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Development of perceptual and conceptual memory in explicit and implicit memory systems

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ABSTRACT

We examined the developmental trajectory of memory while accounting for both memory systems (explicit-implicit) and processing modes (conceptual-perceptual). Four memory tasks that are believed to reflect the four possible combinations of memory systems and processing modes were administered to 96 individuals in three age groups: mid-childhood, mid-adolescence and young-adulthood (mean age 7.7, 13.7 and 21.8, respectively). For perceptual processing, participants performed a Picture Fragment Identification task and a Pictorial Cued Recall task taping the implicit and explicit memory systems, respectively. For conceptual processing, participants performed Category Production and Category Cued Recall tasks taping the implicit and the explicit memory systems, respectively. The study revealed (1) robust maturation effects in the explicit memory system; (2) comparable performance levels for adolescents and adults in all but the explicit-conceptual task; and (3) more pronounced maturation effects for perceptual than for conceptual processing within the implicit memory system.

The idea that memory is not a single faculty of the mind, but rather is comprised of several components, is not a new one. Considerable behavioral and neuroimaging findings point to dissociations between different Memory Systems (explicit vs. implicit) and different Processing Modes (perceptual vs. conceptual), or, alternatively, between different processing components (Cabeza and Moscovitch, 2013). Nevertheless, little is known about the development of these mnemonic components across the human lifespan. As differential maturation rates of cognitive functions can elucidate the nature of functional dissociations, the current study employs a developmental perspective to investigate maturation patterns of different mnemonic components. We sampled the proposed mnemonic space using tasks that represent different combinations of memory components, and tested participants in three age-groups, to evaluate the developmental trajectory of these components.

Memory systems: explicit vs. implicit memory

In past decades, differences in memory performance due to experimental manipulations or brain damage were addressed by distinguishing an explicit memory system from an implicit one. The explicit system can be tapped using recall tasks in which studies information that is not presented at test is retrieved (either freely or following the presentation of a cue), or using recognition tasks in which presented information is classified as either old or new. There is a general consensus that recall tasks require recollection, that is, retrieval of additional contextual details about the encoded event. Recognition, on the other hand, can also be supported by familiarity, that is, a sense of having encountered something or someone before, without retrieval of additional information (e.g., (Yonelinas, 2002)). Notably, both recall and recognition are considered to be explicit (or "declarative") memory tasks, as they both require intentional retrieval.

On the other hand, in tasks like motor skill learning and priming that utilize the implicit system, remembrance can occur incidentally, or without awareness, and memory is inferred by changes in performance such as increased speed and accuracy (Gabrieli, 1998; Schacter, 1990; Squire, 2004). One task that taps the implicit memory system is the Fragment Completion task. In this task, participants view items (e.g., object pictures) during an initial study phase. Next, they view fragments (e.g., degraded versions of object pictures) of studied and unstudied items and are asked to name the items. Facilitation (or priming as indicated by reduced reaction times, for example) is usually observed for correctly identified fragments that were seen before, relative to those that were not previously seen. This facilitation is taken as evidence that retention of the previously encountered items has occurred (e.g., (Cycowicz, 2000)).

Ample evidence supports this distinction between the explicit and implicit memory systems. For example, although amnesic patients are

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severely impaired in their ability to recall or recognize learned stimuli (i.e., explicit memory), they demonstrate robust learning of a variety of skills, and can benefit from various forms of implicit memory, including priming (Brooks and Baddeley, 1976; Cohen et al., 1985; Cohen and Squire, 1980; Shimamura, 1986). Furthermore, patients with damage to the medial temporal lobe (MTL) show impairments in explicit memory and preserved implicit memory, while the opposite pattern of performance is observed in patients with bilateral lesions in the occipital-lobes (Gabrieli et al., 1995; Keane et al., 1995). These findings demonstrate a double dissociation between these memory systems.

Processing modes: conceptual vs. perceptual memory

Another common framework focuses on memory effects that are produced by different types of processing modes. In particular, studies have emphasized the distinction between conceptual and perceptual memory processes (e.g., (Blaxton, 1989; Roediger and McDermott, 1993)). Perceptual memory depends on preliminary stages that analyze physical or sensory features of the stimuli. Conceptual memory, on the other hand, requires higher-level processing and focuses on extraction of meaning and semantic features (Blaxton, 1992; Srinivas and Roediger, 1990). This framework proved highly valuable for accounting for various findings in memory research, including the level of processing effect (Blaxton, 1989; Challis et al., 1996; Challis and Brodbeck, 1992; Craik et al., 1994; Craik and Lockhart, 1972; Srinivas and Roediger, 1990) and divided attention manipulations (e.g., (Insingrini et al., 1995; Vakil and Hoffman, 2004); and see (Mulligan, 1997) for review).

