when source information is retrieved (Wilding, 2000), in line with the notion that this is a defining characteristic of recollective retrieval. Thus, for both familiarity and recollection, the magnitude of ERP differences is considered an indicator of the quality of episodic memory retrieval and the amount of details retrieved. Notably, both familiarity (e.g., Tsivilis et al., 2001; Zimmer & Ecker, 2010) and recollection comprise several underlying processes, a notion also implicated in the term "late positive complex" (LPC) for the ERP component of recollection.

A third latent ERP component during memory retrieval, the late parietal negativity (LPN), has received much less attention. It has been found in conditions with increased difficulty, as a result of response conflict or increased effort of remembering source-specifying information (for a review on the LPN, see Mecklinger et al., 2016). Accordingly, the LPN is found close to the response, i.e. often during the time-window of recollection (Mecklinger et al., 2007), but takes the form of a relative negativity for correctly recognized items. Hence, both LPC and LPN share topographical and temporal characteristics and can diminish each other's amplitude due to their opposite polarity. The dissociation of the LPC and the LPN is further complicated by the large variability of LPN magnitudes, presumably due to its association with highly variable factors like response conflict and effort that are difficult to control for experimentally, and hence the characteristics of the LPN are still not fully understood.

The goal of this report is to demonstrate that temporo-spatial PCA serves to dissociate latent ERP components elicited during memory retrieval. To achieve this, we will detail our methodological approach, present the results of the PCA analyses on our dataset and compare them with the classic approach. Finally, we illustrate that the PCA provides corresponding results for a related dataset (originally analyzed with the standard approach, Study 1).

Method

Participants

Twenty-five students (mean age 21.2 years; 5 male) from the local university campus participated in this study in exchange for course credit. All participants had normal or corrected-to-normal visual acuity; none of them reported to have been diagnosed with neurological or psychiatric disorders. Before participation, all participants were informed about the procedure and signed an informed consent form, the local ethic committee approved of the administration of the study.

Material

In our paradigm, we employed a set of pictorial stimuli used in a previous study (Haese & Czernochowski, 2015), most of which were taken from Rossion and Pourtois (2004). These stimuli were colored drawings of everyday objects that were easy to identify (even by children; Haese & Czernochowski, 2016). For most stimuli, the stimulus pool had easily discernable matches for which at least one perceptual feature was changed (different size, orientation, or color; sometimes a different specimen of the shown object altogether). Most changed exemplars of the stimuli used in this study consisted of at least two feature changes, hence it was not possible to focus on single item characteristics such as color during study.

Procedure

Participants took part in the memory paradigm together with a task-switching paradigm not reported here, in counterbalanced order in a session of about 2 hours. The memory paradigm consisted of a study phase and a retrieval phase. In the study phase, participants were instructed to memorize each of 160 items while deciding whether the item was more commonly found indoors or outdoors. They were informed that they would re-encounter these items along with new items either in an identical or a changed version. After a fixation cross of 1000 ms duration, participants viewed a single image at the center of the screen. After 1000 ms, the item disappeared to keep encoding times constant. Next, the response options "indoors" and "outdoors" appeared on the screen, button press initiated the next trial. During the two-minute retention interval, we engaged participants in conversation. In the retrieval phase, a fixation cross of 1000 ms was followed by the test items presented at the center of the screen along with the three response options "same", "different", "new". As soon as participants terminated a trial with a button press, the fixation cross preceding the following trial appeared. In the test phase, 240 items were presented: 80 of these items were identical to the exemplar in the study phase, 80 were changed, and 80 were entirely new distractors. Participants categorized these items as identical, changed or new. For identical and changed items, index and middle finger of one hand were used; the index finger of the other hand was used for new items. Assignment to left or right hand was counterbalanced across participants. Before study and test, practice trials were presented to make sure all participants understood the instructions and used all response options. All responses were self-paced – if participants did not press a button within 5 seconds, we encouraged them to react more spontaneously and advised them not to wait until they are completely certain. After presentation of a central fixation cross (1000 ms), stimuli were present for 1000 ms.

Behavioral Analyses

We include behavioral analyses in this methodological report as converging evidence to verify that memory performance was sufficiently high and to validate the observed pattern of electrophysiological results. Note that a low memory performance or atypical reaction times would be in line with attenuated ERP correlates of memory retrieval and could be related to increased guessing.

Hence, we disambiguated the ability to discriminate between old and new items from the ability to discriminate between old items presented in identical or changed perceptual format. These behavioral analyses mainly served to verify that memory performance was sufficiently high, as performance close to chance levels attenuates the ERP correlates of episodic memory performance due to frequent guessing. Old/new memory performance was defined by the sensitivity score Pr (Hit rate - False Alarm rate; cf. Snodgrass & Corwin, 1988), whereas we measured specific memory performance by computing Feature Hits for identical and changed items. These Feature Hits were defined as the proportion of correct "identical" or "changed" classifications for identical and changed items, respectively. As differences between these scores may also reflect differences in response bias, we further computed paired *t*-tests on the response rates for correctly recognized old items. Response Rate Identical and Response Rate Changed were defined as items categorized as "identical" or "changed" (respectively) when old. Complementarily, we evaluated false alarm rates (i.e., the rate of "old" responses given a new item) for identical and changed items separately.

In order to evaluate differences between identical and changed items in Feature Hits and Response Rates, we conducted two paired sample *t*-tests.

Furthermore, we compared RTs of items correctly attributed to their respective item category as well as to those correctly recognized as old but with false source attribution (i.e., Feature misses). Reaction times below 200 ms and above 3000 ms were discarded from analysis. For these analyses, we computed a Repeated-measures ANOVA on the factor Reaction Time (Feature Hits Identical, Features Misses Identical, Feature Hits Changed, Feature Misses Changed, Correct Rejections). Statistically significant differences were subjected to (Bonferroni-corrected) post-hoc t-tests to further qualify this effect.

Data Preprocessing

We measured EEG with active Ag/AgCl electrodes according to the extended 10-20 system at the following positions: FP1, FP2, AF7, AF3, AFz, AF4, AF8, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, CP1, CP2, P7, P3, Pz, P4, P8, O1, O2. After offline re-referencing to linked mastoids, we restored FCz. Impedances were kept below 25 kΩ (500 Hz sampling rate, A-D converted with 16 bit resolution; offline Butterworth band-pass filter of 0.1 Hz – 30 Hz, 24 dB/oct).

We corrected for ocular movements by applying an ICA-based correction on the basis of the EOG, for which electrodes above and below the right eye as well as F9 and F10 were used. In order to detect artifacts, we used a semi-automatic procedure, in which trials meeting at least one of the following criteria were detected: (1) gradient of the EEG amplitude exceeded 20 μV/ms at any electrode site, (2) within 200 ms, the voltage increased or decreased more than 75 μV, or (3) for 100 ms, activity fell below 0.5 μV. These trials were manually inspected and were rejected when necessary. Muscular artifacts were corrected during the ocular ICA based on magnitude and topography. For all EEG preprocessing steps, Vision Analyzer 2.0.3 (Brainproducts GmbH, Gilching, Germany) was used. If necessary, we applied a spherical spline interpolation (Perrin et al., 1989).

We analyzed correct responses for each item type to investigate ERP effects of successful memory retrieval in epochs from -100 ms prior to stimulus onset (baseline correction) until 3000 ms. For comparison of ERPs reflecting successful memory retrieval, we compared Feature Hits for identical and changed items (i.e. "identical" responses to identical and "changed" responses to changed items) to correct rejections. We excluded responses that took more than 3000 ms. Means and ranges of trial numbers, after artefact rejection, were as follows: 53 Feature Hits Identical (31-76), 36 Feature Hits Changed (20-53), 60 Correct Rejections (38-78).

PCA analyses

We computed a PCA using the ERP PCA toolkit for Matlab (Dien, 2010a) in the two-step PCA procedure described by Dien (2010b; see also Spencer, Dien, & Donchin, 1999; 2001) to identify the channels in which activity was most pronounced. This PCA procedure consists of two steps: First, a temporal PCA is computed to separate ERP effects based on their temporal distribution to discover peaks in the time course of an ERP. Second, a spatial PCA is conducted on the factor solutions to further separate these effects on a spatial level (i.e., the location on the scalp). We closely followed the protocol suggested by Dien (2010a), using first a Promax rotation (kappa of 3, covariance relationship matrix) to calculate the temporal PCA and then a spatial Infomax rotation (Delorme & Makeig, 2004). For both of these steps in the temporo-spatial PCA, we used the parallel analysis (Horn, 1965) implemented in the PCA toolkit to determine factors that explained more variance than simulated random data. Among those factors, we then pre-selected those explaining up to 95% of the total variance before evaluating the latencies and topographical distributions of these factors to determine those resembling the established ERP correlates of episodic memory. Notably, we only used the spatial PCA to evaluate the topographical distribution in order to evaluate whether these temporal PCA factors plausibly reflect established ERP components of episodic memory retrieval.

ERP Analyses

During time windows identified by use of PCA as detailed above, we compared ERP differences during memory retrieval between old and new items, separately for identical and changed items. Our ERP analyses were based on the following 12 electrode sites forming the topographical 4 X 3 electrode grid used for further analyses: AF3, AFz, AF4 (anterio-frontal); F3, Fz, F4 (frontal); C3, Cz, C4 (central); P3, Pz, P4 (parietal). In order to characterize these ERP old/new effects, we computed Repeated Measures ANOVAs with the factors Anterior-Posterior (anterio-frontal, frontal, central, and parietal) and LAT (left, middle, right electrodes), and Item Type (Feature Hits Identical, Feature Hits Changed, and Correct rejections). For a further inspection of effects of Item Type, we compared planned contrasts for Feature Hits Identical vs. Correct Rejections and Feature Hits Changed vs. Correct Rejections. ERP correlates of familiarity and recollection are commonly distributed at frontal and parietal electrode sites, respectively, so we performed subsidiary analyses separately at anteriofrontal, frontal, central, and parietal electrode sites to further disentangle these effects. In order to allow a direct comparison of the PCA-based method with the standard approach for time window selection, we provide the results of the ANOVA on standard time windows in the Appendix. For the sake of brevity, we only report effects that are associated with the factor Item Type. Greenhouse-Geisser correction (Jennings & Wood, 1976) was applied where necessary; in these instances, corrected p values are reported with the appropriate ε-values, whereas degrees of freedom are reported in their uncorrected form.

Results

Memory performance

In comparison to other studies (see e.g. Zimmer & Ecker, 2010 for a review), participants exhibited a high memory performance (Pr = .72, SD = .12). An evaluation of Feature Hits revealed a higher specific memory performance for identically presented items (.83, SD = .10) than for perceptually changed items (.67, SD = .11), $t\,(24) = 4.59$, $p < .001$. Participants did not show a tendency to respond "old" rather than "new" (bias index Br = .47, SD = .2, cf. Snodgrass & Corwin, 1988); however, response rates for identical and changed items showed that participants were more likely to respond "identical" (.59) than "changed" (.41) to items correctly recognized as old, $t(24) = 5.68$, $p < .001$. A detailed overview on the proportions of the different participant responses is given in Table 11. Accordingly, based on the literature, reliable ERP correlates of familiarity and recollection are to be expected at this level of memory performance.

Table 11. Proportions of participants' responses to each item type (standard deviations are given in brackets).

		Participant response		
		"Identical"	"Changed"	"New"
Item Type	Identical	.76 (.12)	.15 (.08)	.09 (.06)
	Changed	.26 (.09)	.54 (.11)	.20 (.09)
	New	.06 (.05)	.08 (.06)	.86 (.09)

Reaction times

Reaction times are given in Table 12. Analyzes on RTs revealed a reliable difference across item types, $F = 18.79$, $p < .001$ (ε = .61, Greenhouse-Geisser correction applied). As illustrated in Figure 10, follow-up t-tests suggest that Feature Hits Identical were faster than the remaining "old" responses (all ps < .01), but comparable in speed to Correct Rejections ($p = .68$). Generally, RTs were larger for changed items (Feature Misses Changed vs. Feature Hits Identical: $p < .01$; Feature Hits Changed vs. Correct Rejections and Feature Hits Identical: both ps < .001). Feature Misses Identical were also associated with longer RTs (vs. Feature Misses Changed: $p < .05$; vs. Correct Rejections: $p < .01$), but were comparable to Feature Hits Changed, $p > .99$). This pattern of RT data suggests that latency differences are modulated by response uncertainty: fast RTs were observed when response uncertainty was low, whereas RTs increased along with response uncertainty, i.e. for changed items or Feature Misses. Together with the high memory performance, this finding further supports our expectation that successful memory retrieval should also be reflected in ERPs.

Table 12. Reaction Times of correct responses, i.e. Feature Hits, Correct Rejections, and Feature Misses (correct old judgment with incorrect source attribution). Standard deviations are given in brackets.

