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Autobiographical memory in children: relation to neural white matter

Josh Litwin[a], Kate Hill[b], Julia M. Foley[c], Naoya Tani[c], Samantha S. Cohen[c], Nora S. Newcombe[c] and Ingrid R. Olson[c]

[a]Department of Neurology, Boston Children's Hospital, Boston, MA, United States; [b]Brain and Cognitive Sciences, Department of Psychology, University of Illinois at Chicago, Chicago, IL, United States; [c]Department of Psychology and Neuroscience, Temple University, Philadelphia, PA, United States

ABSTRACT

Autobiographical memory involves the integration of self-referential memory into a coherent narrative of life experiences. Recently, several studies of healthy adults and older adults with neurodegenerative disorders have utilised diffusion imaging to construct a network of cortical regions that support autobiographical memory. We extend this work to an age range, 4 to 7 years, when autobiographical memory is still developing. We correlated the recall of autobiographical events with limbic white matter tracts that have been previously implicated in episodic and autobiographical recall, i.e., the uncinate fasciculus and cingulum bundle. While there was no evidence for a link between the uncinate and autobiographical memory, we found a strong association between cingulum microstructure (fractional anisotropy; FA) and the number of autobiographical details provided. No relation was found between limbic tract microstructure and other measures of episodic recall. These findings extend work in adult samples, suggesting that the cingulum bundle may contribute in a meaningful way to autobiographical memory across a wide age range.

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Memory; default mode network; development; white matter; diffusion imaging; cingulum bundle

Episodic memory refers to the recollection of events set within a particular time and place (Conway & Pleydell-Pearce, 2000). Tulving (2002) suggested that episodic memory involves both the specific "what", "where", and "when" of the event, and an awareness of the self being present in the event, also known as "autonoetic consciousness". Autobiographical memory (AM) builds on this framework, relating event knowledge to an individual's past experiences and future goals. Conway and Pleydell-Pearce (2000) propose three broad levels of specificity in autobiographical memory: lifetime periods, general events, and event-specific knowledge. These domains are often woven together during autobiographical recall, allowing individuals to create a narrative of their life experiences and to construct an identity from this narrative (Habermas & Bluck, 2000). However, only the last of the three levels, event-specific knowledge, is episodic.

The emergence of "what", "where", and "when" in episodic memory is not uniform. Spatial episodic memory first develops between 18–24 months, at which point children can detect changes in spatial context and use landmarks to inform decisions (Newcombe et al., 2022). "What-where" memory, in which items are linked with an allocentric spatial location or context, improves steeply between three and eight years old (Bauer et al., 2012; Bevandić et al., 2024; Newcombe et al., 2022). By approximately two years old, children begin to understand temporal order when encoding a sequence of actions (Newcombe et al., 2022). However, this "what-when" memory is weak throughout early childhood, with a protracted developmental period that lasts until about six or eight years (Pathman et al., 2013). At four, children start to exhibit memory of specific object details (Newcombe & Nguyen, 2023). This ability improves noticeably from four to six years, aligning with the timeline for holistic recollection of event details (in which different pairs of event elements can be associated with each other) (Conway & Pleydell-Pearce, 2000). Autonoetic recall has not been studied in-depth during this age range, as it is often difficult to gauge in young children. It seems to improve over the course of grade school (six to 11 years) (Bevandić et al., 2024), suggesting a later development for this component of Tulving's model.

Our goal was to study the neural underpinnings of individual variation in the development of autobiographical memory. Episodic memory is often measured in laboratory settings, with tasks that evaluate spatial navigation, memory for lists of words, and object-location recognition, to name a few examples. This type of memory has been linked at the neural level to the hippocampus along with

CONTACT Josh Litwin litwin222@gmail.com Department of Psychology, University of Houston, 4849 Calhoun Road, Houston TX 77004, United States

surrounding regions of the medial temporal lobe (Eichenbaum et al., 2012; Nyberg et al., 1996; Ranganath, 2010), portions of the frontal lobe (Kramer et al., 2005; Wheeler et al., 1997) and parietal lobe (Berryhill et al., 2007; Sestieri et al., 2017; Wagner et al., 2005), as well as essential subcortical regions, e.g., thalamic nuclei and basal forebrain nuclei (Aggleton & Brown, 1999; Cabeza et al., 1997). The neural foundation of autobiographical memories, however, is less clear, do in part to the fact that involved brain regions are highly distributed. They involve areas traditionally linked with those implicated in episodic memory such as the medial temporal lobe. However, autobiographical memory has also been linked to regions implicated in other behaviours such as imagery (precuneus, posterior cingulate), visuospatial processing (retrosplenial cortex, occipital cortex), and semantic memory (anterior temporal lobe) (Bauer et al., 2017; Cabeza et al., 1997; Catani et al., 2013; Irish et al., 2014; Maddock et al., 2001; Steinvorth et al., 2005; Svoboda et al., 2006).