Neuroimaging studies have indicated that perceptual priming is associated with reduced activation in parts of the occipital and inferior temporal brain regions, while conceptual priming is associated with reduced activation in the inferior prefrontal cortex (Cabeza and Nyberg, 2000; Schacter and Buckner, 1998). The notion that these mnemonic processes are distinct was further supported by several studies, in which different groups of patients were examined. For example, in a study by Keane, Gabrieli, Fennema, Growdon, and Corkin (Keane et al., 1991), patients with occipital lesions showed preserved conceptual but not perceptual priming effects. Interestingly, in other studies, patients suffering from closed head injuries (CHI) with damage to the frontal lobes (Bigler and Maxwell, 2012; Levine et al., 2013; Stuss and Gow, 1992; Vakil, 2005), showed the opposite pattern of intact perceptual priming but deficits in conceptual priming (Vakil and Sigal, 1997). More recently, Gong et al. (Gong et al., 2015) demonstrated this double dissociation in a single study: patients with frontal lobe injury showed decreased performance in a conceptual memory task, while patients with damage to the occipital lobe showed decreased performance in a perceptual memory task.

Taken together, previous studies have validated the Memory Systems approach, as well as the Processing Mode approach. However, it is yet to be determined whether these systems and processing modes are orthogonal or if there are any dependencies between them. The current study relies on the assumption that development of mnemonic components depends on maturation of brain regions and the connection pathways that support them. Therefore, the evaluation of these proposed mnemonic components and their interactions can benefit from a developmental perspective.

Developmental perspective

The traditional developmental perspective on memory systems suggested that explicit memory increases with age, reaching maturation relatively late in adolescence or even adulthood (e.g., (Mecklinger et al., 2011; Ofen et al., 2007; Sprondel et al., 2011; Van Strien et al., 2011)), while implicit memory is already developed during early childhood, and does not usually demonstrate a developmental trend (Cycowicz, 2000; Ofen and Shing, 2013; Vöhringer et al., 2017). Nevertheless, some studies have challenged this perspective by demonstrating age-effects in implicit memory tasks as well (Cycowicz et al., 2000; Mecklenbräuker et al., 2003; Vaidya et al., 2007). For example, Cycowicz et al. (Cycowicz et al., 2000) evaluated developmental trends of both implicit and explicit memory in a single study. In their study, participants in 4 age groups (5–7, 9–11, 14–16, and 22–28 years of age) completed a modified version of the picture fragment task. After viewing object pictures, they were asked to identify degraded versions of old and new items, to test their implicit memory. This was followed by a recall task and a recognition task of the same studied items, to test their explicit memory. As expected, performance on the explicit tasks showed improvement with age. Notably, changes were also observed in the implicit task: although facilitation (priming) was significant in all age groups, the amount of priming increased with age. This suggests that even though the implicit memory system is already functional very early on, it continues to develop into adulthood.

Developmental studies on processing modes also show conflicting results. Although some studies do not report any developmental trajectory for perceptual processing (Mecklenbräuker et al., 2003; Perez et al., 1998), other studies challenge these results (e.g., (Cycowicz et al., 2000; Haese and Czernochowski, 2016)). In their recent investigation, Haese and Czernochowski (Haese and Czernochowski, 2016) measured event-related potentials (ERPs) as 7-year-old and 10-year-old children performed an explicit recognition task. Participants studied object pictures and were later asked to discriminate between studied, modified and new pictures. In this case, feature memory (perceptual processing) is indicated by the proportion of correct "identical" responses to identical items, which would require memory of the fine perceptual details (as opposed to memory for the overall "gist"). Although the two groups did not differ in their behavioral performance, robust modulation of the frontal old/new effect (the putative ERP correlate of familiarity-based retrieval) following intentional encoding was observed for identical versus new items in older children, but not in young children. Moreover, modulation of this ERP component for modified versus new items, that is typically observed in young adults (e.g., (Haese and Czernochowski, 2015)), was not observed in either group. This indicates that even when coarse behavioral outcomes do not reveal age-related differences, the underlying neuro-cognitive mechanisms can still shift (e.g., from recollection to familiarity-based recognition) and develop with maturation.