		Participant response		
		"Identical"	"Changed"	"New"
Item Type	Identical	Feature Hit Identical 1261 ms (130 ms)	Feature Miss Identical 1596 ms (272 ms)	—
	Changed	Feature Miss Changed 1392 ms (191 ms)	Feature Hit Changed 1531 ms (222 ms)	—
	New	—	—	Correct Rejection 1309 ms (189 ms)

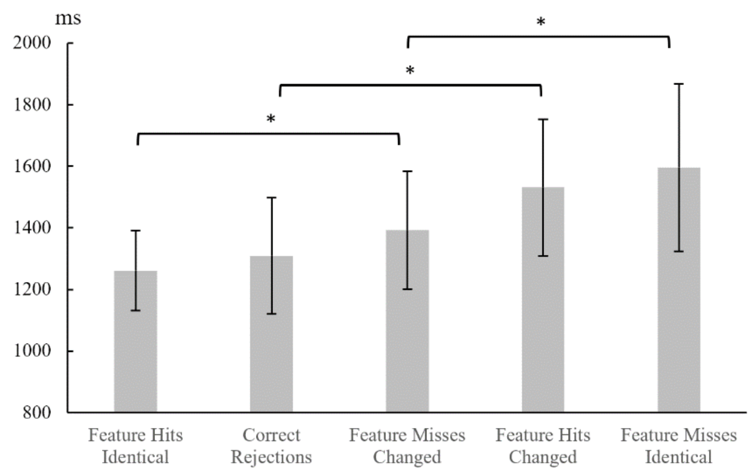

Figure 10. Reaction times for each correct response category, arranged by response speed.

ERP old/new effects

Visual inspection of the ERP data suggests that old/new differences in amplitudes occur at frontal electrodes at about 350 – 400 ms; similar differences were difficult to discern at parietal electrodes where many prior studies demonstrated robust old/new effects associated with recollection around 500 – 800 ms. In the present dataset, negative amplitudes for remembered items emerged at around 600 – 800 ms. The temporal and topographic characteristics suggest that this is due to the concurrent onset of an LPN.

As can be seen in Figure 11, ERP differences between conditions in this study were much more difficult to discern than in comparable studies . However, in both time windows under investigation here effects are apparent upon visual inspection. We hence first analyze effects in theory-driven time windows (300 – 500 ms for familiarity, 500 – 800 ms for recollection) and then additionally use a PCA to adjust the theory-driven selection of time windows. As the paradigm used here to investigate episodic memory retrieval was not investigated with the PCA method before, we re-analyzed the findings reported by Haese and Czernochowski (2015) as supplementary analysis.

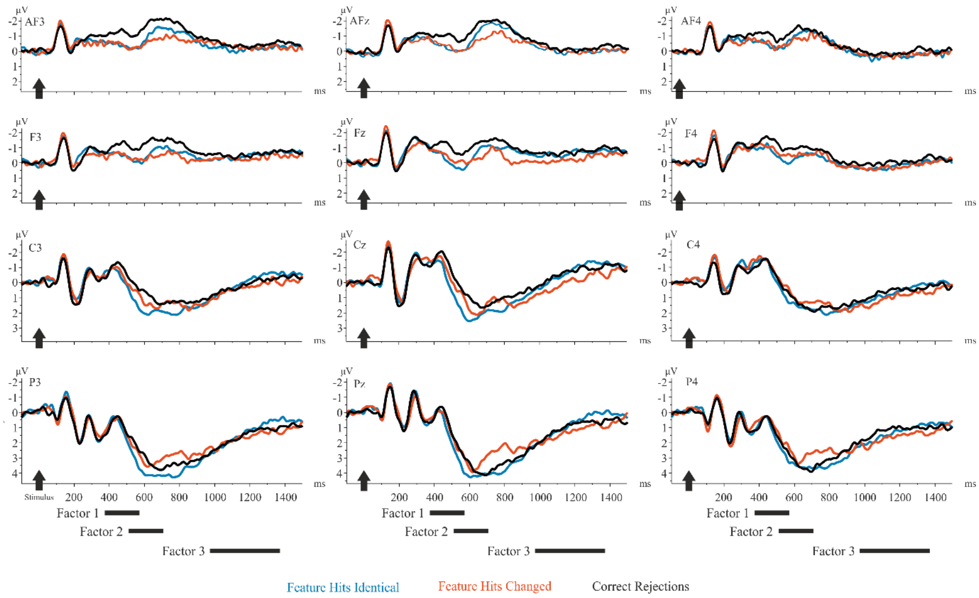

Figure 11. ERP amplitudes of successful episodic memory retrieval for identical items (green) and changed items (red) as well as correct rejections (black) in the current study. The black bars below the graphs demark the time windows adjusted on the basis of the PCA factor peaks.

ERP analyses with PCA-based time windows

Based on a first temporal PCA with the steps outlined above (25 factors retained, accounting for 92% of variance by Promax solution), we determined factors that each explained more than 10 % of variance: TF01 (peak at 708 ms), TF02 (1176 ms), and TF03 (474 ms). Together, these temporal factors accounted for 57% of total variance. Consecutively, we computed a temporo-spatial PCA in order to evaluate if these factors plausibly reflect the established ERP components of familiarity and recollection. In this second PCA, 3 factors were retained, together accounting for 75% of variance (Infomax solution). As the paradigm has previously (Haese & Czernochowski, 2015) succeeded in eliciting ERP components of familiarity and recollection, we selected factors resembling these components based on both temporal latency and topographical distribution. We concluded that Factor 1 reflects the FN400 (TF03 at 474 ms), Factor 2 reflects the LPC (TF01 at 708 ms); although not explicitly predicted, we evaluated Factor 3 as a late onset of recollection selectively for changed items (TF02 at 1176 ms); these factors are depicted in Figure 12. Based on these temporal durations, we then analyzed grand averages of time windows based on the following time windows: 374 – 574 ms, 508 – 908 ms, 976 – 1376 ms. A complete overview of ERP old/new effects in these selected time windows can be seen in Table 13.

374 – 574 ms (Factor 1)

More positive amplitudes for identical item repetitions versus correct rejections were observed at anteriofrontal, frontal, and central electrode sites, all *p*s < .05, whereas changed items only elicited

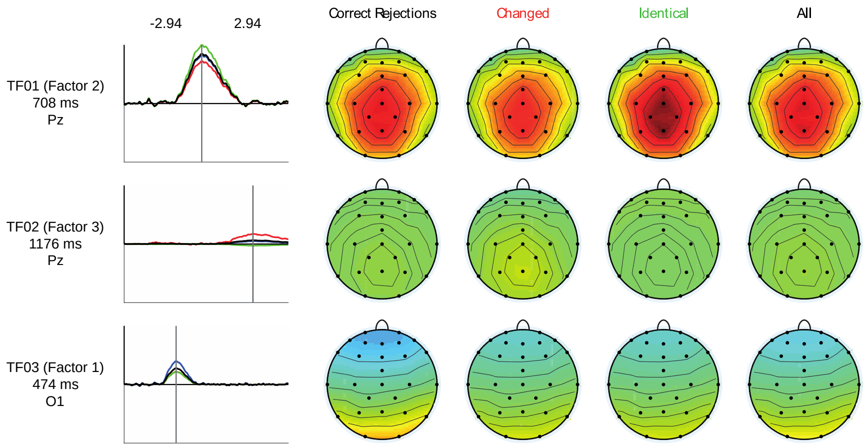

Figure 12. Topographies of the three PCA factors calculated from episodic memory data of study 3. The image was exported from the PCA toolkit (Dien, 2010a) and slightly modified for enhanced clarity. Factors have been relabeled in their temporal order.

reliably more positive amplitudes than correct rejections at anteriofrontal electrode sites, $p < .05$. Effects at parietal electrode sites were not observed, $p = .28$.

508 – 908 ms (Factor 2)

In this time window, we observed a widespread positivity for old items, in particular for those presented identically. Identical and changed items exhibited more positive amplitudes than new items at anteriofrontal and frontal electrodes, *p*s < .05. In addition, we observed a parietal old/new effect, $F(2,48) = 5.99$, $p < .01$, $\eta^2_p = .20$. Planned contrasts revealed a trend towards more positive amplitudes for identical compared to new items (old/new difference = 0.5 µV, $p = .08$), whereas changed items elicited numerically more negative amplitudes than new ones (old/new difference = -0.4 µV, $p = .14$). Interactions between Condition X Laterality indicate that old/new differences were larger at left than at right electrodes at anteriofrontal, frontal and central electrodes in this time window, all *p*s < .05. For parietal electrode sites, this interaction was observed as a statistical trend ($p = .06$), and old/new effects were restricted to identical items eliciting more positive amplitudes than new items, $t(24) = 2.67$, $p < .05$ at electrode P3, but not PZ or P4.

976 – 1376 ms (Factor 3)

We observed a trend for an interaction of Itemtype x LAT, $F\,(4, 96) = 2.36$, $p = .059$, $\eta^2_p = .089$. Reliable condition effects were observed at midline ($p = .02$) and right electrode sites ($p = .04$). Planned contrasts indicated reliable effects between changed and new items at midline

$F(1,24) = 4.77$, $p = .04$, $\eta^2_p = .17$ and right electrode sites $F(1,24) = 5.21$, $p = .03$, $\eta^2_p = .18$, but not between identical and new items (all ps > .09).

Cross-validation of PCA-based time window selection in another dataset

Irrespective of ERP component overlap, any valid method needs to provide comparable results for corresponding data. Hence, we used the PCA-based selection of ERP time windows on a related dataset with a highly similar paradigm[10] and compared the results to the standard analysis approach reported in Study 1. A complete overview of the selection of time windows and the associated ERP old/new effects can be found in Table 14, the corresponding PCA factors are depicted in Figure 13.

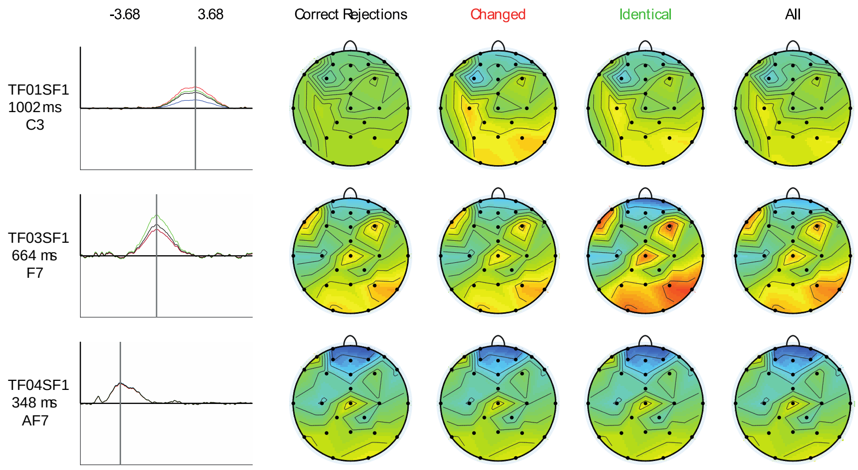

Figure 13. PCA topographies calculated from the reanalysis of previously published episodic memory data. Image exported from the PCA toolkit, slightly modified for enhanced clarity.

248 – 448 ms (Factor 1)

We observed a main effect of Itemtype, $F(2,34) = 9.95$, $p < .001$, $\eta^2_p = .37$, with planned contrasts indicating that both identical and changed items were associated with more positive amplitudes than new items, both ps < .01. There were no reliable interactions, ps > .22.

464 – 864 ms (Factor 2)

A main effect of Itemtype was observed, $F(2,34) = 9.65$, $p < .001$, $\eta^2_p = .36$; planned contrasts allow the conclusion that both identical and changed items elicited more positive amplitudes than correct rejections, both ps < .01. No interaction effect exceeded the significance threshold, all ps > .19.

802 – 1202 ms (Factor 3)

ERP analyses on the time window based on the third PCA factor revealed a main effect of Itemtype, $F(2,34) = 5.01$, $p < .05$, $\eta^2_p = .23$; planned contrasts showed that averages of both

[10] The paradigm reported in Study 1 includes an incidental as well as an intentional encoding – test cycle and a slightly smaller number of items to be studied.

identical and changed items exhibited reliably more positive amplitudes than new items. No interactions were statistically significant, all *p*s > .12.

Taken together, these effects are similar to the original results derived from the standard analysis discussed in detail in Study 1. Hence, this reanalysis provides evidence that the method is suitable for related datasets and specifically provides essentially the same results in a highly similar paradigm.

Discussion

In this report, we demonstrate how temporo-spatial PCA can be used to identify time windows for subsequent ERP analyses. We centered the time windows for ERP analyses around the peak of temporal PCA factors, whereas the temporal course of the PCA components served as a guideline for the respective duration. In addition, the spatial topographies served as validation to identify PCA factors representing cognitive processes commonly studied in episodic memory retrieval tasks. Together, the selected temporal PCA factors attributed for 57% of total variance. Despite component overlap that made it difficult to discern latent ERP components, PCA-based results were in line with the high behavioral performance and previous results relying on the standard analytical approach. Notably, PCA-based selection of time windows also yielded highly similar results for a related dataset in which component overlap was less prominent. Together, these results support the use of temporo-spatial PCA as an objective tool for data-driven selection of time windows to account for subtle differences in the timing and complex interaction of the cognitive sub-processes supporting successful task performance.

Use of PCA-based time windows confirmed our initial predictions that ERP correlates for familiarity-based memory retrieval were of comparable magnitude for identical and changed items, whereas recollection-related ERP old/new effects were larger for identical compared to changed items. Note that analyses of recollection-related effects showed very similar results irrespective of the method used to determine time windows, as both time windows are similar in their temporal onset. In addition, a third PCA factor indicated another time window of interest at 976-1376 ms. As we did not observe a reliable correlate of recollection for changed items in the second time window (508-908 ms), together this pattern of results suggests a longer latency of recollection for changed items. Hence, PCA-based time window selection also allows to account for conditions with longer response latencies for which it is unclear whether they should be evaluated in the standard or modified time windows according to visual data inspection.