This study focuses on the neural white matter tracts that connect some of these distributed regions. Axonal tracts link different parts of the brain much like highways link different cities. These tracts (also referred to as pathways, fascicles, or simply "white matter") are highly plastic and show a great deal of individual variation in their volume, internal organisation, and myelination (Rokem et al., 2017). Maturation of neural white matter is prominent in early childhood (Groeschel et al., 2010), reflecting developmental programs as well as experience-driven plastic changes.

Several limbic tracts may be especially important for long-term memories such as autobiographical memory (Catani et al., 2013). The uncinate fasciculus (UF) links the anterior temporal lobe and amygdala to orbitofrontal regions to enable the integration of sensory and emotional content for semantic memory (Olson et al., 2015; Von Der Heide, Skipper, and Olson, 2013). The hippocampal-diencephalic network, connected through the fornix, and the parahippocampal-retrosplenial network (ventral cingulum bundle) are both responsible for episodic memory and spatial orientation (Vann et al., 2009). Finally, the dorsal cingulum bundle (CB) provides links throughout the default mode network (DMN) (Van Den Heuvel et al., 2008). The DMN is a group of regions clustered around medial portions of the parietal, temporal and frontal lobes (Smallwood et al., 2021) that decrease in activity during complex attention-demanding tasks (Raichle et al., 2001; Shulman et al., 1997). The DMN has also been associated with abstract thought and memory (Smallwood et al., 2021). The framework proposed by Catani illustrates the overlapping and complex networks that underly the retrieval of different forms of declarative memory including autobiographical memory.

Here we investigated the potential role of the UF and CB in autobiographical memory in childhood. A small but growing body of research has investigated the role of prefrontal-limbic tracts in episodic memory, with the UF and CB both playing key roles across the lifespan. The UF has been associated with mnemonic control in children aged 7 to 11 (Wendelken et al., 2015), and both UF and CB maturity have been linked to the development of episodic recall and recognition in early-middle childhood (Bouyeure et al., 2022; Samara et al., 2019). Later in adulthood, the CB may contribute to maintenance of verbal and visual recall (Resende et al., 2017). The UF and CB both play a role in mediating autobiographical recall in adulthood (Clark et al., 2022; Irish et al., 2014; LePort et al., 2012; Memel et al., 2020).

Although episodic memory and autobiographical memory are closely related constructs, there is reason to believe that autobiographical memory can be distinct from episodic memory. AM often involves active engagement in memories, and a clearer sense of placing oneself in past events during recollection. However, this relation has yet to be explored in a developmental population. To accomplish this, we examined the autobiographical memories of children between four and seven years. To assess the specificity of these tracts for autobiographical memories, as opposed to episodic memories more generally, we also tested the same children on a different episodic memory task that did not draw from their personal experiences.

Methods and materials

Participants

Our final sample included 50 participants (33 female; Mean age: 5.95 years; see Table 1 for more detailed demographics information) recruited as part of a larger study on the development of episodic memory. This sample size is in line with prior diffusion imaging studies on

Table 1. Participant demographic data.

	Total ($n = 50$)	
	Count	Percent
Race		
Asian or Asian American	6	12%
Black or African American	8	16%
Mixed	5	10%
Other	4	8%
White or Caucasian	27	54%
Ethnicity		
Not Latinx	44	88%
Latinx	6	12%
Sex at birth		
Female	33	66%
Male	17	34%
Age		
4 years	13	26%
5 years	14	28%
6 years	11	22%
7 years	12	24%
Income		
>$100,000/year	29	58%
<$100,000/year	21	42%

autobiographical memory. Ninety-one participants (59 female; Mean age: 5.8 years), between the ages of 4 and 7 years were initially recruited from the greater Philadelphia area. Participants attended two sessions, approximately seven days apart. Participants were compensated with gift cards. An IRB-approved informed consent form was completed by the guardian of all participants, and assent was obtained from all participants older than seven years old. We excluded 35 participants because they did not obtain a diffusion weighted MRI (dMRI) scan, usually because they could not tolerate or were afraid of the scanner environment. We excluded an additional six subjects because they did not meet our imaging quality threshold (see section 2.4, in Methods). All participants were healthy children with no history of neurological or psychological disorders and English proficiency.

Behavioural measures

Autobiographical interview

The procedure for the autobiographical interviews was modelled after those established in prior studies in children (Cleveland & Reese, 2005; Jack et al., 2009). Parents first provided four positive or neutral non-routine events that they shared with their children between two days and six months ago (e.g., a trip to the zoo). Subsequently, events were randomly divided into two conditions: two of the events were discussed between the parent and their child, and the other two were discussed between the child and an experimenter. Parents were instructed to reminisce as naturalistically as possible, with no time limit set for their conversation. Each event was introduced one at a time and discussed until the child did not want to continue conversing. Experimenters began the interview with the prompt "Your [mom/dad] told me that you … " followed by a brief summary of the event and a general request for more information (e.g., "Your mom told me that you went recently went to the zoo. Tell me about that"). After this initial prompting, experimenters were explicitly instructed not to provide guiding questions. Their responses were limited to one of the following: An interjection, such as "Wow!" or "Oh?", repetition of the child's statements, or a simple "Tell me more about that". The order of who the child spoke with first (parent or experimenter) was pseudo-randomised across participants.