As for conceptual processing, some studies do not show maturation effects for conceptual memory (Anooshian, 1997; Billingsley et al., 2002). For example, in the study by Haese and Czernochowski (Haese and Czernochowski, 2016) described above, the developmental trajectory was only revealed in the second block where items were intentionally encoded, but not in the first block where encoding was incidental. Because the task requirements (i.e., memory for perceptual details) were unknown during the first block, it can be argued that focus has shifted from conceptual processing (in the first block) to perceptual processing (in the second), thus revealing maturation effects that are associated only with the latter. Nevertheless, other studies indicated that developmental effects on conceptual processing do exist. In a recent study that focused on utilization of schemas (cognitive structures that organize conceptual knowledge), Brod, Lindenberger, and Shing (Brod et al., 2016) demonstrated an age-related increase, from childhood to adulthood, in the relative importance of schema-based memory. Additionally, studies have shown a developmental trajectory in tasks that involve conceptual priming (Mecklenbräuker et al., 2003; Murphy et al., 2003; Sauzéon et al., 2012).

Different studies use different samples and different sample characteristics, which can account for some of the discrepancies in the current developmental literature. The number of age groups, as well as their range, vary considerably between studies (e.g., 4 age groups [5–7, 9–11, 14–16, 22–28 years of age] in (Cycowicz et al., 2000); 2 age groups [7–8 and 9–11] in (Haese and Czernochowski, 2016); a group of children [8–10] and a group of young adults [19–27] in (Mecklinger et al., 2011); 2 age groups [5.5–6.5, 9.4–10.9] in (Mecklenbräuker et al., 2003)). Therefore, any differences in developmental trajectories of different mnemonic components, or even within the same mnemonic component, might be explained in terms of different characteristics of the selected sample. In addition, tasks that tap the various mnemonic components differ significantly between studies, not just in terms of the component that they trigger, but also in terms of other aspects such as difficulty, modality, measures, etc. These discrepancies, therefore, warrant a systematic investigation of the developmental trajectories of components associated with the Memory Systems and the Processing Modes frameworks within a single study, using the same sample and similar tasks.

The current study

To address these issues, we used two sets of memory tasks (four memory tasks in total) that were previously used in the literature to explicitly and implicitly tap perceptual and conceptual memory. Performance in memory tasks usually entails a combination of processes, with a certain degree of overlap between memory systems and processing modes. Nevertheless, some tasks can still stress the contribution of certain mnemonic components over others. Therefore, we selected four tasks, each emphasizing a different combination of the mnemonic components described above.

In the two perceptual tasks, participants viewed a series of increasingly completed line-drawings of objects and animals, until they were able to identify them. Some of the pictures were viewed previously, while others were new. For the implicit perceptual task, improved performance (indicated by reduction in identification threshold) for previously viewed (old) items compared to newly presented (new) items was taken as an indication of implicit memory. For the explicit perceptual task, participants were informed that some of the objects were viewed beforehand while others were new. In the two conceptual tasks, participants were asked to name exemplars of primed and unprimed categories. In the implicit conceptual task, they were instructed to name the first exemplars that came to mind, while in the explicit conceptual task they were explicitly asked to recall the objects related to categories that were studied before (see the Method section for a more detailed description of the tasks). All four tasks were administered to the same participants, in three age-groups (mid-childhood, mid-adolescence, young adulthood).

This design allows us to draw new insights regarding age-related memory effects within and between different mnemonic components. Unlike previous investigations which only tested one memory component or compared memory components within the same framework (either Memory Systems or Processing Modes), we used different tasks that highlight the various mnemonic components, but are relatively similar (e.g., in terms of difficulty; albeit, admittedly, more similar within Memory Systems than within Processing Modes). The same group of participants performed all four tasks, which was crucial for this study. Therefore, unlike previous attempts to compare developmental trajectories observed in different studies, in our case any discrepancies in maturation effects are more likely to be attributed to actual differences in developmental trajectories of supporting mechanisms, rather than to differences in sample characteristics.

Given the contradicting evidence in the previous developmental literature on processing modes (both perceptual and conceptual), we did not make any predictions regarding the developmental trajectories that would be associated with these components. Nevertheless, as previous studies consistently showed a clear developmental trajectory in the explicit memory system, we predicted that age-effects would be observed in the explicit tasks, regardless of the processing mode. We further predicted that in the explicit tasks, age effects would be more pronounced than in the implicit tasks, although the latter might be observed as well.