Table 13. Overview of ERP differences between identical and changed items in PCA-based time windows in the current study.

Effect (df_1,df_2)	374 – 574 ms			508 – 908 ms			976 – 1376 ms		
	ε	*F*	η^2_p	ε	*F*	η^2_p	ε	*F*	η^2_p
Across all electrode sites									
Item Type (2,48)		4.62*	.16		5.21**	.18	—		
Identical vs. CR (1,24)		10.38**	.30		10.72**	.31	—		
Changed vs. CR (1,24)	—			—			—		
AP X Item Type (6,144)	—			0.40	6.99**	.23	—		
LAT X Item Type (4,96)	—				4.91**	.17	—		
AP X LAT X Item Type (12,288)	—			0.53	2.61*	.10	—		
Anterio-frontal									
Item Type (2,48)	0.81	5.37*	.18		6.15**	.20	—		
Identical vs. CR (1,24)		14.33***	.37		5.34*	.18	—		
Changed vs. CR (1,24)		5.17*	.18		10.77**	.31	—		
LAT X Item Type (4,96)	—			0.74	8.87*** [b]	.27	—		
Frontal									
Item Type (2,48)	0.79	4.77*	.17		7.12**	.23	—		
Identical vs. CR (1,24)		14.07***	.37		10.87**	.31	—		
Changed vs. CR (1,24)	—				10.18**	.30	—		
LAT X Item Type (4,96)	—				4.29** [b]	.15	—		
Central									
Item Type (2,48)		3.40*	.12		4.97*	.17		4.42*	.20
Identical vs. CR (1,24)		5.29*	.18		8.48**	.26	—		
Changed vs. CR (1,24)	—			—				4.81*	.20
LAT X Item Type (4,96)		3.33* [a]	.12		3.08* [b]	.11	—		
Parietal									
Item Type (2,48)	—				5.99**	.20	—		
Identical vs. CR (1,24)	—			—			—		
Changed vs. CR (1,24)	—			—			—		
LAT X Item Type (4,96)	—			—			—		

[a] C3, Cz: Identical > Correct Rejection

[b] AF3: Identical > Correct Rejection < Changed, AFz: Changed > Correct Rejection
F3, Fz: Identical > Correct Rejection < Changed, F4: Identical > Correct
C3,Cz: Identical > Correct Rejection

Table 14. Overview of differences between identical and changed items in all time windows in Haese & Czernochowski (2015)

Effect (df1,df2)	248 – 448 ms			464 – 864 ms			802 – 1202 ms		
	ε	F	η^2_p	ε	F	η^2_p	ε	F	η^2_p
Across all electrode sites									
Item Type (2,34)		9.95***	.37		9.65***	.36		5.01*	.23
Identical vs. CR (1,17)		18.27***	.52		18.87***	.53		5.22*	.24
Changed vs. CR (1,17)		13.26**	.44		13.02**	.43		7.69*	.31
AP X Item Type (6,102)		—			—			—	
LAT X Item Type (4,68)		—			—			—	
AP X LAT X Item Type (12,204)		—			—			—	
Anterio-frontal									
Item Type (2,34)		—			—			—	
Identical vs. CR (1,17)		—			—			—	
Changed vs. CR (1,17)		—			—			—	
LAT X Item Type (4,68)		—			—			—	
Frontal									
Item Type (2,34)		5.03*	.23		4.74*	.22		—	
Identical vs. CR (1,17)		8.17*	.33		8.09*	.32		—	
Changed vs. CR (1,17)		5.11*	.23		5.36*	.24		—	
LAT X Item Type (4,68)		—			—			—	
Central									
Item Type (2,34)		8.09**	.32		8.00**	.32		4.99*	.23
Identical vs. CR (1,17)		10.95**	.39		10.75**	.39		6.18*	.27
Changed vs. CR (1,17)		22.44***	.57		22.27***	.57		6.17*	.27
LAT X Item Type (4,68)		—			—			3.32* [a]	.16
Parietal									
Item Type (2,34)		4.26*	.20		4.18*	.20		—	
Identical vs. CR (1,17)		7.17*	.30		6.86*	.29		—	
Changed vs. CR (1,17)		—			—			—	
LAT X Item Type (4,68)		—			—			—	

[a] Only at C4

Component overlap due to shared temporal and spatial ERP characteristics as illustrated by the LPC and LPN

The ERP component of recollection has been found to be larger when additional source information is retrieved at test (Wilding, 1999, 2000). However, in other paradigms no association between the magnitude of the ERP correlate of recollection and behavioral memory performance is observed (MacLeod & Donaldson, 2017), demonstrating that even well-established ERP components are subject to further evaluation and characterization. Isolating functionally related ERP components may be difficult to realize under certain task characteristics. For instance, when the same items are re-studied repeatedly, eventually new items may become particularly salient and hence elicit an oddball-like P300 positivity that may attenuate the LPC (see also Czernochowski et al., 2009). The close intertwining of recollective search (LPC) and the search for source-specifying information (LPN) is a good example for two cognitive processes sharing topographical and temporal characteristics counteracting each other due to opposite polarity. As complex cognitive processes like episodic memory retrieval tap into a cascade of several subprocesses and only the net outcome is evident in grand averaged ERPs (Tsivilis et al., 2001; Zimmer & Ecker, 2010), it is plausible that different task demands may differentially affect some of the underlying processes and hence contribute to differences in the grand averages of successful memory retrieval Component overlap may be one prominent reason that sometimes a high performance in an episodic memory task requiring contextual details, i.e. behavioral evidence for recollection, does not match the pattern of ERP results. In such cases, it seems worthwhile to reconsider the data with a PCA-based approach and to systematically examine whether an LPN may have been masking LPC effects.

Component overlap with sustained neural activity as illustrated by the potential role of retrieval orientation

An overlap of latent ERP components is not restricted to constellations in which several cognitive processes are associated with ERP effects with similar topography and onset latency, but opposing polarity. Component overlap may also occur with sustained ERP modulations: Comparing the current dataset to our previous study (see Fig. 14) revealed that the main difference between ERP averages was apparent in correct rejections, which took the form of a topographically widespread positivity between 200 ms and 1400 ms post-stimulus, i.e. throughout the time windows used to assess ERP old/new effects. As old/new effects are defined as relative difference between old and new items, a phasic change for new items has considerable effects on the magnitude of old/new effects and hence might account for the small magnitude of these effects in the present dataset that is difficult to reconcile with the high behavioral memory performance. Our current dataset does not allow us to directly compare the two datasets across studies, but we would like to offer a possible account for this phenomenon.

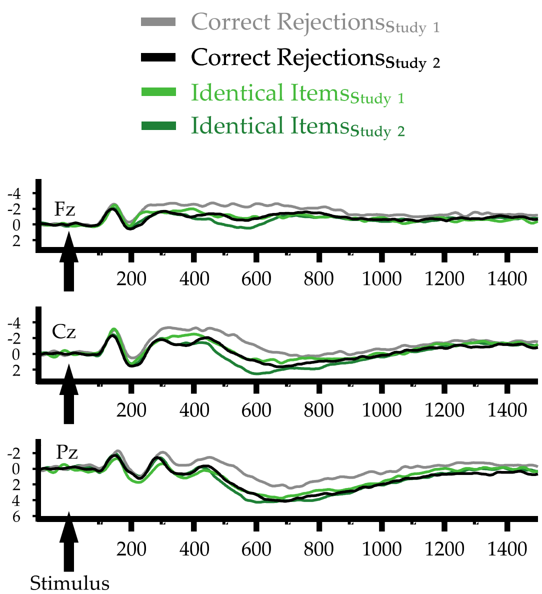

Figure 14. Comparison of ERP averages in Study 1 and Study 3. Green lines indicate successful item recognition for identical items, correct rejections are depicted in black and gray. Note the positive amplitudes of correct rejections in the current study as opposed to the 2015 study.

By definition, differences in correct rejections cannot originate from differences in memory traces as these items are encountered for the first time during the memory test; they cannot reflect successful memory retrieval, but are likely to reflect an attempt to retrieve information from memory (Bridger, Herron, Elward, & Wilding, 2009; Doidge, Evans, Herron, & Wilding, 2017; Rosburg, Mecklinger, & Johansson, 2011). Previous studies have demonstrated that this so-called retrieval orientation – associated with frontally accentuated positive ERP modulation – represents a change in cognitive states in response to specific retrieval requirements (e.g., Herron, Evans, & Wilding, 2016; Rugg & Wilding, 2000; for an overview, see Herron, 2018). For instance, Ecker and Zimmer (2009) used two retrieval cues to ask participants to engage in either an inclusion or an exclusion task, thereby inducing different retrieval orientations. Participants flexibly adjusted their retrieval orientation on a trial-by-trial basis as indexed by ERP differences in correct rejections. Evidently, retrieval orientation can be controlled in a top-down process, as also illustrated by the recent finding of Herron (2018) that the depletion of executive resources due to a preceding Stroop task reduced differences in retrieval orientation. Related investigations revealed that task-specific retrieval orientation increases retrieval accuracy (Bridger et al., 2009; Bridger & Mecklinger, 2012; Roberts, Tsivilis, & Mayes, 2014) and supports strategic recollection of task-relevant information (Dzulkifli & Wilding, 2005; Herron & Rugg, 2003; Morcom &

Rugg, 2012), corroborating the view that retrieval orientation reflects a viable, flexible top-down modulation of attentional resources to enhance the own retrieval attempt. Based on visual inspection (personal communication; raw data available online, Herron, 2019), these effects of retrieval orientation are not restricted to a preparatory interval (Herron, 2018), but also evident during memory retrieval per se.

Since retrieval orientation is a flexible top-down modulation that changes on a trial-by-trial basis, it is plausible that retrieval orientation may also differ across conditions (see also Leynes et al., 2017, for a related argument concerning multiple sources contributing to absolute FN400 amplitudes). For instance, when no memory trace can be identified, as is the case for new items, participants may continue and intensify their memory search. However, this post-hoc explanation needs to be carefully tested in future studies. More research on retrieval orientation and individual differences in cognitive control resources and the motivation to invest increased effort (see also Ferdinand & Czernochowski, 2018) is needed to disentangle positive deflections associated with retrieval orientation vs. retrieval success.

Advantages of employing temporo-spatial PCA for refining time window selection

The present study illustrates how temporo-spatial PCA can be employed to refine the selection of time windows for ERP analyses. The major advantage of this approach is that the need for implicit assumptions is limited as information inherent in each dataset is used in an objective way. For instance, when patient or developmental samples are assessed, in most cases a considerable delay in response times is observed, raising the question whether time windows for ERP analyses should be adapted, and if so, whether this applies to all cognitive sub-processes underlying task performance to the same extend. Visual data inspection may give a first impression, but is not well-suited for informed decisions, as peaks in the net ERPs do not necessarily co-occur with the underlying latent components (cf. Luck, 2005).

In the present dataset, we used the spatial characteristics of PCA factors to cross-validate the proposed cognitive processes under investigation. However, a similar logic applies to the spatial domain, in which the selection of electrode locations may be refined by the spatial characteristics of PCA factors. Of course, PCA is not tailored for all difficulties encountered with standard ERP analyses. When the main research question is by which point in time two conditions start to diverge, jackknifing techniques (e.g., J. Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001) offer far better solutions. Another limitation is that the PCA does not maximize differences between conditions, but serves to reveal the factors underlying the overall signal instead (cf. Figure 13). Unfortunately, to date only a handful of previous investigations employed this method to complement standard analyses of episodic memory processes (e.g., Curran et al., 2006; Curran & Dien, 2003; Curran & Friedman, 2004; Kayser et al., 2007). Another example is the application for the detection and quantification of developmental within-subject changes in spatial and temporal characteristics of ERP components (Mulligan, Infantolino, Klein, & Hajcak, 2019). This phenomenon may be related to a more general reluctance in the field to base new findings on a different statistical ground as compared to previous work. However, when PCA is used to refine rather than replace standard ERP analyses, new findings are readily integrated in a larger body of literature. As a result, inconsistencies across investigations may start to be resolved and attributed to more subtle changes in cognitive operations, for instance how individuals strategically modulate and control cognitive sub-processes in the service of overall task performance.

Conclusion

As evident in this study, the disambiguation of latent ERP components can prove difficult, for instance when positive and negative deflections co-occur with similar temporal and spatial characteristics. In these cases, the established approach of using standard electrode locations and time windows based on theoretical considerations as well as (potentially limited) prior evidence may not suffice. Here we used the results of a temporal PCA to select time windows for more refined ERP analyses. In PCA-based time windows, old/new effects reflecting both familiarity and recollection in episodic memory retrieval were revealed. We propose that two factors were responsible for the small magnitude of ERP effect sizes in the present investigation, despite high memory performance: (1) the occurrence of a large LPN which diminished the LPC indexing recollection in particular for items with changed perceptual features, and (2) an increased effort to retrieve perceptual details (i.e., change in retrieval orientation) when no memory trace could be identified (c.f. Herron, 2018)

(cf. Herron, 2018). Future studies need to consider conceptual versus perceptual task requirements in more detail, specifically when participants can strategically invest differential effort for each memory condition. Complementing standard approaches of ERP research with new tools like PCA can help to disentangle the flexible use of subprocesses involved in memory retrieval like item saliency, familiarity and recollection as well as differential search for source-specifying information and their respective role for retrieval success.