Conversations were recorded using *Audacity*, transcribed using *Otter.ai* (https://otter.ai/) and checked manually for accuracy. The transcripts were then divided into the four discussed events. The dialogue within each event was then divided into utterances, defined as conversational turns containing a verb or implied verb, such that there was one verb per clause. The child's utterances were then coded for memory elaborations using an adapted version of a reliable coding scheme established in the literature (Reese et al., 1993). Utterances were additionally coded for structure in accordance with previously used coding schemes that measure memory elaborations, repetitions, confirmations, questions, meta-memory comments, and associated event talk (Haden, 1998; Reese et al., 1993; Reese & Brown, 2000). Examples of the coding scheme can be found in Table 2. Ultimately only the child's memory elaborations, which provide new information relevant to the discussed event, were used in the present analyses (Cleveland & Reese, 2005). A reliable coding scheme was established on 22 coded transcripts, with a Cohen's Kappa of 0.813, indicating substantial agreement between raters (Cohen, 1960; Landis & Koch, 1977). The number of memory elaborations were averaged across all four events to yield a measure of autobiographical recall.

Cartoon recall

There were two testing sessions, seven days apart. During Session 1, participants were presented with a series of six short, animated silent cartoons (30–73 seconds) about a small mouse and his friends (*Die Sendung mit der Maus*). These German cartoons were selected partly since we expected American children to be unfamiliar with them.

Table 2. Autobiographical interview coding scheme.

Code	Description	Example
Memory Elaborations	On-topic utterances that provide new information	"We went to the ice cream shop"
Memory Questions	The child asks a question that requests information	"Did we go to the ice cream shop after school?"
Memory Repetitions	On topic utterances that do not provide any new information	Mother: "You got chocolate ice cream". Child: "I got chocolate".
Child Place Holder	Only coded if there is nothing else in the conversational turn	"I don't know", "Oh", "Um"
Meta Comments	Comments about the process of remembering	"I don't remember the flavour I got because it was a long time ago".
Confirmations	Confirming a prior statement by the other speaker	Mother: "You ate the ice cream very fast". Child: "Yes, I did!"
Negations	Negating a prior statement by the other speaker	Mother: "You got chocolate all over your face". Child: "No, I didn't".
Off Topic	Includes behaviours, talk about the tape recorder	"Can we leave now?", "I'm bored".
Unintelligible	Unintelligible utterances or utterances where it's unclear whether they are on or off topic	
Associations to the past	Referring to a related past event	"I got strawberry the last time we went to that ice cream shop".
Associations to the future	Referring to a future occurrence of the event	"Next time we go I will get chocolate again".
Fantasy Talk	Utterances that concern the event in question, but are not grounded in fantasy	Child: "There were dragons at the ice cream store". Mother: "No there weren't!"
Semantic Knowledge	General facts about the world that arose in conjunction with the event	"Ice cream is made from milk"

During Session 2, participants were shown still pictures from each video and memory for cartoon content tested. The experimenter presented the task to children by saying,

> Okay, now we want to see what you can remember about the cartoons we watched last time. I will show you a picture, and then I want you to tell me a story about what happened in the cartoon. Tell me whatever you can remember! Then I'll ask you a couple of questions about each story.

After each picture was presented, participants were asked, "Can you tell me this story as much as you remember?" Participants then retold the story to the best of their ability. Once the researcher asked, "Anything else?" and the child responded with "no/the end/I don't remember" the task ended. Stimuli were presented on a 14" MacBook Pro.

To assess accuracy on the task, an answer key with all possible correct answers was created from transcripts of 10 adults who described the cartoons. The number of possible correct answers ranged from 19 to 28 per cartoon. The recalls were separated into clauses and the transcripts were scored by a single researcher after establishing reliability between two independent coders (ICC = 0.89, CI = 0.84-0.92) on 25% of all transcripts collected ($n = 19$). If the participant's clause matched a response on the answer key, 1 point was given. If the participant omitted any correct answers or gave false answers, they were given a 0. Points were averaged across all six cartoons yielding an overall accuracy score.

KBIT-2

The Kaufman Bright Intelligence Test (KBIT) (Kaufman & Kaufman, 1990) is a standardised intelligence test that measures verbal and non-verbal knowledge in individuals 4–90 years old. For this study, only the Crystalised (verbal) Scale was used, comprised of a verbal knowledge subtest, to evaluate an individual's accumulated knowledge and verbal comprehension, and a riddles subtest. The verbal knowledge subtest requires participants to understand and answer questions about a wide range of topics, such as vocabulary, facts, and concepts. The riddles subtest was designed to measure an individual's ability to comprehend and use language effectively.

The standard score was used to assess verbal IQ. Assessments were scored and recorded by two separate researchers. Any discrepancies were looked at by a third researcher. Two participants did not complete the KBIT and were excluded from all subsequent analyses that involved verbal IQ. We included all participants in analyses that did not involve verbal IQ as the outcome or control. To ensure that including those who did not have KBIT scores in the main analysis did not skew the results, we performed a sensitivity analysis excluding them from the primary analyses.