Method

Participants

Recruiting process and inclusion criteria

After obtaining the necessary approval to conduct the research from the Ministry of Education, the Research Authority of the Nes-Ziona Metropolitan Area (Israel), and Bar-Ilan Institutional Review Board, inquiries were sent to several schools. Informed consent was obtained from all participants (or their parents, for minors), for a protocol approved by the Bar Ilan Institutional Review Board. With the approval of the school principals, teachers of relevant classes (according to the predetermined age groups) asked for parents' consent for their children to participate in the study. Second and eighth-grade students were then recruited. These children and adolescents were randomly selected from among all of the children in these schools whose parents gave their informed consent, and complied with the inclusion criteria of (1) lack of severe behavioral problems and known neurological and/or behavioral syndromes, based on the child's portfolio and teacher's reports; (2) native Hebrew speakers; and (3) at age-appropriate educational levels. All adult participants were healthy young adults with no history of neurological and/or neuropsychological issues (based on self-reports), who volunteered ($n = 20$) or participated in exchange for academic credits. The vast majority of the participants were of middle-high socioeconomic status.

Characteristics

Three age-groups consisting of 32 volunteers each (16 females in each group) participated in the study. The age groups were: 6.5–8.5-year old children (mid-childhood group: mean age 7.7 ± 0.58); 13–14.5-year old adolescents (mid-adolescence group: mean age, 13.7 ± 0.51); and 20.5–24-year old adults (young-adulthood group: mean age, 21.8 ± 0.89). Seven participants (2 children, 4 adolescents and 1 adult) were excluded from the analyses due to misunderstanding of the instructions (3), incompatibility with inclusion criteria (1), or a technical error made by the experimenter resulting in deletion of the data (3). Those excluded were replaced with aged-matched participants.

Procedure

Participants were tested individually in a single sessions which lasted approximately one hour for each participant. Before beginning the experimental tasks, the experimenter provided a brief description of the experiment and told the participants that they were chosen to participate in an experiment that includes several tasks. All tasks (the 4 tasks reported here + 2 additional tasks) were computerized, and were presented on a 15″ monitor connected to a laptop. Responses were obtained using a standard keyboard and computer mouse connected to a laptop. The pictorial stimuli displayed on-screen were 10 × 15 cm (height x width) in size, corresponding to a visual angle of approximately 11° by 17° from a viewing distance of 50 cm. As mentioned before, we employed two tasks that rely on perceptual processing and two tasks that rely on conceptual processing. For each of these processing modes, one task was an explicit memory task, and one was an implicit memory task. The selected tasks were used in previous studies to measure the memory components that were tested in the current study (e.g., (Blaxton, 1989; Blaxton, 1992; Roediger and McDermott, 1993; Srinivas and Roediger, 1990)).

Implicit perceptual task: Picture Fragment Identification (PFI)

The stimuli used for the implicit perceptual task consisted of 60 unambiguous line drawings of common objects, normed for children and adults (Berman et al., 1989; Cycowicz et al., 1997; Snodgrass and Vanderwart, 1980). The present study used only pictures that were normed for children in order to use the exact same items in all age groups. Furthermore, in order to deal with possible cultural differences, we conducted a pre-test with a group of 30 young children aged 5 to 6 years old. For the current study, pictures that all of these children named and identified correctly were selected.

The 60 pictures were divided into two comparable sets of 30 pictures each. Each set was again divided into two comparable subsets of 15 pictures each. Pictures in all sets were fragmented into a series of images at eight levels of completion using the Snodgrass, Smith, Feenan, and Corwin (Snodgrass et al., 1987) picture fragment algorithm. The most fragmented image represented level one, and the most complete image, level eight.

The PFI task was divided into two phases – study and test. In the *study phase*, participants viewed 15 un-fragmented pictures. Half of the participants viewed List 1 and the other half viewed List 2. Half of the participants who were presented with List 1 viewed set A during the study phase and the other half viewed set B. During the study phase, each un-fragmented picture was presented for 3000 milliseconds with 500-millisecond inter-stimulus intervals between pictures, and participants were asked to name the object that appeared in the picture. During this phase, the experimenter logged the participants' responses in a table that listed the correct responses. Exact matches were marked with "V". Other responses were logged in the table. In case of a mismatch, the experimenter encouraged the participant to try to correctly identify the object by saying "can this be anything else?" In one case the participant was unable to provide the correct response, and was given the correct answer by the experimenter who marked the trial as "did not know".