General discussion

This dissertation was part of a research project aimed at elucidating the complex interplay between executive functions and episodic memory retrieval. In these studies, participants participated in two experiments in counterbalanced order which investigated episodic memory (detailed in the studies above, Haese & Czernochowski, 2015, 2016, under review; Köster et al., 2017) and cognitive control (Czernochowski, 2014, 2015).

In Study 1, a newly developed paradigm tailored to facilitate familiarity-based retrieval in children was administered to young adults in order to critically test its viability for the purpose of the project. As described above, the characteristics of the paradigm allowed the investigation of both familiarity and recollection in retrieval phases after incidental and intentional encoding. In line with Zimmer and Ecker (2010), perceptual modifications in combination with our exclusion task allowed the investigation of the ERP components of familiarity and recollection as well as the LPN. Here, the comparison of stimulus-locked and response-locked analyses supported the rationale that the LPC reflecting recollection and the LPN may, due to their shared temporal and spatial characteristics and their opposite polarities, attenuate each other, possibly impairing measurement of recollection in ERPs. It is plausible that such effects have been confounding factors in recent studies (MacLeod & Donaldson, 2017) which brought up evidence seemingly contrasting early studies of memory retrieval correlates (Wilding, 2000). In Study 2, this paradigm was used to bridge the gap in the literature that no ERP correlate of familiarity was observable in most developmental studies of episodic memory retrieval in spite of behavioral evidence suggesting children employing this process. Older children aged 9 to 11 exhibited ERP correlates of both familiarity and recollection after intentional encoding and for identically presented pictures. This gives strong support to the notion that the ERP component of familiarity is affected by task characteristics as well as by age (or brain maturation). In an effort to further understand the exact factors eliciting familiarity-related ERP old/new effects, we changed a few aspects of the experimental task employed in the paradigm in Study 3. Surprisingly, this led to a very different pattern of results, giving rise to the question which cognitive subprocesses underly ERPs of episodic memory retrieval. In an effort to reduce biases, we used a principal component analysis to adjust time windows used for the ERP analysis in an unbiased data-driven approach. Taken together, the studies demonstrate the complexity of cognitive processes involved during episodic memory retrieval (as discussed in Study 3 and as previously suggested in articles of, for instance, Ecker & Zimmer, 2009; Henke, 2010; Tsivilis et al., 2001) and the successful application of this paradigm to the involved research questions in both young adults and children. Accordingly, it seems worthwhile to consider addressing the remaining open questions with this paradigm or related experimental tasks. I will discuss the implications of the studies for the investigation of episodic memory retrieval in this section.

While the paradigm used for the investigation of episodic memory in the Studies 1 – 3 has proven effective, there are, of course, alternative viable approaches to the investigation of episodic memory retrieval. Past ERP studies evaluated memory processes with pictorial (e.g., Curran & Cleary, 2003) or verbal stimuli, i.e. words or pseudowords (e.g., Curran, 1999) and with different response formats like inclusion and exclusion tasks. These tasks were implemented either via different instructions, e.g. "pay no heed to the perceptual details", and the corresponding response formats like the traditional old/new response (e.g., Curran & Dien, 2003), threefold responses (e.g., source 1/source 2/new, Curran & Friedman, 2004; or same/different/new, Ecker & Zimmer, 2009), or even a sequential combination of both (e.g., first old/new, then source 1/source 2, Wilding, 2000). This brief enumeration already shows both the innovative and fruitful approaches in research that sprouted from the establishment of ERP components of episodic memory retrieval (Curran, 2000; Wilding, 1999, 2000). After decades of research on familiarity and recollection (Yonelinas, 2002), the majority of which was based on behavioral data, this paved the way for neuroscientific methods investigating the neural correlates underlying the theories of cognitive psychology. These studies constitute a broad foundation (e.g., Eichenbaum et al., 2007; Henke, 2010; Mecklinger, 2006; Nyberg et al., 2000; Opitz, 2010b; Opitz & Cornell, 2006; Ranganath & Paller, 2000; Rugg & Curran, 2007; Rugg & Wilding, 2000; Squire, Wixted, & Clark, 2007; Vilberg & Rugg, 2008; Wagner, Shannon, Kahn, & Buckner, 2005) for the further characterization both of the cognitive processes during retrieval as well as their corresponding neural ERP signatures.

Still, the developmental trajectories of familiarity and recollection have been not as clear. Tulving and Markowitsch (1998) described that children can access their knowledge of the world, i.e. their semantic memory, earlier than their past experiences, i.e. their episodic memory. They took this as implication that children can, generally, store and retrieve information although common phenomena associated with episodic memory retrieval were not observed in young children. Their rationale was that unlike semantic memory, episodic memory is associated with retrieval of context information as well as the "autonoetic" experience of remembering; the subjective feeling to "remember" a past episode which we associate with recollective retrieval. Accordingly, semantic memory was assumed to develop earlier than episodic memory. Hence, this led to the assumption that episodic memory develops later in children, with an earlier onset of familiarity, as familiarity can be utilized without the autonoetic experience (a vague feeling that something seems familiar). Thus, conscious and strategic retrieval ought to develop later (Czernochowski et al., 2004). Still, an ERP correlate reflecting recollection was observed in children (Cycowicz, 2000; Cycowicz et al., 2003; Czernochowski et al., 2005), whereas only a handful of studies observed frontal effects attributable to familiarity (e.g., Study 2; Boucher et al., 2016; Congdon et al., 2012; Mecklinger et al., 2011). It is noteworthy that the evidence for an ERP correlate of familiarity was found as early as 2011, whereas the lack thereof was reported before that point of time, clearly documenting how the absence of frontal old/new effects led to a further refinement of existing paradigms in an effort to find the missing link in research literature. As up to date only the four studies given above succeeded in eliciting ERP components of familiarity in children, it seems productive to closely compare the methods employed by these research groups. Which of the utilized methods played a key role that a) children employed familiarity or b) the ERP curves reflected children employing familiarity? In the next paragraph, I will summarize the similarities and differences between these studies which may help understand this phenomenon.

Obviously, age is one of the determinants for observing the FN400. It has been shown that both recollection and familiarity are employed to a different extent with increasing age on the basis of behavioral performance (Ghetti & Angelini, 2008). This is in line with studies showing that with ongoing age children rely on prior knowledge (e.g., Brod et al., 2013) in memory. In the four studies cited above, children were aged between 8 and 12 (Boucher et al.: mean age 11.3 years; Congdon et al.: mean age 10.2 years; Study 2: mean age 10.5 years; Mecklinger, Brunnemann, & Kipp: mean age 9.1 years), suggesting that either familiarity is utilized consistently in this age group or maturational changes in this time frame allow the measurement of previously unobtainable neural signatures. Among these four studies, Study 2 also investigated the cognitive processes in a sample of younger children, aged 7 to 8. Notably, no early midfrontal old/new effect attributable to familiarity was observed at that age, suggesting that between 8 and 10 years of age, a component representing familiarity emerges in children's ERP curves.

In three of the four studies given (Study 2, Boucher et al., 2016; Mecklinger et al., 2011) pictures were administered, so it is tempting to assume that the usage of pictures would enable to children to use familiarity. This is corroborated by the finding of Study 2 that only perceptually identical pictures – but not changed ones – elicited a midfrontal positivity attributable to familiarity. One might hence argue that children rely on familiarity primarily when pictorial information is identical between study and test (note however that changes were not only perceptual in nature in Study 2). This is in line with evidence that children tend to process items on a more perceptual level than adults (c.f. Sloutsky &

Fisher, 2004). However, the study of Congdon et al. (2012) undermines this conclusion, as they used words and succeeded in eliciting a midfrontal old/new effect reflecting familiarity. A possible key to this puzzle is the fact that both Congdon et al. (2012) and Boucher et al. (2016) used a continuous recognition paradigm, in contrast to the two other studies (but see Czernochowski et al., 2009). In a continuous recognition paradigm, participants see items on the screen, one at a time, and will re-encounter some of these items among the test list. Often the amount of items intervening the first and the second presentation, the so-called lag, is manipulated systematically. In these two studies, lags of 1, 2, 4, and 5 items (Congdon et al., 2012) as well as lags of 2, 5, and 10 items (Boucher et al., 2016) were presented. As the working memory capacity of about "seven plus or minus two" items (G. A. Miller, 1956; c.f. Eysenck & Keane, 2007) has been established, it seems conceivable that at least some of the trials underlying correct recognition represented not episodic (long-term) memory retrieval, but instead short-term memory. If this supposed confound was not responsible, however, one might consider if this untypically short retention interval fostered familiarity-based retrieval. The brief amount of time passed between study and test might have induced a high feeling of familiarity allowing children to base their judgment on the strong "feeling of knowing" that the item has been presented earlier. While the handful of studies allow no clear-cut conclusion, it is seems likely that future studies using the continuous recognition paradigm will be able to bridge the gap between the early frontal positivity in correct old responses reported by Boucher et al. (2016, 2 to 10 lag items) and Congdon et al. (2012, 1 to 5 lag items) and the early frontal negativity in correct old responses reported by Czernochowski et al. (2009, 10-15 lag items).

In spite of these open questions, I may conclude that task characteristics play a crucial role for the employment and measurement of the ERP component of familiarity. This notion is further corroborated by the results of Study 3 which show that the interdependent processes underlying episodic memory retrieval may attenuate each other or even cancel each other out. Previous data may not allow a clear-cut answer to the question which stimulus properties and task characteristics in particular give rise to familiarity in children's ERP averages, but it is worthwhile to enhance the likelihood of its occurrence. The study of Mecklinger et al. (2011) suggests that the paradigm ought to segregate familiarity from successful recollection based on the speed of judgment. As recollection is the slower of the two processes (Yonelinas, 2002), this procedure would severely impair recollection, leaving familiarity intact. The short response time window employed in their study (1050 ms for children) allowed the observation of early frontal old/new effects in children's ERPs. In other words, children only employed familiarity if recollection was not readily available. In a similar vein, our own paradigm

(Study 2) allowed the observation of familiarity under certain conditions. Presenting perceptually modified distractors alongside perceptually identical items at test led to children employing familiarity for the subgroup of perceptually identical item repetitions, although only after the second encoding phase with an intentional encoding procedure. As only this second retrieval phase revealed reliable old/new effects on mid-frontal electrode sites, it seems that the experience of the preceding phase played a key role for this. There are several possible post-hoc explanations: It is conceivable that children benefitted from the second encoding phase either because of the intentional encoding procedure (they knew that there would be a retrieval phase afterwards and thus memorized more efficiently). Alternatively, they might have benefitted from prior experience with the particular item modifications, as they learnt, during retrieval, which item modifications were commonly used at test. Either way, children could employ familiarity for perceptually identical stimuli. One might consider this trivial, arguing recollective engagement might merely be less taxing than familiarity-based retrieval. If that was the case, however, children ought to be more likely to use familiarity after the first (i.e. incidental) than after the second (i.e. intentional) encoding phase, not vice versa. Furthermore, as described above, half of the sample had previously participated in a task-switching paradigm which, similar to the Stroop task employed by Herron (2018), would rather have drained their executive resources. Accordingly, the old/new effects of familiarity would be even less likely, rendering this explanation unlikely. It seems worthwhile to further adapt – or even combine – the existing paradigms to address this unresolved research question.

Evidently, the onset of correlates of episodic memory retrieval is affected by task characteristics. In addition, the results of Study 3 gives rise to the notion that further cognitive processes may co-occur and hence affect the ERP correlates reflecting familiarity and recollection (as, for instance, demonstrated by Zimmer & Ecker, 2010). The fact that old/new effects in traditional time windows were either small or even non-existent, in contrast to previous literature and studies, led us to believe that this was due to a methodological issue. In order to solve it, we re-evaluated the results by means of a data-driven approach. Using the results of the PCA analysis for time window adjustment, the data revealed reliable ERP old/new effects attributable to both familiarity and recollection. The comparison of data across Studies 1 and 3 (see Fig. 14) suggested a special role of correct rejections for the magnitude of the old/new effects. Interestingly, this signifies that this lack of old/new effects is not necessarily related to successful memory retrieval and hence may be more related to retrieval attempt per se (c.f. Bridger et al., 2009; Doidge et al., 2017; Rosburg et al., 2011).

As such, there are two possible explanations as to why the observation of ERP effects of successful episodic memory retrieval was impaired in our paradigm, even in the adult sample. The data of Study 1 suggest a positivity for new items centered around parietal electrode sites as a consequence of subjective salience, plausibly due to the sequential procedure of incidental and intentional encoding. While saliency may have affected the averages of new items, the data of Study 3 speak in favor of a more extensive account as the assumption of oddball-related effects cannot sufficiently explain the severe magnitude reduction in ERP old/new effects in spite of the behavioral memory performance clearly indicating successful retrieval. We hence discussed the role of a strategic modulation of attentional allocation towards item features (Study 3). It is also plausible that both oddball-related effects (bottom-up) and strategic modulations (top-down) affected the data. Further studies are necessary to fully resolve this issue. A possible contribution of subjective saliency ought to be addressed by varying task difficulty, for instance by changing perceptual item features either on a miniscule or a large scale. Several item modifications were implemented with the developmental sample in mind as a difficult task would have rendered the data of the samples in Study 2 difficult to compare. It is conceivable that the change of only minor perceptual item attributes (e.g., the eye color of animals depicted) would greatly affect task difficulty, likely leading to a high error rate in children. Additionally, such a manipulation would affect the retrieval orientation of the task as the attentional allocation would be tuned to a certain picture property.