MRI scan

MRI data were collected at The Temple University Brain Research and Imaging Centre. Children went into a mock scanner during Session 1, allowing them to get comfortable with the MRI environment and practice staying still to reduce movement artifacts during the MRI scan. All MRI data was collected on a 3T Siemens scanner with a 64-channel head coil. Padding placed within the head coil helped to reduce movement artifacts. Children watched videos during the MRI scan to further reduce movement.

Image acquisition included a T1 magnetisation-prepared rapid gradient-echo (MPRAGE) sequence (176 contiguous sagittal slices, 0.9 mm isotropic voxel size; 1900ms TR; 2.32 ms TE; 9-degree flip angle; 256 × 256-pixel matrix). T1 images were visually inspected immediately following the scan to ensure sufficient data quality. If the quality of the image was deemed to be too low, due to visual banding or visible blurring, the scan was immediately repeated.

Image acquisition also included a hybrid diffusion imaging sequence HYDI; a sequence that allows for many different analyses such as standard diffusion tensor imaging, or neurite orientation and diffusion dispersion density imaging, with a parallel imaging mode (GRAPPA) at an acceleration factor of 2. The diffusion scheme comprised of 145 non-collinear diffusion-weighted acquisitions. Of these, the volumes consisted of 6 b = 250 s/mm^2, 21 b = 1000 s/mm^2, 24 b = 2000 s/mm^2, 30 b = 3250 s/mm^2, 61 b = 5000 s/mm^2 and 3 T2-weighted $b = 0$ s/mm^2 acquisitions (2683 ms TR; 83.6 ms TE; 128 × 128 matrix; 69 slices with 2 mm isotropic voxels). In our analyses of the dMRI data, we elected to exclude the b = 250 s/mm^2 shells due to the designation of outliers in movement during this volume acquisition by FSL's Eddy QUAD (Quality Assessment of dMRI). Our final diffusion scheme was therefore comprised of 139 non-collinear diffusion-weighted acquisitions, which is more diffusion directions that prior studies in this literature. Additionally, non-diffusion-weighted field-maps with anterior to posterior and inverse phase-encoding directions were collected to measure echo-planar imaging (EPI) distortions. These images consisted of two b0 volumes each. All other parameters for field-map acquisition were matched to that of our diffusion-weighted volumes.

Diffusion MRI processing and analysis

Diffusion-weighted MRI (dMRI) images were processed using tools in the FMRIB Software Library (FSL v6.0.6.5; Image Analysis Group, FMRIB, Oxford, UK) and using Advanced Normalisation Tools (ANTs v2.4.4(Avants et al., 2014)). The T1 with the least amount of movement was manually chosen as the designated T1 scan for subjects with multiple T1 images. Subjects' T1-weighted images were then skull-stripped using ANTs. Using the FMRIB Diffusion Toolbox, susceptibility artifacts, EPI distortions, subject motion and eddy current-induced distortions were corrected (Andersson et al., 2003; Andersson &

Sotiropoulos, 2016). FSL's motion and eddy current correction were applied using the – repol flag, instructing EDDY to remove any slices deemed as movement outliers and replace them with predictions made by the Gaussian process. An outlier is defined as a slice whose average intensity is at least four standard deviations lower than the expected intensity, where the expectation is given by the Gaussian Process prediction (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/eddy/UsersGuide#A–repol). We then used the EDDY QUAD quality control tool to generate single subject reports and store the quality assessment indices for each of our subjects. A binary brain mask was created by removing the non-brain tissue with ANTs Brain Extraction Tool from each participant's topup-corrected, time-collapsed b0 image. Intracranial Volume (ICV) values were retrieved using FSL's FreeSurfer SynthStrip method (Hoopes et al., 2022). This uses Atropos, an ITK-based multivariate n-class open-source segmentation algorithm distributed with ANTs. Volumes for cerebrospinal fluid, gray matter, and white matter were calculated with *fslstats*. The most popular dMRI metric is fractional anisotropy (FA Nir et al., 2017). Since this measure is ubiquitous and lends itself to straightforward interpretation, we use this as our diffusion scalar of interest.

dMRI data were visually inspected for quality issues and any participant with more than five volumes with excessive intensity artifacts were excluded. Participants with more than 2 mm of average absolute motion were excluded. Perhaps due to the use of a mock-scanner prior to obtaining MRI, most subjects (45/50 participants) had less than 1 mm of absolute motion.

We selected tracts of interest based on those that have been consistently associated with autobiographical memory in adults (Clark et al., 2022; Irish et al., 2014; LePort et al., 2012; Memel et al., 2020): the uncinate fasciculus (UF) and the cingulum bundle (CB). Although two studies have linked the fornix to autobiographical memory in adults (Hodgetts et al., 2017; Memel et al., 2020), we did not include it because Automated Fibre Quantification, described below, does not include it in its default library. We had no *a priori* hypotheses about laterality so we examined both left and right tracts.