The *test phase* immediately followed the study phase. Participants viewed a total of 30 items, 15 seen beforehand during the study phase (test-old), and 15 new items (test-new) from the second subset of stimuli. Thus, each participant saw all 30 pictures in the subset, but stimuli assignment to experimental conditions was counterbalanced across participants and within each age group. Moreover, the order of the pictures within each phase was randomized individually for each participant. At the beginning of the test phase, participants were informed that they will view fragmented pictures and were asked to name the object that appears in the picture. They were told that if they cannot identify the object, the experimenter will press a key on the keyboard to add more fragments to the object picture. After seven key presses, the full picture was shown (eight levels of completion).

Explicit perceptual task: Pictorial Cued Recall (PCR)

Each participant was presented with the set of stimuli that complemented the one used for that participant in the PFI task. During the study phase, participants viewed stimuli from one of two subsets presented in random order, and performed the task described above for the study phase of the PFI task. During the test phase, participants were asked to identify fragmented objects, as in the PFI task, only this time they were explicitly told that some of the objects were viewed beforehand while others were new.

Implicit conceptual task: Category Production (CP)

In the implicit conceptual task, thirty line-drawings of objects (a different set from the one used for the PFI and the PCR tasks) from six semantic categories, were applied. To avoid chance production of learned objects (see procedure below), we ensured that all objects were infrequent exemplars of their category. Frequency was previously determined in a study by Vakil and Sigal (Vakil and Sigal, 1997) which used a large cohort ($n = 324$) to acquire normative data on frequency of category exemplars in the Hebrew language. All objects used in the current study scored nine or more on this scale, meaning that they were not among the 9 most frequent exemplars of each category. The stimuli were divided into two lists, each including objects associated with one of three different categories (i.e., five objects X three categories in each of the two lists). The categories in the first list were: (1) mammals; (2) vehicles; and (3) musical instruments. The categories in the second list were: (1) fruits; (2) birds; and (3) kitchenware. Lists were counterbalanced across participants within each age group, and presentation order was randomized.

The task included a study and a test phase. During the *study phase*, participants viewed the object pictures in one of the two lists, and performed the same study task described above for the PFI task. The *test phase* immediately followed the study phase and contained all six categories. Three were the primed categories, associated with objects that were viewed beforehand in the study phase. The three remaining categories were new, unprimed categories. Categories were presented alternately, starting with a new unprimed category. Participants were asked to provide eight exemplars for each category. The experimenter presented a new category once the participant provided eight exemplars or could not think of any additional ones. Performance in this task does not depend on perceptual or functional relations between the items, but rather on taxonomic categorical relations. Therefore, in this task, participants were required to utilize their conceptual understanding of the semantic categories and their associated exemplars.

Explicit conceptual task: Category Cued Recall (CCR)

This task resembled the CP task. For each participant, the complementary list to the one used for the CP task was used. During the *study phase*, participants viewed object pictures, and performed the same study task described above for the CP task. During the *test phase*, participants viewed the studied categories in the same manner described above, but were explicitly asked to recall the objects seen before, that fit each category.

Administration

The four tasks were administered in a pre-defined order: PFI (1st position), CP (2nd position), PCR (4th position), and CCR (6th position). Two additional tasks (Tower of Hanoi and Maze Master) which are not reported here because they exceed the scope of the present study, varied in their administration at either the 3rd or 5th position (yielding two administration protocols, counterbalanced across participants within each age-group). We constrained the order of the four tasks of interest for two reasons. First, in order to avoid intentional encoding in the implicit tasks, the implicit tasks always preceded the explicit ones. Second, administration of the perceptual and conceptual tasks was interleaved to avoid interference effects between tasks that use similar materials.

Results

Analyses were performed separately for the perceptual and conceptual tasks, because these tasks varied in their dependent measures. Gender, Administration Protocol, and Picture List variables (for the PFI and PCR tasks) were entered as covariates in all analyses but did not interact with the other factors, and are therefore not reported. All results reported below were corrected for alpha inflation due to multiple comparisons using Bonferroni correction.

Perceptual tasks

The overall percentage of identified pictures was very high, and did not differ between age groups. All participants were able to name the vast majority of objects easily, although some participants identified them with alternative names to those that were originally noted. These variations were accounted for when calculating the scores for the test phase (that is, if a participant identified an object designated as an "umbrella" as a "parasol" during study, than a "parasol" response during the test phase was considered correct). For both perceptual tasks, the level at which the participant could identify the picture during the test phase was designated as the *identification threshold* for that particular picture. For each participant, the mean identification threshold was computed separately for old and new items.