While the paradigm employed in the three studies of the dissertation varied perceptual attributes, the changes could be further refined in future studies in order to clearly investigate which kind of perceptual (or conceptual) change affects ERPs reflecting retrieval orientation (Herron, 2018) and familiarity (Zimmer & Ecker, 2010). For adults, a handful of studies have used different approaches to elucidate how different levels of item changes affect the ERP component of familiarity (Ecker & Zimmer, 2009; Ecker, Zimmer, et al., 2007a, 2007b; Ecker, Zimmer, Groh-Bordin, et al., 2007) which led to the insightful review of Zimmer and Ecker (2010) who concluded that the instruction on how to process item manipulations determines whether the ERP component of familiarity is affected by perceptual changes or not. This was a highly relevant finding as previous studies used the magnitude of the prefrontal ERP component to determine whether familiarity is a modal or an a-modal process (e.g., Curran & Dien, 2003). A similarly highly structured approach seems promising to elucidate the exact impact of the diverse perceptual modifications that have, so far, been implemented in the existing body of research to elicit familiarity in older children. In the same vein, a careful and systematic variation of the different task characteristics (inclusion task, exclusion task; exclusion task with three response formats; consecutive old vs. new – Source A vs. Source B decisions; possibly also consecutive old vs. new – Remember vs. Know judgments) seems also interesting in order to select which task characteristics used in the existing literature may be most promising to elicit robust ERP components of familiarity and recollection and which may actually impair its measurement – if measurement is impaired, an additional question would be which cognitive process impaired its measurement. In the Similarly, the simultaneous co-occurrence of other ERP effects diminishing the established ERP components of familiarity and recollection like the LPN ought to be considered in future studies to learn more about the exact interplay cognitive processed induced by an experimental procedure. Of special importance may be strategic and control processes as Herron (2018) recently demonstrated that a preceding Stroop task diminishes the effect of the experimental task on retrieval orientation. It seems promising to further evaluate if other tasks requiring executive functions (i.e., inhibition, shifting, updating; c.f. Miyake et al., 2000) equally affect retrieval orientation and other strategic processes of episodic memory retrieval.

Because children do not employ strategic processes to the same extent as adults (e.g., Czernochowski, 2014), further developmental studies may be helpful. Due to the reduced executive resources in developmental populations leading to rudimentary forms of perceptual, semantic, and episodic systems (Ofen & Shing, 2013), it is likely that the overlap of multiple simultaneous processes is largely reduced in these populations. As cortical areas in adults are more fine-tuned for their respective tasks (e.g., Bunge et al., 2002; Casey et al., 2000; Casey, Tottenham, Liston, & Durston, 2005; DeMaster & Ghetti, 2013; DeMaster et al., 2013), it is likely that more complex approaches to episodic memory tasks become available, possibly affecting the measurement of its underlying neural signatures. Hence, children would rely on less (additional) cognitive processes and thus alleviate the investigation of memory retrieval. A further understanding of developmental trajectories would furthermore allow the implementation of these findings into primary school and modern teaching approaches.

Conclusion

In 2002, Yonelinas' sophisticated and overarching review on the two retrieval processes familiarity and recollection gave a broad overview over 30 years of research. The following two decades brought up evidence in line with this prior data, but also new questions that necessitated a re-evaluation of these processes. The nature of ERP research not only allows researchers to better understand the cognitive processes of their research domain. While establishing a full understanding of the neural correlates of these processes, the instruments of measurement themselves become characterized further. In addition to the inferences derived from these studies, other research groups report evidence seemingly in contradiction to prior evidence. A few years ago, MacLeod and Donaldson (2017) challenged the initial finding that the magnitude of the LPC is related to the amount of memory retrieved (Wilding, 2000). Similarly, the exact task characteristics capable of eliciting the FN400 have been re-characterized (Zimmer & Ecker, 2010) or even associated with a new role altogether: Leynes et al. (2017) suggested that the FN400 may not only represent familiarity, but also processing fluency (but see also Tsivilis et al., 2015), potentially reconciling the concepts of familiarity and conceptual priming (Paller, Voss, & Boehm, 2007). Similarly, the emergence of new evidence (Ecker & Zimmer, 2009; Herron, 2018; Herron et al., 2016) led to the conclusion that retrieval orientation (Rugg & Wilding, 2000), can be used rather flexibly as a goal-directed process. Another ERP component the LPN (Mecklinger et al., 2007), is still under investigation but has been proposed to be a multi-faceted component comprising of response inhibition and source-specifying retrieval (Mecklinger et al., 2016). These examples suggest that the initial neuroscientific findings are currently re-evaluated in the light of the last two decades of research, which may promote further – possibly more complex – paradigms, further extending the foundation of ERP research on episodic memory retrieval.

Appendix

Results of analyses computed on the standard time windows of familiarity and recollection in Study 3 (see Table A1)

300 – 500 ms (Familiarity)

Old/new effects in this time window were not statistically significant, all *p*s > .12.

500 – 800 ms (Recollection)

Across all electrode sites that entered the analysis, identical items were associated with more positive amplitudes versus new items ($p < .01$). Interactions with the factors Anterior-Posterior ($p < .001$) and LAT ($p < .01$) as well as a three-way interaction ($p < .05$) indicate further effects that justify a separate analysis on each Anterior-Posterior factor level. We found reliable effects of Item Type at anterio-frontal, frontal, and central (each $p < .01$) electrode sites as well as at parietal ($p < .05$) electrode sites. At anteriofrontal and frontal electrodes, the planned contrasts revealed reliable effects for both identical and changed items, whereas at central electrode sites identical items – but not changed items – elicited reliably more positive amplitudes than new items. At parietal electrode sites, contrasts did not allow any conclusion on whether the effect of Itemtype was due to more positive amplitudes for identical items or more negative amplitudes for changed items compared to new items.

Table A1. Overview of ERP differences between identical and changed items in theory-based time windows of Study 3.

Effect (df_1,df_2)	300 – 500 ms			500 – 800 ms		
	ε	*F*	η^2_p	ε	*F*	η^2_p
Across all electrode sites						
Item Type (2,48)		–			5.70**	.19
Identical vs. CR (1,24)		–			11.32**	.32
Changed vs. CR (1,24)		–			–	
AP X Item Type (6,144)		–		.40	6.25**	.21
LAT X Item Type (4,96)		–			5.71***	.19
AP X LAT X Item Type (12,288)		–		.53	2.18* [a]	.08
Anterio-frontal						
Item Type (2,48)		3.85*	.14		6.91**	.22
Identical vs. CR (1,24)		7.87**	.25		7.76*	.24
Changed vs. CR (1,24)		–			10.64**	.31
LAT X Item Type (4,96)		–		.74	7.12*** [a]	.23
Frontal						
Item Type (2,48)		–			7.29**	.23
Identical vs. CR (1,24)		–			14.24***	.37

Changed vs. CR (1,24)	–	8.13**	.25
LAT X Item Type (4,96)	–	3.33* [a]	.12
Central			
Item Type (2,48)	–	5.54**	.19
Identical vs. CR (1,24)	–	8.23**	.26
Changed vs. CR (1,24)	–	–	
LAT X Item Type (4,96)	–	3.97** [a]	.14
Parietal			
Item Type (2,48)	–	4.92*	.17
Identical vs. CR (1,24)	–	–	
Changed vs. CR (1,24)	–	–	
LAT X Item Type (4,96)	–	3.49* [a]	.13

[a] F3: Identical > Correct Rejection < Changed, AFz: Identical > Correct Rejection
F3, Fz: Identical > Correct Rejection < Changed, F4: Identical > Correct Rejection
C3, Cz: Identical > Correct Rejection
P3: Identical > Correct Rejection

References

Atkinson, R. C., & Juola, J. F. (1973). Factors influencing speed and accuracy of word recognition. *Attention and performance IV*, 583-612.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation* (Vol. 2, pp. 89-195). New York: Academic Press.

Azimian-Faridani, N., & Wilding, E. L. (2006). The influence of criterion shifts on electrophysiological correlates of recognition memory. *Journal of Cognitive Neuroscience, 18*(7), 1075-1086. doi:10.1162/jocn.2006.18.7.1075

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2018). From short-term store to multicomponent working memory: The role of the modal model. *Memory & Cognition, 47*(4), 575-588. doi:10.3758/s13421-018-0878-5

Bader, R., Mecklinger, A., Hoppstädter, M., & Meyer, P. (2010). Recognition memory for one-trial-unitized word pairs: evidence from event-related potentials. *Neuroimage, 50*(2), 772-781. doi:10.1016/j.neuroimage.2009.12.100

Besson, G., Ceccaldi, M., Tramoni, E., Felician, O., Didic, M., & Barbeau, E. J. (2015). Fast, but not slow, familiarity is preserved in patients with amnestic mild cognitive impairment. *Cortex, 65*, 36-49. doi:10.1016/j.cortex.2014.10.020

Billingsley, R. L., Smith, M. L., & McAndrews, M. P. (2002). Developmental patterns in priming and familiarity in explicit recollection. *Journal of Experimental Child Psychology, 82*(3), 251-277. doi:10.1016/S0022-0965%2802%2900007-3 12093109

Block, R. A. (2009). Intent to remember briefly presented human faces and other pictorial stimuli enhances recognition memory. *Memory & Cognition, 37*(5), 667-678. doi:10.3758/MC.37.5.667

Boucher, O., Chouinard-Leclaire, C., Muckle, G., Westerlund, A., Burden, M. J., Jacobson, S. W., & Jacobson, J. L. (2016). An ERP study of recognition memory for concrete and abstract pictures in school-aged children. *International Journal of Psychophysiology*. doi:10.1016/j.ijpsycho.2016.06.009

Brainerd, C. J., Holliday, R. E., & Reyna, V. F. (2004). Behavioral measurement of remembering phenomenologies: so simple a child can do it. *Child Development, 75*(2), 505-522. doi:10.1111/j.1467-8624.2004.00689.x

Bridger, E. K., Bader, R., & Mecklinger, A. (2014). More ways than one: ERPs reveal multiple familiarity signals in the word frequency mirror effect. *Neuropsychologia, 57*, 179-190. doi:10.1016/j.neuropsychologia.2014.03.007

Bridger, E. K., Herron, J. E., Elward, R. L., & Wilding, E. L. (2009). Neural Correlates of Individual Differences in Strategic Retrieval Processing. *Journal of Experimental Psychology: Learning Memory and Cognition, 35*(5), 1175-1186. doi:10.1037/a0016375

Bridger, E. K., & Mecklinger, A. (2012). Electrophysiologically dissociating episodic preretrieval processing. *Journal of Cognitive Neuroscience, 24*(6), 1476-1491. doi:10.1162/jocn_a_00152

Brod, G., Bunge, S. A., & Shing, Y. L. (2017). Does One Year of Schooling Improve Children's Cognitive Control and Alter Associated Brain Activation? *Psychological Science, 28*(7), 967-978. doi:10.1177/0956797617699838

Brod, G., Werkle-Bergner, M., & Shing, Y. L. (2013). The influence of prior knowledge on memory: a developmental cognitive neuroscience perspective. *Frontiers in Behavioral Neuroscience, 7*, 139. doi:10.3389/fnbeh.2013.00139

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: evidence from fMRI. *Neuron, 33*(2), 301-311.

Cabeza, R., Ciaramelli, E., & Moscovitch, M. (2012). Cognitive contributions of the ventral parietal cortex: an integrative theoretical account. *Trends in Cognitive Sciences, 16*(6), 338-352. doi:10.1016/j.tics.2012.04.008

Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology, 54*(1-3), 241-257.

Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? *Trends in Cognitive Sciences, 9*(3), 104-110. doi:10.1016/j.tics.2005.01.011

Congdon, E. L., Westerlund, A., Algarin, C. R., Peirano, P. D., Gregas, M., Lozoff, B., & Nelson, C. A. (2012). Iron Deficiency in Infancy is Associated with Altered Neural Correlates of Recognition Memory at 10 Years. *Journal of Pediatrics, 160*(6), 1027-1033. doi:10.1016/j.jpeds.2011.12.011

Craik, F. I., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior, 11*(6), 671-684. doi:10.1016/S0022-5371(72)80001-X

Curran, T. (1999). The electrophysiology of incidental and intentional retrieval: ERP old/new effects in lexical decision and recognition memory. *Neuropsychologia, 37*(7), 771-785.