Diffusion images were analyzed with Automated Fibre Quantification (AFQ) (Kruper et al., 2021) through Python version 3.10.9 (pyAFQ version 1.1) and Diffusion Imaging in Python (DIPY) (Garyfallidis et al., 2014; Kruper et al., 2021; Yeatman et al., 2012) to model the voxel-wise diffusion profiles and implement tractography. We provided our own brain masks, rather than having pyAFQ create them for us. Constrained spherical deconvolution (CSD) was used as our orientation distribution function (ODF) measure. PyAFQ breaks each major tract into 100 equidistant nodes. It then calculates 100 different diffusion measurement (FA) values at every node, for every tract, for every subject. This is important as FA values are not the same along the whole tract, so in averaging across the entirety of the tract, potential systematic variability across each bundle is blurred.

Statistical analyses

Statistical analyses were primarily performed in RStudio version 4.2.3 (R Core Team, 2023) (http://www.R-project.org/). We examined the correlation between FA values and Autobiographical memory scores using a node-wise approach. By subdividing white matter fibre bundles into multiple segments, nodewise analysis is a technique that can reveal relations between local microstructures and behavioural indicators that cannot be captured by a tract-wide average. It is understood that myelination differs across long fibre tracts; a node-wise analysis can help reveal these differences. Through permutation testing, we determined the minimum number of significant consecutive nodes necessary for each tract to establish a true connection between each tract of interest and memory elaborations at an alpha level of $p < .05$. Permutation testing was used as a method of correcting for multiple comparisons. We modified and ran the AFQ_MultiCompCorrection.m (Nichols & Holmes, 2002) MATLAB script to achieve this through MATLAB version 23.2.0 (The MathWorks Inc., 2022).

Results

First-level analyses

First, we calculated descriptive statistics for both measures of episodic memory. During the autobiographical interview, participants (N = 50) averaged 12.42 memory elaborations across all stories (*SD = 8.77, range = 42.25*). For the cartoon recall (N = 49), the average accuracy score was 5.51 (*SD = 2.44, range = 11*). We then correlated participant scores on both memory tasks. As expected, we found a robust link between the two measures (*rho = .49, p < .01*). This association remained significant even after controlling for verbal IQ and participant age (*rho = .31, p = .04*). Second, we asked if there were any differences between males and females on any of our variables of interest by using Mann Whitney U-tests. There were no differences, thus biological sex was not included in any further analyses.

Finally, we assessed bivariate correlations between age and whole brain FA, and age and memory (see Figure 1). As expected based on prior findings (Bauer & Fivush, 2014), we found a highly significant positive relation between age and autobiographical (*rho* = .45, $p = .001$) and cartoon (*rho* = .63, $p < .001$) recall. Prior studies have shown that FA increases across many (but not all) white matter tracts in childhood (Lebel et al., 2012; Schmithorst et al., 2002). As expected, there was a significant positive correlation between age and whole brain FA (*rho* = .35, $p = .01$). We found no significant relation between