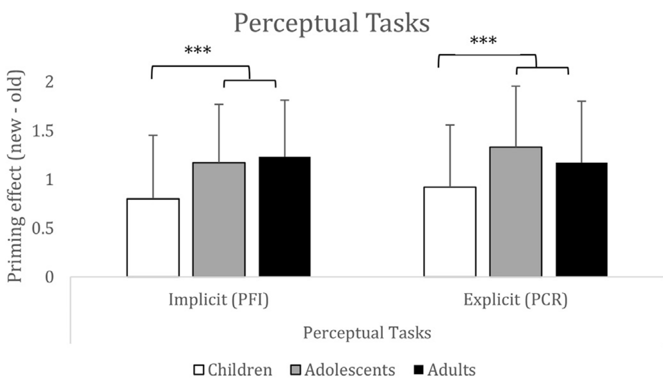

Fig. 1. Mean and *SE* of the Identification threshold of the perceptual tasks: Implicit (PFI) and explicit (PCR) for the three age groups, mid-childhood, mid-adolescene and young adults, 32 participants in each. *** $p < .005$.

To analyze the data of the perceptual tasks, as depicted in Figs. 1, repeated measures ANOVA was used, with Task (implicit vs. explicit) and Item Type (old vs. new) as within-subjects factors; Age Group (mid-childhood vs. mid-adolescence vs. young-adulthood) as a between-subjects factor; and the mean identification threshold as the dependent measure. This analysis revealed a significant main effect for Task, $F(1, 93) = 18.99$, $p < .001$, $\eta_p^2 = 0.17$, indicating overall earlier identification in the explicit task compared to the implicit task, a significant main effect for Item Type, $F(1, 93) = 727.31$, $p < .001$, $\eta_p^2 = 0.89$, indicating an overall lower identification threshold for old pictures compared to new ones, and a significant effect for Age Group, $F(2, 93) = 63.19$, $p < .001$, $\eta_p^2 = 0.58$. These main effects should be interpreted cautiously because a significant interaction between Item Type and Age Group, $F(2, 93) = 8.85$, $p < .001$, $\eta_p^2 = 0.16$ was also revealed. We decomposed the interaction using three repeated measures ANOVAs with Item Type (old vs. new) as a repeated factor and two of the three age groups as a between-subject factor in each ANOVA. This revealed that the difference in identification thresholds between old and new items was greater in the mid-adolescence group than in the mid-childhood group, $F(1, 62) = 14.61$, $p < .001$, $\eta_p^2 = 0.19$, and greater among the young-adulthood group than among the mid-childhood group, $F(1, 62) = 11.27$, $p < .001$, $\eta_p^2 = 0.15$, but did not differ between mid-adolescence and young-adulthood $F(1, 62) = 0.27$, $p = .60$, $\eta_p^2 = 0.01$.

-Insert Figs. 1a & 1b about here-.

Conceptual tasks

To analyze the data of the conceptual tasks depicted in Fig. 2, repeated measures ANOVA was used with Task (implicit vs. explicit) as a within-subjects factor, and Age Group (mid-childhood vs. mid-adolescence vs. young-adulthood) as a between-subjects factor. The dependent measure was the mean number of items attributed to primed categories (in the 0–15 range). This analysis revealed a main effect for Task, $F(1, 93) = 344$, $p < .001$, $\eta_p^2 = 0.79$, indicating that overall, more primed items were reported in the explicit task than in the implicit task, and a main effect for Age Group, $F(2, 93) = 36.68$, $p < .001$, $\eta_p^2 = 0.44$. Nevertheless, these main effects should be cautiously interpreted because of a significant interaction between these two factors, $F(2, 93) = 13.05$, $p < .001$, $\eta_p^2 = 0.22$. Decomposition of the interaction revealed that while the groups significantly differed in their performance in the CCR (explicit) task, $F(2, 93) = 44.197$, $p < .001$, $\eta_p^2 = 0.49$, with significant differences between all three age groups (mid-childhood vs. mid-adolescence: $t(62) = 4.94$, $p < .001$; mid-adolescence vs. young-adulthood: $t(62) = 4.12$, $p < .001$; mid-childhood vs. young-adulthood: $t(62) = 9.06$, $p < .001$), only marginal differences in performance emerged in the CP (implicit) task, $F(2, 93) = 3.07$, $p = .051$, $\eta_p^2 = 0.062$, with significant differences in performance shown only between mid-adolescence and mid-childhood, $t(62) = 2.5$, $p < .05$.