Curran, T. (2000). Brain potentials of recollection and familiarity. *Memory & Cognition, 28*(6), 923-938. doi:10.3758/BF03209340

Curran, T. (2004). Effects of attention and confidence on the hypothesized ERP correlates of recollection and familiarity. *Neuropsychologia, 42*(8), 1088-1106. doi:Doi 10.1016/J.Neuropsychologia.2003.12.011

Curran, T., & Cleary, A. M. (2003). Using ERPs to dissociate recollection from familiarity in picture recognition. *Cognitive Brain Research, 15*(2), 191-205. doi:10.1016/S0926-6410(02)00192-1

Curran, T., DeBuse, C., Woroch, B., & Hirshman, E. (2006). Combined pharmacological and electrophysiological dissociation of familiarity and recollection. *Journal of Neuroscience, 26*(7), 1979-1985. doi:10.1523/Jneurosci.5370-05.2006

Curran, T., & Dien, J. (2003). Differentiating amodal familiarity from modality-specific memory processes: an ERP study. *Psychophysiology, 40*(6), 979-988. doi:10.1111/1469-8986.00116

Curran, T., & Doyle, J. (2011). Picture superiority doubly dissociates the ERP correlates of recollection and familiarity. *Journal of Cognitive Neuroscience, 23*(5), 1247-1262. doi:10.1162/jocn.2010.21464

Curran, T., & Friedman, W. J. (2004). ERP old/new effects at different retention intervals in recency discrimination tasks. *Cognitive Brain Research, 18*(2), 107-120.

Cycowicz, Y. M. (2000). Memory development and event-related brain potentials in children. *Biological Psychology, 54*(1-3), 145-174.

Cycowicz, Y. M., & Friedman, D. (1999). The effect of intention to learn novel, environmental sounds on the novelty P3 and old/new recognition memory. *Biological Psychology, 50*(1), 35-60.

Cycowicz, Y. M., & Friedman, D. (2003). Source memory for the color of pictures: Event-related brain potentials (ERPs) reveal sensory-specific retrieval-related activity. *Psychophysiology, 40*(3), 455-464. doi:Doi 10.1111/1469-8986.00047

Cycowicz, Y. M., & Friedman, D. (2007). Visual novel stimuli in an ERP novelty oddball paradigm: effects of familiarity on repetition and recognition memory. *Psychophysiology, 44*(1), 11-29. doi:10.1111/j.1469-8986.2006.00481.x

Cycowicz, Y. M., Friedman, D., & Duff, M. (2003). Pictures and Their Colors: What Do Children Remember? *Journal of Cognitive Neuroscience, 15*(5). doi:10.1162/jocn.2003.15.5.759 12965048

Cycowicz, Y. M., Friedman, D., Snodgrass, J. G., & Duff, M. (2001). Recognition and source memory for pictures in children and adults. *Neuropsychologia, 39*(3), 255-267.

Czernochowski, D. (2014). Conflict Monitoring Across the Life Span: How to Tell Right From Wrong and Act Accordingly. *Journal of Psychophysiology, 28*(3), 124-135. doi:10.1027/0269-8803/a000120

Czernochowski, D. (2015). ERPs dissociate proactive and reactive control: Evidence from a task-switching paradigm with informative and uninformative cues. *Cognitive, Affective & Behavioral Neuroscience*. doi:10.3758/s13415-014-0302-y

Czernochowski, D., Brinkmann, M., Mecklinger, A., & Johansson, M. (2004). When binding matters: an ERP analysis of the development of recollection and familiarity. In A. Mecklinger, H. D. Zimmer, & U. Lindenberger (Eds.), *Bound in Memory. Insights from Behavioral and Neuropsychological Studies* (pp. 93-128). Aachen: Shaker Verlag.

Czernochowski, D., Horn, S., & Bayen, U. J. (2012). Does frequency matter? ERP and behavioral correlates of monitoring for rare and frequent prospective memory targets. *Neuropsychologia, 50*(1), 67-76.

Czernochowski, D., Mecklinger, A., & Johansson, M. (2009). Age-related changes in the control of episodic retrieval: an ERP study of recognition memory in children and adults. *Developmental Science, 12*(6), 1026-1040. doi:10.1111/j.1467-7687.2009.00841.x

Czernochowski, D., Mecklinger, A., Johansson, M., & Brinkmann, M. (2005). Age-related differences in familiarity and recollection: ERP evidence from a recognition memory study in children and young adults. *Cognitive, Affective & Behavioral Neuroscience, 5*(4), 417-433. doi:10.3758/CABN.5.4.417

de Chastelaine, M., Friedman, D., & Cycowicz, Y. M. (2007). The development of control processes supporting source memory discrimination as revealed by event-related potentials. *Journal of Cognitive Neuroscience, 19*(8), 1286-1301. doi:10.1162/jocn.2007.19.8.1286

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9-21. doi:10.1016/j.jneumeth.2003.10.009

DeMaster, D., & Ghetti, S. (2013). Developmental differences in hippocampal and cortical contributions to episodic retrieval. *Cortex, 49*(6), 1482-1493. doi:Doi 10.1016/J.Cortex.2012.08.004

DeMaster, D., Pathman, T., & Ghetti, S. (2013). Development of memory for spatial context: Hippocampal and cortical contributions. *Neuropsychologia, 51*(12), 2415-2426. doi:10.1016/J.Neuropsychologia.2013.05.026

Destan, N., Hembacher, E., Ghetti, S., & Roebers, C. M. (2014). Early metacognitive abilities: The interplay of monitoring and control processes in 5- to 7-year-old children. *Journal of Experimental Child Psychology, 126*, 213-228. doi:10.1016/j.jecp.2014.04.001

Dewhurst, S. A., & Robinson, C. A. (2004). False memories in children - Evidence for a shift from phonological to semantic associations. *Psychological Science, 15*(11), 782-786. doi:10.1111/J.0956-7976.2004.00756.X

Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2010). Medial Temporal Lobe Activity during Source Retrieval Reflects Information Type, not Memory Strength. *Journal of Cognitive Neuroscience, 22*(8), 1808-1818. doi:DOI 10.1162/jocn.2009.21335

Dien, J. (2010a). The ERP PCA Toolkit: an open source program for advanced statistical analysis of event-related potential data. *Journal of Neuroscience Methods, 187*(1), 138-145. doi:10.1016/j.jneumeth.2009.12.009

Dien, J. (2010b). Evaluating two-step PCA of ERP data with Geomin, Infomax, Oblimin, Promax, and Varimax rotations. *Psychophysiology, 47*(1), 170-183. doi:10.1111/j.1469-8986.2009.00885.x

Dien, J. (2012). Applying Principal Components Analysis to Event-Related Potentials: A Tutorial. *Developmental Neuropsychology, 37*(6), 497-517. doi:10.1080/87565641.2012.697503

Dien, J., & Frishkoff, G. A. (2004). Principal components analysis of event-related potential datasets. In T. C. Handy (Ed.), *Event-Related Potentials: A Methods Handbook* (pp. 189 - 207). Cambridge, Massachusetts: MIT Press.

Doidge, A. N., Evans, L. H., Herron, J. E., & Wilding, E. L. (2017). Separating content-specific retrieval from post-retrieval processing. *Cortex, 86*, 1-10. doi:10.1016/j.cortex.2016.10.003

Donaldson, D. I., & Rugg, M. D. (1998). Recognition memory for new associations: electrophysiological evidence for the role of recollection. *Neuropsychologia, 36*(5), 377-395. doi:10.1016/S0028-3932(97)00143-7

Donchin, E. (1966). A multivariate approach to the analysis of average evoked potentials. *IEEE Transactions on Biomedical Engineering, 13*(3), 131-139. doi:10.1109/tbme.1966.4502423

Donchin, E., & Heffley, E. (1979). Multivariate analysis of event-related potential data: A tutorial review. In D. A. Otto (Ed.), *Multidisciplinary perspectives in event-related potential research (EPA 600/9-77-043)* . (pp. 555-572). Washington, DC: U.S. Government Printing Office.

Dzulkifli, M. A., & Wilding, E. L. (2005). Electrophysiological indices of strategic episodic retrieval processing. *Neuropsychologia, 43*(8), 1152-1162. doi:10.1016/j.neuropsychologia.2004.11.019

Ebbinghaus, H. (1885). *Über das Gedächtnis: Untersuchungen zur experimentellen Psychologie*. Leipzig: Duncker & Humblot.

Ecker, U. K. H., Arend, A. M., Bergström, K., & Zimmer, H. D. (2009). Verbal predicates foster conscious recollection but not familiarity of a task-irrelevant perceptual feature - an ERP study. *Consciousness and Cognition, 18*(3), 679-689. doi:10.1016/j.concog.2009.04.005

Ecker, U. K. H., & Zimmer, H. D. (2009). ERP evidence for flexible adjustment of retrieval orientation and its influence on familiarity. *Journal of Cognitive Neuroscience, 21*(10), 1907-1919. doi:10.1162/jocn.2009.21135

Ecker, U. K. H., Zimmer, H. D., & Groh-Bordin, C. (2007a). Color and context: An ERP study on intrinsic and extrinsic feature binding in episodic memory. *Memory & Cognition, 35*(6), 1483-1501. doi:10.3758/BF03193618

Ecker, U. K. H., Zimmer, H. D., & Groh-Bordin, C. (2007b). The influence of object and background color manipulations on the electrophysiological indices of recognition memory. *Brain Research, 1185*, 221-230. doi:10.1016/j.brainres.2007.09.047

Ecker, U. K. H., Zimmer, H. D., Groh-Bordin, C., & Mecklinger, A. (2007). Context effects on familiarity are familiarity effects of context - an electrophysiological study. *International Journal of Psychophysiology, 64*(2), 146-156. doi:10.1016/j.ijpsycho.2007.01.005

Eichenbaum, H., Yonelinas, A. P., & Ranganath, C. (2007). The medial temporal lobe and recognition memory. *Annual Review of Neuroscience, 30*, 123-152. doi:10.1146/annurev.neuro.30.051606.094328

Evans, K. M., & Federmeier, K. D. (2005). Hemispheric asymmetries in verbal memory over time. *Journal of Cognitive Neuroscience*, 139-139.

Evans, L. H., Herron, J. E., & Wilding, E. L. (2012). Electrophysiological insights into control over recollection. *Cognitive Neuroscience, 3*(3-4), 168-173. doi:10.1080/17588928.2012.662217

Eysenck, M. W., & Keane, M. T. (2007). *Cognitive Psychology: A Student's Handbook* (5th ed.). New York: Psychology Press Ltd.

Ferdinand, N. K., & Czernochowski, D. (2018). Motivational Influences on Performance Monitoring and Cognitive Control across the Adult Lifespan. *Frontiers in Psychology, 9*, 1018.

Friedman, D., Cycowicz, Y. M., & Bersick, M. (2005). The late negative episodic memory effect: the effect of recapitulating study details at test. *Cognitive Brain Research, 23*(2-3), 185-198. doi:10.1016/j.cogbrainres.2004.10.005

Friedman, D., de Chastelaine, M., Nessler, D., & Malcolm, B. (2010). Changes in familiarity and recollection across the lifespan: An ERP perspective. *Brain Research, 1310*, 124-141. doi:10.1016/j.brainres.2009.11.016 19914220

Friedman, D., & Johnson, R. (2000). Event-related potential (ERP) studies of memory encoding and retrieval: A selective review. *Microscopy Research and Technique, 51*(1), 6-28. doi:10.1002/1097-0029(20001001)51:1<6::Aid-Jemt2>3.0.Co;2-R

Galli, G., & Otten, L. J. (2011). Material-specific neural correlates of recollection: Objects, words, and faces. *Journal of Cognitive Neuroscience, 23*(6), 1405-1418. doi:10.1162/jocn.2010.21442 20146595

Ghetti, S., & Angelini, L. (2008). The development of recollection and familiarity in childhood and adolescence: Evidence from the dual-process signal detection model. *Child Development, 79*(2), 339-358. doi:10.1111/J.1467-8624.2007.01129.X

Ghetti, S., & Bunge, S. A. (2012). Neural changes underlying the development of episodic memory during middle childhood. *Developmental Cognitive Neuroscience, 2*(4), 381-395. doi:10.1016/j.dcn.2012.05.002

Ghetti, S., DeMaster, D. M., Yonelinas, A. P., & Bunge, S. A. (2010). Developmental differences in medial temporal lobe function during memory encoding. *Journal of Neuroscience, 30*(28), 9548-9556. doi:10.1523/JNEUROSCI.3500-09.2010

Goldinger, S. D. (1996). Words and voices: episodic traces in spoken word identification and recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(5), 1166-1183. doi:10.1037/0278-7393.22.5.1166

Groh-Bordin, C., Zimmer, H. D., & Ecker, U. K. H. (2006). Has the butcher on the bus dyed his hair? When color changes modulate ERP correlates of familiarity and recollection. *Neuroimage, 32*(4), 1879-1890. doi:10.1016/j.neuroimage.2006.04.215

Groh-Bordin, C., Zimmer, H. D., & Mecklinger, A. (2005). Feature binding in perceptual priming and in episodic object recognition: evidence from event-related brain potentials. *Cognitive Brain Research, 24*(3), 556-567. doi:10.1016/j.cogbrainres.2005.03.006

Gulya, M., Rossi-George, A., Hartshorn, K., Vieira, A., Rovee-Collier, C., Johnson, M. K., & Chalfonte, B. L. (2002). The development of explicit memory for basic perceptual features. *Journal of Experimental Child Psychology, 81*(3), 276-297. doi:10.1006/jecp.2001.2654

Haese, A., & Czernochowski, D. (2015). Sometimes we have to intentionally focus on the details: Incidental encoding and perceptual change decrease recognition memory performance and the ERP correlate of recollection. *Brain and Cognition, 96*, 1-11. doi:10.1016/j.bandc.2015.02.003

Haese, A., & Czernochowski, D. (2016). Task characteristics are critical for the use of familiarity: An ERP study on episodic memory development in middle childhood. *Cognitive Development, 40*, 82-100. doi:10.1016/j.cogdev.2016.08.008

Haese, A., & Czernochowski, D. (under review). Using temporo-spatial principal component analysis as tool to dissociate latent ERP components of episodic memory retrieval. *Journal of Psychophysiology*.