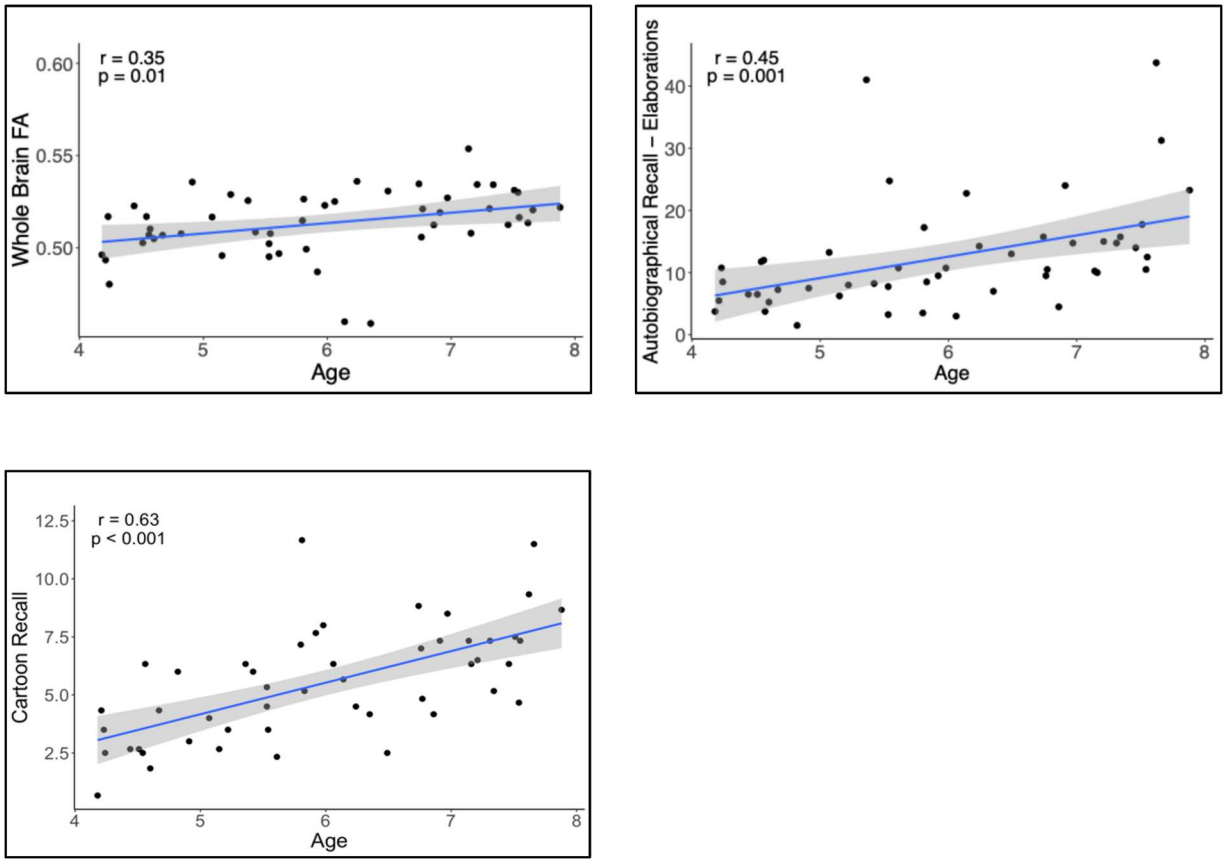

Figure 1. Correlations between chronological age and whole brain FA, autobiographical recall, and cartoon recall measures.

autobiographical memory elaborations and whole brain FA (*rho* = .18, *p* = .19).

Second-level analyses: autobiographical recall and white matter microstructure

To capture the relation between FA and autobiographical recall, we used node-wise Pearson correlations and for significant tracts, partial correlations were conducted controlling for verbal IQ and age. We conducted node-wise correlation analyses for each tract to examine the relation between memory elaborations and FA values along the length of the UF and CB. Tracts reaching or surpassing the threshold of number of significant consecutive nodes determined by the permutation test were tracts determined as significantly correlated with autobiographical memory. Following the determination of significant consecutive nodes required in our tracts of interest, we ran node-wise correlation analyses. Note that for all reported statistics, Pearson's r and *p*-values are averaged across significant nodes to provide a summary for ease of interpretation (see Figure 2 and Table 3).

Using the node-wise analysis, we failed to find a significant relation between memory and FA in the left UF (nodes 63-67: observed/required number of nodes = 5/15), right UF (0 significant nodes), and right CB (nodes 65-68: observed/required number of nodes = 4/19). However, we did find significant positive correlations between autobiographical recall and FA values in the left cingulum bundle (nodes 19–48: observed/required number of nodes = 30/19). This relation held even after controlling for verbal IQ and age (*rho* = .30, *p* = .04). Based on the framework proposed by Heilbronner and Haber (2014) and adapted by Bubb et al. (2018) significant nodes were primarily located in and around the retrosplenial cingulum, along with small portions of the parahippocampal cingulum and midcingulate.

Specificity of findings: cartoon recall and white matter microstructure

Autobiographical memory is different from many other forms of memory tested in the laboratory because one's subjective viewpoint is a key part of the recollective experience. To understand whether the findings in the cingulum bundle are particular to memory processes imbued with subjective experience, we used data from another recall task called "Maus Memory" in which participants watched a short cartoon then later recalled what they saw (see Methods section). Similarly to our autobiographical memory task, this task requires verbal free recall. Unlike our autobiographical memory task

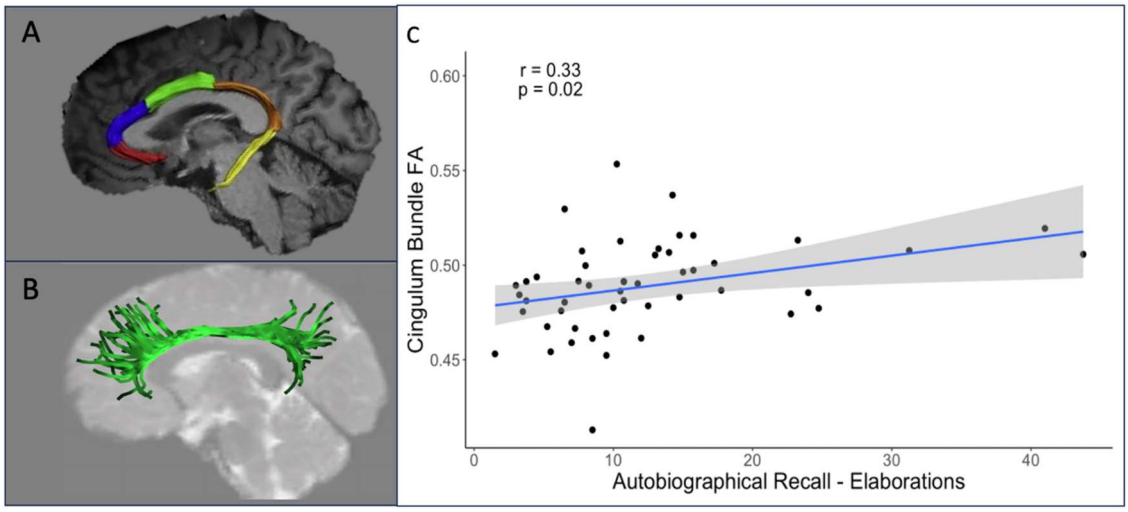

Figure 2. A. Proposed subdivisions of the cingulum bundle (Bubb et al., 2018 – Adapted from Heilbronner and Haber (2014)). B. AFQ output of an individual participant's cingulum. C. Scatterplot of left cingulum FA and autobiographical recall.