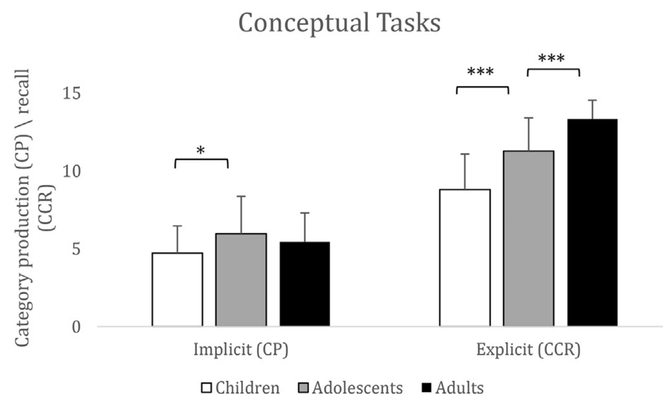

Fig. 2. Mean and *SE* of the number of old items reported in the conceptual tasks: Implicit (CP) and explicit (CCR) for the three age groups, mid-childhood, mid-adolescene and young adults, 32 participants in each. * $p < .05$, *** $p < .005$.

-Insert Fig. 2 about here-.

Discussion

The current study explored whether mnemonic components associated with the Memory Systems framework (explicit-implicit) and the Memory Processes framework (conceptual-perceptual) show similar or otherwise distinct developmental trajectories. All four mnemonic components assessed in our study showed a developmental trajectory, although the exact pattern differed for the various components. These variations revealed several interesting patterns. First, maturation effects were robust in the explicit memory system, and were more apparent in the explicit than in the implicit memory systems for conceptual processing. Second, performance levels in the mid-adolescence group were comparable with those of young adults, except for the explicit conceptual task. Third, within the implicit memory system, maturation effects were more apparent for perceptual than for conceptual processing. Below we discuss the theoretical significance of these findings.

Robust maturation effects in the explicit memory system

Robust maturation effects were found in the explicit memory system. For perceptual processing, children underperformed compared to both adolescents and adults (who did not differ), and this effect was comparable to that observed in the implicit system. For conceptual processing, our study revealed a linear developmental trajectory (mid-childhood < mid-adolescence < young adulthood) in the explicit memory system, but an attenuated trajectory in the implicit system. These findings coincide with our initial hypotheses. Indeed, while developmental effects in the explicit memory system were frequently reported in previous literature (e.g., (Mecklinger et al., 2011; Ofen et al., 2007; Sprondel et al., 2011; Van Strien et al., 2011)), reports on developmental effects in the implicit memory system were less consistent (e.g., (Cycowicz, 2000; Ofen and Shing, 2013; Vöhringer et al., 2017); but see (Cycowicz et al., 2000; Mecklenbräuker et al., 2003; Vaidya et al., 2007)). We therefore predicted that age-effects in the explicit system would be robust, and possibly more pronounced than in the implicit system.

It has been suggested before that the implicit memory system is associated with an attenuated developmental pattern relative to the explicit memory system, because the former is more primitive, both phylogenetically and ontogenetically, and is operational even in infancy (Schacter and Moscovitch, 1984; Squire, 1987; Tulving and Schacter, 1990). Nevertheless, our results join a growing body of evidence suggesting that even if the implicit system is already functional to some extent from a very early age, it still continues to develop during childhood and into adolescence. Thus, even though maturation effects in the explicit memory system seem to be more robust, they are also reliable in the implicit memory system.

Prolonged developmental trajectory for explicit conceptual processing

In the current study, performance levels in the mid-adolescence group were comparable with those of young adults in both perceptual tasks as well as in the implicit conceptual task. In contrast, young adults outperformed both age groups in the explicit conceptual task. In other words, cognitive development at mid-adolescence was sufficient for coping with perceptual and implicit conceptual tasks at an adult-like level, but not for coping with an explicit conceptual task.

This pattern can be explained by the variations in neural regions and pathways that are required for explicit access to perceptual vs. conceptual information. Arguably, explicit memory for (visual) perceptual information relies more heavily on interactions between the MTL and occipital regions, while explicit memory for conceptual information relies more heavily on interactions between the MTL and the prefrontal cortex. Previous studies have shown that structural maturation of the prefrontal cortex is relatively slow (e.g., (Shaw et al., 2008; Sowell et al., 2003)), and that continued structural development also occurs within the MTL (and more specifically – in the hippocampus; (DeMaster et al., 2013; Ghetti et al., 2010; Ghetti and Bunge, 2012; Gogtay et al., 2006)). Furthermore, relatively slow structural changes to white matter tracts connecting these regions have also been documented (reviewed by (Ghetti and Bunge, 2012)). Together, these neural maturation patterns can explain the linear developmental trend observed in the explicit conceptual task in our study.