Henke, K. (2010). A model for memory systems based on processing modes rather than consciousness. *Nature Reviews Neuroscience, 11*(7), 523-532. doi:10.1038/nrn2850

Herron, J. E. (2018). Direct electrophysiological evidence for the maintenance of retrieval orientations and the role of cognitive control. *Neuroimage, 172*, 228-238. doi:10.1016/j.neuroimage.2018.01.062

Herron, J. E. (2019). *Direct electrophysiological evidence for the maintenance of retrieval orientations and the role of cognitive control.*

Herron, J. E., Evans, L. H., & Wilding, E. L. (2016). Electrophysiological evidence for flexible goal-directed cue processing during episodic retrieval. *Neuroimage, 132*, 24-31. doi:10.1016/j.neuroimage.2016.02.025

Herron, J. E., & Rugg, M. D. (2003). Retrieval orientation and the control of recollection. *Journal of Cognitive Neuroscience, 15*(6), 843-854. doi:10.1162/089892903322370762

Hintzman, D. L. (2001). Similarity, global matching, and judgments of frequency. *Memory & Cognition, 29*(4), 547-556.

Hintzman, D. L. (2002). Context matching and judgments of recency. *Psychonomic Bulletin & Review, 9*(2), 368-374. doi:10.3758/BF03196295

Hockley, W. E. (2008). The picture superiority effect in associative recognition. *Memory & Cognition, 36*(7), 1351-1359. doi:10.3758/MC.36.7.1351

Hockley, W. E., & Consoli, A. (1999). Familiarity and recollection in item and associative recognition. *Memory & Cognition, 27*(4), 657-664. doi:Doi 10.3758/Bf03211559

Horn, J. L. (1965). A Rationale and Test for the Number of Factors in Factor Analysis. *Psychometrika, 30*, 179-185.

Hyde, T. S., & Jenkins, J. J. (1973). Recall for Words as a Function of Semantic, Graphic, and Syntactic Orienting Tasks. *Journal of Verbal Learning and Verbal Behavior, 12*(5), 471-480. doi:Doi 10.1016/S0022-5371(73)80027-1

Jacoby, L. L. (1991). A Process Dissociation Framework - Separating Automatic from Intentional Uses of Memory. *Journal of Memory and Language, 30*(5), 513-541. doi:10.1016/0749-596x(91)90025-F

Jennings, J. R., & Wood, C. C. (1976). The ε-adjustment procedure for repeated-measures analyses of variance. *Psychophysiology, 13*(3), 277-278. doi:10.1111/j.1469-8986.1976.tb00116.x

Johansson, M., & Mecklinger, A. (2003). The late posterior negativity in ERP studies of episodic memory: action monitoring and retrieval of attribute conjunctions. *Biological Psychology, 64*(1-2), 91-117. doi:10.1016/S0301-0511(03)00104-2

Johnson, R. (1995). Event-related potential insights into the neurobiology of memory systems. In F. Boller & J. Grafman (Eds.), *Handbook of Neuropsychology* (Vol. 10, pp. 135-163). Amsterdam: Elsevier.

Juola, J. F., Caballero-Sanz, A., Muñoz-García, A. R., Botella, J., & Suero, M. (2019). Familiarity, recollection, and receiver-operating characteristic (ROC) curves in recognition memory. *Memory & Cognition, 47*(4), 855-876. doi:10.3758/s13421-019-00922-8

Katayama, J., & Polich, J. (1998). Stimulus context determines P3a and P3b. *Psychophysiology, 35*(1), 23-33.

Kayser, J., Tenke, C. E., Gates, N. A., & Bruder, G. E. (2007). Reference-independent ERP old/new effects of auditory and visual word recognition memory: Joint extraction of stimulus- and response-locked neuronal generator patterns. *Psychophysiology, 44*(6), 949-967. doi:10.1111/j.1469-8986.2007.00562.x

Keil, A., Debener, S., Gratton, G., Junghofer, M., Kappenman, E. S., Luck, S. J., . . . Yee, C. M. (2014). Committee report: publication guidelines and recommendations for studies using electroencephalography and magnetoencephalography. *Psychophysiology, 51*(1), 1-21. doi:10.1111/psyp.12147

Koenig, L., Wimmer, M. C., & Hollins, T. J. (2015). Process dissociation of familiarity and recollection in children: Response deadline affects recollection but not familiarity. *Journal of Experimental Child Psychology, 131*, 120-134. doi:10.1016/j.jecp.2014.11.003

Köster, M., Haese, A., & Czernochowski, D. (2017). Neuronal oscillations reveal the processes underlying intentional compared to incidental learning in children and young adults. *Plos One, 12*(8). doi:doi.org/10.1371/journal.pone.0182540

Küper, K., Groh-Bordin, C., Zimmer, H. D., & Ecker, U. K. (2012). Electrophysiological correlates of exemplar-specific processes in implicit and explicit memory. *Cognitive, Affective & Behavioral Neuroscience, 12*(1), 52-64. doi:10.3758/s13415-011-0065-7

Lange, K., & Czernochowski, D. (2013). Does this sound familiar? Effects of timbre change on episodic retrieval of novel melodies. *Acta Psychologica, 143*(1), 136-145. doi:10.1016/j.actpsy.2013.03.003

Leynes, P. A., Bruett, H., Krizan, J., & Veloso, A. (2017). What psychological process is reflected in the FN400 event-related potential component? *Brain and Cognition, 113*, 142-154. doi:10.1016/j.bandc.2017.02.004

Luck, S. J. (2005). *An introduction to the event-related potential technique*. Cambridge, Massachusetts: The MIT Press.

MacLeod, C. A., & Donaldson, D. I. (2017). Investigating the Functional Utility of the Left Parietal ERP Old/New Effect: Brain Activity Predicts within But Not between Participant Variance in Episodic Recollection. *Frontiers in Human Neuroscience, 11*, 580. doi:10.3389/fnhum.2017.00580

Malmberg, K. J., Raaijmakers, J. G. W., & Shiffrin, R. M. (2019). 50 years of research sparked by Atkinson and Shiffrin (1968). *Memory & Cognition, 47*(4), 561-574. doi:10.3758/s13421-019-00896-7

Mandler, G. (1979). Organization and repetition: Organizational principles with special reference to rote learning. In L. G. Nilsson (Ed.), *Perspectives on memory research* (pp. 293–327). Hillsdale, NJ: Erlbaum.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. *Psychological Review, 87*(3), 252-271.

Maril, A., Avital, R., Reggev, N., Zuckerman, M., Sadeh, T., Ben Sira, L., & Livneh, N. (2011). Event congruency and episodic encoding: A developmental fMRI study. *Neuropsychologia, 49*(11), 3036-3045. doi:10.1016/J.Neuropsychologia.2011.07.004

Marshall, D. H., Drummey, A. B., Fox, N. A., & Newcombe, N. S. (2002). An Event-Related Potential Study of Item Recognition Memory in Children and Adults. *Journal of Cognition and Development, 3*(2), 201-224. doi:Doi 10.1207/S15327647jcd0302_4

Mecklinger, A. (2000). Interfacing mind and brain: a neurocognitive model of recognition memory. *Psychophysiology, 37*(5), 565-582.

Mecklinger, A. (2006). Electrophysiological measures of familiarity memory. *Clinical Eeg and Neuroscience, 37*(4), 292-299. doi:10.1177/155005940603700406

Mecklinger, A., Brunnemann, N., & Kipp, K. (2011). Two processes for recognition memory in children of early school age: an event-related potential study. *Journal of Cognitive Neuroscience, 23*(2), 435-446. doi:10.1162/jocn.2010.21455

Mecklinger, A., Johansson, M., Parra, M., & Hanslmayr, S. (2007). Source-retrieval requirements influence late ERP and EEG memory effects. *Brain Research, 1172*, 110-123. doi:10.1016/j.brainres.2007.07.070

Mecklinger, A., Rosburg, T., & Johansson, M. (2016). Reconstructing the past: The late posterior negativity (LPN) in episodic memory studies. *Neuroscience and Biobehavioral Reviews, 68*, 621-638. doi:10.1016/j.neubiorev.2016.06.024

Miller, G. A. (1956). The magical number seven plus or minus two: some limits on our capacity for processing information. *Psychological Review, 63*(2), 81-97.

Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35*(1), 99-115.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "Frontal Lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi:10.1006/cogp.1999.0734

Montaldi, D., & Mayes, A. R. (2010). The Role of Recollection and Familiarity in the Functional Differentiation of the Medial Temporal Lobes. *Hippocampus, 20*(11), 1291-1314. doi:10.1002/hipo.20853

Morcom, A. M., & Rugg, M. D. (2012). Retrieval orientation and the control of recollection: an fMRI study. *Journal of Cognitive Neuroscience, 24*(12), 2372-2384. doi:10.1162/jocn_a_00299

Mulligan, E. M., Infantolino, Z. P., Klein, D. N., & Hajcak, G. (2019). Developmental trajectory of the late positive potential: Using temporal-spatial PCA to characterize within-subject developmental changes in emotional processing. *Psychophysiology*, e13478. doi:10.1111/psyp.13478

Nyberg, L., Persson, J., Habib, R., Tulving, E., McIntosh, A. R., Cabeza, R., & Houle, S. (2000). Large scale neurocognitive networks underlying episodic memory. *Journal of Cognitive Neuroscience, 12*(1), 163-173.

Nyhus, E., & Curran, T. (2012). Midazolam-induced amnesia reduces memory for details and affects the ERP correlates of recollection and familiarity. *Journal of Cognitive Neuroscience, 24*(2), 416-427. doi:10.1162/jocn_a_00154

Ofen, N., Chai, X. J., Schuil, K. D., Whitfield-Gabrieli, S., & Gabrieli, J. D. (2012). The development of brain systems associated with successful memory retrieval of scenes. *Journal of Neuroscience, 32*(29), 10012-10020. doi:10.1523/JNEUROSCI.1082-11.2012

Ofen, N., & Shing, Y. L. (2013). From perception to memory: changes in memory systems across the lifespan. *Neuroscience and Biobehavioral Reviews, 37*(9B), 2258-2267. doi:10.1016/j.neubiorev.2013.04.006

Opitz, B. (2010a). Context-dependent repetition effects on recognition memory. *Brain and Cognition, 73*(2), 110-118. doi:10.1016/j.bandc.2010.04.003

Opitz, B. (2010b). Neural binding mechanisms in learning and memory. *Neuroscience & Biobehavioral Reviews, 34*(7), 1036-1046. doi:10.1016/j.neubiorev.2009.11.001

Opitz, B., & Cornell, S. (2006). Contribution of familiarity and recollection to associative recognition memory: insights from event-related potentials. *Journal of Cognitive Neuroscience, 18*(9), 1595-1605. doi:10.1162/jocn.2006.18.9.1595

Paivio, A., Rogers, T. B., & Smythe, P. (1968). Why are pictures easier to recall than words. *Psychonomic Science, 11*(4), 137-138.

Paller, K. A., Voss, J. L., & Boehm, S. G. (2007). Validating neural correlates of familiarity. *Trends in Cognitive Sciences, 11*(6), 243-250. doi:10.1016/j.tics.2007.04.002

Paz-Alonso, P. M., Ghetti, S., Donohue, S. E., Goodman, G. S., & Bunge, S. A. (2008). Neurodevelopmental correlates of true and false recognition. *Cerebral Cortex, 18*(9), 2208-2216. doi:10.1093/cercor/bhm246

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology, 72*(2), 184-187. doi:10.1016/0013-4694(89)90180-6

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., Jr., . . . Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. *Psychophysiology, 37*(2), 127-152.

Picton, T. W., & Taylor, M. J. (2007). Electrophysiological evaluation of human brain development. *Developmental Neuropsychology, 31*(3), 249-278.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128-2148. doi:10.1016/j.clinph.2007.04.019

Pratte, M. S., & Rouder, J. N. (2011). Hierarchical single- and dual-process models of recognition memory. *Journal of Mathematical Psychology, 55*(1), 36-46. doi:10.1016/j.jmp.2010.08.007

Ranganath, C., & Paller, K. A. (1999). Frontal brain potentials during recognition are modulated by requirements to retrieve perceptual detail. *Neuron, 22*(3), 605-613. doi:10.1016/S0896-6273(00)80714-X

Ranganath, C., & Paller, K. A. (2000). Neural correlates of memory retrieval and evaluation. *Cognitive Brain Research, 9*(2), 209-222.