Table 3. Node-wise Pearson Correlations between fractional anisotropy and autobiographical recall and cartoons (non-autobiographical memory recall). Node ID refers to the location of the largest string of consecutive nodes. Abbreviations: UF = uncinate fasciculus; CB = cingulum bundle; SD = standard deviation.

Hemisphere	Tract	Required vs. Actual Nodes	Node ID	Avg. *rho* (SD)	Avg. *p*-value (SD)
Autobiographical memory					
Left	*UF*	15/5	63–67	0.313 (0.014)	.027 (.007)
	CB	19/30	19–48	0.359 (0.034)	.013 (.010)
Right	*UF*	14/0	~	~	~
	CB	19/4	65–68	.301 (0.013)	.034 (.007)
Cartoon memory					
Left	*UF*	15/8	32–39	0.348 (0.028)	.017 (.010)
	CB	19/10	29–38	0.320 (0.022)	.027 (.011)
Right	*UF*	14/8	30–37	0.327 (0.026)	.024 (.013)
	CB	18/6	7–12	0.342 (0.029)	.019 (.012)

however, there is an absence of subjective embeddedness in the recalled experience since the subjects are tested on their memory for passively viewed videos rather than a real-world experience that they have actively participated in.

Maus Memory recall correlated significantly with age (*rho* = .64, $p < .001$) and whole brain FA (*rho* = .28, $p = .04$). However, nodewise analysis of cartoon recall and FA in the left CB failed to reach significance (nodes 29-38: observed/required number of nodes = 10/19). In the context of nodewise analysis, failure to pass the permutation test indicates that there is no relation between a tract and behavioural data. This finding was reaffirmed after controlling for age and verbal IQ, at which point the correlation between left Cingulum FA and cartoon recall is nonexistent (*rho* < *.01*, *p* = *.96*).

Nodewise analysis of the right CB, (nodes 33-37: observed/required number of nodes = 5/19) left UF (nodes 32-39: observed/required number of nodes = 8/15) and right UF (nodes 30-37: observed/required number of nodes = 8/14) also failed to reach significance. These findings suggest a unique association between autobiographical recall and cingulum bundle microstructure, rather than episodic recall more broadly.

General discussion

The goal of this study was to determine whether variation in white matter in young children explains variance in their autobiographical memory. Our results corroborate several adult findings in the small diffusion literature on autobiographical memory in adults (Clark et al., 2022; Memel et al., 2020). We found that differences in microstructure of the cingulum bundle are correlated with autobiographical memory in children between the ages of four and seven years. This association was not found in another limbic tract previously associated with autobiographical memory, the uncinate fasciculus (Clark et al., 2022; Irish et al., 2014; LePort et al., 2012). We did not find a relation between FA in the cingulum and a non-autobiographical measure of episodic memory. Our analysis suggests a critical role for the posterior cingulum bundle in the generation of autobiographical detail during early-middle childhood.

We note that there was a great deal of variability in children's recall of autobiographical events at this age. Some children (especially the 4-year-olds) simply did not remember the events that their parents had chosen. In other cases, lower scores were due to factors more related to temperament, mood, or verbal skills. We tested several children who were shy and unwilling to speak with strangers beyond a few words. We also tested children who were tired, angry, or generally uncompliant – common risks of acquiring behavioural data in children. In other work from our laboratory, we have found that free recall is strongly intertwined with verbal skills in young children (Benear et al., 2024). On the other hand, some of our children were exceptionally verbose, adding rich detail to their memories. We chose to retain all children in the sample because this is how children's memory works "in the wild".

The cingulum bundle and uncinate fasciculus: anatomy and functionality

The cingulum bundle (CB) is a complex white matter structure that connects frontal, parietal, and medial-temporal lobes (Bubb et al., 2018). Primarily lying within the cingulate gyrus, the cingulum extends from the orbitofrontal cortex to the temporal lobe, curving along the dorsal surface of the corpus callosum and into the hippocampus/parahippocampal gyrus forming a ring-shaped tract (Bubb et al., 2018; Schmahmann et al., 2007). The CB does not have a unitary function and there are many u-shaped fibres that enter and exit it. As a result, its anatomical properties change as it traverses the dorsal/ventral and anterior/posterior axes (Bubb et al., 2018). It is believed that the cingulum experiences a prolonged period of maturation during development, with peaks in FA seen well into adulthood (Lebel et al., 2012).