While performance in the explicit conceptual task required further maturation into adulthood, mid-adolescents and young-adults did not differ significantly in their performance in the other three tasks. Furthermore, a surprising numerical trend of mid-adolescents > young-adults was observed in the explicit perceptual task and the implicit conceptual task. Previous studies have shown that adolescents sometimes outperform adults in memory tasks, e.g., when the outcome is rewarding (e.g., (Davidow et al., 2016)). Linking these findings to our current data would be premature, as the numerical difference observed in our study was unpredicted and non-significant. Nevertheless, evaluation of non-linear developmental trajectories of mnemonic components would be an interesting topic for future investigations.

Maturation effects within the implicit memory system

Within the implicit memory system, both perceptual and conceptual processing revealed a similar developmental trajectory of mid-childhood < mid-adolescence = young-adulthood. Nevertheless, the difference in performance between the mid-childhood age-group and the other two groups was more robust for perceptual than for conceptual processing. One possible reason for this attenuated age effect is that performance of adolescents and adults in this task interacts with their ample prior knowledge. For example, suppose that a young child is familiar with only 30 mammals, while an adolescent is familiar with 500 mammals. When asked to name mammals, the probability that the adolescent would choose the ones from the study phase, when not explicitly instructed to do so, is reduced. This reduction does not reflect decreased memory of studied items (as evident by performance levels of adolescents and adults in the explicit task) but rather a larger conceptual space from which adolescents and adults can choose an appropriate response. This might overshadow or decrease the age-effect observed in this task. However, any difference in effect size across processing modes should be treated with caution, because the dependent measures were different for conceptual and perceptual processing. Indeed, while the data collected for the conceptual task was discrete (total number of primed items), the data collected for the perceptual task was continuous (averaged identification threshold). Therefore, the perceptual task was potentially more sensitive to age-related differences.

Limitations of the current study

As noted above, for each processing mode, the implicit and explicit tasks were closely matched, differing only in the instructions given at test. However, the tasks used for the different processing modes were not as similar, and differed in their dependent measures. Therefore, evaluation of effects within each task and between implicit and explicit components is straightforward, but formal comparison of perceptual vs. conceptual components cannot be achieved with our current design.

Another limitation of the current study is that each combination of mnemonic components was only sampled with a single task, which may not represent the entire spectrum. Furthermore, although the tasks used here are known to tap the components of interest, mnemonic tasks never reflect a single or a pure process. Rather, a mnemonic task might stress certain primary process, but also involve additional ones (e.g., (Jacoby, 1991)). Therefore, our conclusions should be re-tested in future studies, using a variety of tasks that tap the different mnemonic components.

Finally, the developmental patterns observed in our study might be explained, to some extent, by prior experience with similar experimental settings. In particular, it is possible that young adults were more familiar with the psychological tests and correctly appreciated the mnemonic nature of the implicit memory tasks. Nevertheless, familiarity with experimental procedures does not only increase from childhood to adolescence, but also (and perhaps even more so), from adolescence to adulthood. Therefore, the fact that no difference was observed between the two older groups in the implicit conceptual task suggests that previous experience is unlikely to account for our findings.

Applications and outlook

The results of our study may facilitate the development of evaluation methods in educational settings. Of particular interest is our finding that developmental trajectories are prolonged for explicit conceptual processing, suggesting that the mechanisms required to cope with such tasks are not fully developed before adulthood. High-school students are often expected to demonstrate that they have successfully acquired new conceptual knowledge. Controversially, however, the means used for their evaluations are almost always explicit. Given that for conceptual processing, the explicit system is not fully developed at mid-adolescence, traditional evaluation methods might not fully capture the progress made by high-school students in understanding and remembering classroom material. Development of implicit evaluation methods, such as implicitly using learned conceptual knowledge for problem solving or decision making, can provide educators, assessors and the students themselves with a better sense of their progress.

Conclusion

We demonstrated that different combinations of Memory Systems (explicit or implicit) and Processing Modes (perceptual or conceptual) produce different patterns of developmental trajectories. Our findings thus provide insights on the developmental patterns of these components, and validate the notion that in order to understand maturation effects on memory, both frameworks should be taken into account.

Author's note

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