Riggins, T., Rollins, L., & Graham, M. (2013). Electrophysiological investigation of source memory in early childhood. *Developmental Neuropsychology, 38*(3), 180-196. doi:10.1080/87565641.2012.762001

Roberts, J. S., Tsivilis, D., & Mayes, A. R. (2014). Strategic retrieval processing and the impact of knowing when a memory was first created. *Brain and Cognition, 86*, 124-130. doi:10.1016/j.bandc.2014.02.005

Rollins, L., & Riggins, T. (2013). Developmental changes in memory encoding: insights from event-related potentials. *Developmental Science, 16*(4), 599-609. doi:Doi 10.1111/Desc.12072

Rollins, L., & Riggins, T. (2015). Processing and rejection of novel items in childhood: event-related potential study of similar lures and novel foils. *Developmental Psychobiology, 57*(2), 263-270. doi:10.1002/dev.21281

Rosburg, T., Mecklinger, A., & Johansson, M. (2011). Electrophysiological correlates of retrieval orientation in reality monitoring. *Neuroimage, 54*(4), 3076-3084. doi:10.1016/j.neuroimage.2010.10.068

Rossion, B., & Pourtois, G. (2004). Revisiting Snodgrass and Vanderwart's object pictorial set: the role of surface detail in basic-level object recognition. *Perception, 33*(2), 217-236. doi:10.1068/p5117

Ruchkin, D. S., Villegas, J., & John, E. R. (1964). An Analysis of Average Evoked Potentials Making Use of Least Mean Square Techniques. *Annals New York Academy of Science, 115*, 799-826.

Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences, 11*(6), 251-257. doi:10.1016/j.tics.2007.04.004

Rugg, M. D., Mark, R. E., Walla, P., Schloerscheidt, A. M., Birch, C. S., & Allan, K. (1998). Dissociation of the neural correlates of implicit and explicit memory. *Nature, 392*(6676), 595-598. doi:10.1038/33396

Rugg, M. D., Schloerscheidt, A. M., & Mark, R. E. (1998). An electrophysiological comparison of two indices of recollection. *Journal of Memory and Language, 39*(1), 47-69. doi:10.1006/jmla.1997.2555

Rugg, M. D., & Wilding, E. L. (2000). Retrieval processing and episodic memory. *Trends in Cognitive Sciences, 4*(3), 108-115. doi:Doi 10.1016/S1364-6613(00)01445-5

Sauvage, M. M., Fortin, N. J., Owens, C. B., Yonelinas, A. P., & Eichenbaum, H. (2008). Recognition memory: opposite effects of hippocampal damage on recollection and familiarity. *Nature Neuroscience, 11*(1), 16-18. doi:10.1038/nn2016

Senkfor, A. J., & Van Petten, C. (1998). Who said what? An event-related potential investigation of source and item memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*(4), 1005-1025. doi:10.1037/0278-7393.24.4.1005

Simons, J. S., & Spiers, H. J. (2003). Prefrontal and medial temporal lobe interactions in long-term memory. *Nature Reviews Neuroscience, 4*(8), 637-648. doi:10.1038/nrn1178

Sloutsky, V. M., & Fisher, A. V. (2004). Induction and categorization in young children: a similarity-based model. *Journal of Experimental Psychology: General, 133*(2), 166-188. doi:10.1037/0096-3445.133.2.166

Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: applications to dementia and amnesia. *Journal of Experimental Psychology: General, 117*(1), 34-50. doi:10.1037/0096-3445.117.1.34

Snodgrass, J. G., Hirshman, E., & Fan, J. (1996). The sensory match effect in recognition memory: Perceptual fluency or episodic trace? *Memory & Cognition, 24*(3), 367-383. doi:10.3758/Bf03213300

Spencer, K. M., Dien, J., & Donchin, E. (1999). A componential analysis of the ERP elicited by novel events using a dense electrode array. *Psychophysiology, 36*(3), 409-414.

Spencer, K. M., Dien, J., & Donchin, E. (2001). Spatiotemporal analysis of the late ERP responses to deviant stimuli. *Psychophysiology, 38*(2), 343-358.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied, 74*(11), 1-29. doi:10.1037/h0093759

Sprondel, V., Kipp, K. H., & Mecklinger, A. (2011). Developmental changes in item and source memory: evidence from an ERP recognition memory study with children, adolescents, and adults. *Child Development, 82*(6), 1938-1953. doi:10.1111/j.1467-8624.2011.01642.x

Sprondel, V., Kipp, K. H., & Mecklinger, A. (2012). Electrophysiological evidence for late maturation of strategic episodic retrieval processes. *Developmental Science, 15*(3), 330-344. doi:10.1111/j.1467-7687.2011.01130.x 22490174

Sprondel, V., Kipp, K. H., & Mecklinger, A. (2013). Timing matters: age-related changes in episodic retrieval control as revealed by event-related potentials. *Brain Research, 1537*, 143-155. doi:10.1016/j.brainres.2013.09.005

Squire, L. R., Wixted, J. T., & Clark, R. E. (2007). Recognition memory and the medial temporal lobe: A new perspective. *Nature Reviews Neuroscience, 8*(11), 872-883. doi:10.1038/nrn2154

Stuss, D. T., Murphy, K. J., Binns, M. A., & Alexander, M. P. (2003). Staying on the job: the frontal lobes control individual performance variability. *Brain, 126*, 2363-2380. doi:10.1093/Brain/Awg237

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. *Science, 150*(3700), 1187-1188. doi:10.1126/science.150.3700.1187

Trott, C. T., Friedman, D., Ritter, W., & Fabiani, M. (1997). Item and source memory: differential age effects revealed by event-related potentials. *Neuroreport, 8*(15), 3373-3378.

Trott, C. T., Friedman, D., Ritter, W., Fabiani, M., & Snodgrass, J. G. (1999). Episodic priming and memory for temporal source: event-related potentials reveal age-related differences in prefrontal functioning. *Psychology and Aging, 14*(3), 390-413. doi:10.1037/0882-7974.14.3.390

Tsivilis, D., Allan, K., Roberts, J., Williams, N., Downes, J. J., & El-Deredy, W. (2015). Old-new ERP effects and remote memories: the late parietal effect is absent as recollection fails whereas the early mid-frontal effect persists as familiarity is retained. *Frontiers in Human Neuroscience, 9*. doi:10.3389/fnhum.2015.00532

Tsivilis, D., Otten, L. J., & Rugg, M. D. (2001). Context effects on the neural correlates of recognition memory: an electrophysiological study. *Neuron, 31*(3), 497-505. doi:10.1016/S0896-6273(01)00376-2

Tulving, E. (1985). Memory and Consciousness. *Canadian Psychology/Psychologie Canadienne, 26*(1), 1-12. doi:DOI 10.1037/h0080017

Tulving, E., & Markowitsch, H. J. (1998). Episodic and declarative memory: role of the hippocampus. *Hippocampus, 8*(3), 198-204.

Tulving, E., & Schacter, D. L. (1990). Priming and human memory systems. *Science, 247*(4940), 301-306.

Ulrich, R., & Miller, J. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38*(5), 816-827.

van Hooff, J. C. (2005). The influence of encoding intention on electrophysiological indices of recognition memory. *International Journal of Psychophysiology, 56*(1), 25-36. doi:10.1016/j.ijpsycho.2004.09.010

Van Petten, C., Luka, B. J., Rubin, S. R., & Ryan, J. P. (2002). Frontal brain activity predicts individual performance in an associative memory exclusion test. *Cerebral Cortex, 12*(11), 1180-1192. doi:10.1093/cercor/12.11.1180

Van Strien, J. W., Glimmerveen, J. C., Martens, V. E., & De Bruin, E. A. (2009). Age-related differences in brain activity during extended continuous word recognition in children. *Neuroimage, 47*(2), 688-699. doi:10.1016/j.neuroimage.2009.05.020

Van Strien, J. W., Hagenbeek, R. E., Stam, C. J., Rombouts, S. A., & Barkhof, F. (2005). Changes in brain electrical activity during extended continuous word recognition. *Neuroimage, 26*(3), 952-959. doi:10.1016/j.neuroimage.2005.03.003

Veselis, R. A., Pryor, K. O., Reinsel, R. A., Li, Y. L., Mehta, M., & Johnson, R. (2009). Propofol and Midazolam Inhibit Conscious Memory Processes Very Soon after Encoding: An Event-related Potential Study of Familiarity and Recollection in Volunteers. *Anesthesiology, 110*(2), 295-312.

Vilberg, K. L., Moosavi, R. F., & Rugg, M. D. (2006). The relationship between electrophysiological correlates of recollection and amount of information retrieved. *Brain Research, 1122*(1), 161-170. doi:10.1016/j.brainres.2006.09.023

Vilberg, K. L., & Rugg, M. D. (2008). Memory retrieval and the parietal cortex: A review of evidence from a dual-process perspective. *Neuropsychologia, 46*(7), 1787-1799. doi:Doi 10.1016/J.Neuropsychologia.2008.01.004

von Aster, M., Neubauer, A., & Horn, R. (2006). *Wechsler Intelligenztest für Erwachsene WIE. Deutschsprachige Bearbeitung und Adaptation des WAIS-III von David Wechsler* (2nd ed.). Frankfurt: Pearson Assessment.

Wagner, A. D., Shannon, B. J., Kahn, I., & Buckner, R. L. (2005). Parietal lobe contributions to episodic memory retrieval. *Trends in Cognitive Sciences, 9*(9), 445-453. doi:10.1016/j.tics.2005.07.001

Wetzel, N., Widmann, A., Berti, S., & Schroger, E. (2006). The development of involuntary and voluntary attention from childhood to adulthood: A combined behavioral and event-related potential study. *Clinical Neurophysiology, 117*(10), 2191-2203. doi:10.1016/j.clinph.2006.06.717

Wiegand, I., Bader, R., & Mecklinger, A. (2010). Multiple ways to the prior occurrence of an event: an electrophysiological dissociation of experimental and conceptually driven familiarity in recognition memory. *Brain Research, 1360*, 106-118. doi:10.1016/j.brainres.2010.08.089

Wilding, E. L. (1999). Separating retrieval strategies from retrieval success: an event-related potential study of source memory. *Neuropsychologia, 37*(4), 441-454. doi:10.1016/S0028-3932(98)00100-6

Wilding, E. L. (2000). In what way does the parietal ERP old/new effect index recollection? *International Journal of Psychophysiology, 35*(1), 81-87. doi:10.1016/S0167-8760(99)00095-1

Wilding, E. L., Doyle, M. C., & Rugg, M. D. (1995). Recognition memory with and without retrieval of context: an event-related potential study. *Neuropsychologia, 33*(6), 743-767. doi:10.1016/0028-3932(95)00017-W

Wilding, E. L., & Rugg, M. D. (1997). Event-related potentials and the recognition memory exclusion task. *Neuropsychologia, 35*(2), 119-128. doi:10.1016/S0028-3932(96)00076-0

Wixted, J. T. (2007). Dual-process theory and signal-detection theory of recognition memory. *Psychological Review, 114*(1), 152-176. doi:10.1037/0033-295x.114.1.152

Yonelinas, A. P. (1994). Receiver-operating characteristics in recognition memory: evidence for a dual-process model. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 20*(6), 1341-1354.
Yonelinas, A. P. (1997). Recognition memory ROCs for item and associative information: The contribution of recollection and familiarity. *Memory & Cognition, 25*(6), 747-763.
Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*(3), 441-517. doi:10.1006/Jmla.2002.2864
Yonelinas, A. P., Otten, L. J., Shaw, K. N., & Rugg, M. D. (2005). Separating the brain regions involved in recollection and familiarity in recognition memory. *Journal of Neuroscience, 25*(11), 3002-3008. doi:10.1523/JNEUROSCI.5295-04.2005
Yonelinas, A. P., & Parks, C. M. (2007). Receiver operating characteristics (ROCs) in recognition memory: A review. *Psychological Bulletin, 133*(5), 800-832. doi:10.1037/0033-2909.133.5.800
Zimmer, H. D., & Ecker, U. K. H. (2010). Remembering perceptual features unequally bound in object and episodic tokens: Neural mechanisms and their electrophysiological correlates. *Neuroscience and Biobehavioral Reviews, 34*(7), 1066-1079. doi:10.1016/j.neubiorev.2010.01.014
Zimmermann, P., Gondan, M., & Fimm, B. (2004). *Testbatterie zur Aufmerksamkeitsprüfung für Kinder (KITAP)*. Herzogenrath: Psytest.

Übersicht über den wissenschaftlichen Werdegang

2006 – 2011	Studium der Psychologie Heinrich-Heine-Universität Düsseldorf (Gesamtnote „mit Auszeichnung“) Diplomarbeit: „Evaluating the effectiveness of an electronic memory assistant— Does the "InBad" decrease memory failure?“ GutachterIn: Prof. Dr. Ute J. Bayen und Prof. Dr. Jochen Musch
2011 – 2014	Beginn des Promotionsstudiums Heinrich-Heine-Universität Düsseldorf Dr. Daniela Czernochowski
2014 – 2020	Fortsetzung des Promotionsstudiums Technische Universität Kaiserslautern Jun.-Prof. Dr. Daniela Czernochowski (Gesamtnote der Promotion „summa cum laude“)

Adresse:	Technische Universität Kaiserslautern Fachbereich Sozialwissenschaften – Dekanat Postfach 3049 67663 Kaiserslautern
Tel.:	+49 631 205 4960
Fax:	+49 631 205 2012
E-Mail:	dekanat(at)sowi.uni-kl.de