The multifaceted nature of the tract makes it difficult to identify a specific function. Bubb et al. (2018) predicted that anterior portions of the CB may relate more closely to attention and executive function, whereas the posterior CB may play an essential role in learning and memory. The small literature on this tract has primarily focused on memory functions. For instance, in rodent research, lesions to this tract can cause deficits in spatial memory, particularly tasks involving allocentric cues (reviewed in Bubb et al., 2018). In humans, CB microstructure has been linked with free and cued recall in healthy older adults (Ezzati et al., 2016) and the CB is known to be affected in disorders of memory such as mild cognitive impairment (Choo et al., 2010; Fellgiebel et al., 2005; Nir et al., 2013) and Alzheimer's Dementia (Choo et al., 2010; Lin et al., 2014; Nir et al., 2013).

The nodes in the CB that significantly related to autobiographical memory were located in and around the retrosplenial cortex (RSC) and the medial parietal lobe. Both rodent (Vann et al., 2009) and human (Epstein, 2008; Rolls et al., 2023) studies strongly indicate that the retrosplenial cortex plays an important role in spatial navigation. Epstein (2008) suggests that the RSC enables the transfer of information between allocentric and egocentric representations of space. This specialised function may be linked to scene construction, the process of creating and maintaining a complex scene in the mind's eye. Scene construction is utilised in planning a route, thinking about the future, and autobiographical recall. Portions of the neighbouring parietal lobe play an essential role in spatial representations (Olson & Berryhill, 2009; Van Asselen et al., 2006) used to guide movements in personal space (Graziano & Cooke, 2006). Portions of the parietal lobe also play a role in memory vividness and subjective confidence related to episodic memory (Hower et al., 2014). Perhaps most compelling is evidence that bilateral parietal lobe damage leads to deficits in the ability to recall details of one's own autobiographical memories (Berryhill et al., 2007; Olson & Berryhill, 2009; Simons et al., 2008). Taken together, these prior results may indicate that the portions of the CB that we found are highly correlated with autobiographical memory are those that helped children remember the spatial features of their life experiences.

We did not find any significant effects in the UF. Markowitsch (1982) proposed that the UF plays a key role in autobiographical memory based on studies of rare patients who suffered from retrograde amnesia following gross damage to the frontal and temporal lobes. However, broader empirical support for this notion is sparse. Numerous findings point towards the UF's role in semantic memory and social-emotional memory such as recalling individuals and their social relevance (Thomas et al., 2012; Von Der Heide, Skipper, Klobusicky, et al., 2013). However, extending these findings to young children is a challenge due to the fact that the UF's main window of development is between puberty and adulthood (Lebel et al., 2008). It is possible that we did not observe a relation between autobiographical memory and UF microstructure because the UF has not fully developed in children in the age range we studied.

The cingulum bundle and the default mode network

The cingulum bundle is believed to be the white matter backbone of the default mode network (Van Den Heuvel et al., 2008). It has been hypothesised that the DMN is involved in processes that are uncoordinated with task demands such as mind wandering and remembering one's past (Buckner, 2013). For instance, Spreng and Grady (2010) found that activity in the medial prefrontal cortex correlated with activity in other regions of the DMN during autobiographical remembering, prospection, and theory-of-mind reasoning. This suggests that the DMN supports shared aspects of these processes such as those related to remembering internalised experiences (Spreng & Grady, 2010). Other researchers have linked the DMN to a sense of self, a non-mnemonic, social psychological

construct (Kelley et al., 2002). It has also been linked to states of reflective self-awareness (Herbet et al., 2014). All these functions can be related to autobiographical recall which inherently draws upon a wide range of processes ranging from theory of mind to self-awareness.

The small lesion literature definitively demonstrates that the DMN is essential to autobiographical memory. Damage to the medial frontal and medial temporal lobes may contribute to diminished autobiographical recall (Steinvorth et al., 2005; Buchanan, Tranel, & Adolphs, 2005; Grilli, Wank, & Verfaellie, 2018). Interestingly, those with medial parietal lobe deficits, the region most close to the portion of the CB where we found significant results, had the most severe deficits, across both episodic and semantic domains of AM (Philippi et al., 2015). Although white matter damage was not described in Philippi et al. (2015), given the size of the lesions and the phenomenon of Wallerian degeneration (in which the distal part of an axon degenerates following injury to regions nearer the cell body; Coleman & Freeman, 2010), white matter damage most likely accompanies the lesions they examined. The development of the DMN is thus likely playing a role in the association between the CB and autobiographical memory in childhood.

Comparison to diffusion imaging findings in adult populations

The literature relating autobiographical memory with neural white matter is small. LePort et al. (2012) found increased FA within the uncinate among individuals with Highly Superior Autobiographical Memory, a condition in which individuals can spontaneously recall a wide array of autobiographical information without cues or mnemonics. These findings, while fascinating, are difficult to directly compare with our own, given the age range and atypical nature of its participants.

It is also hard to compare the results from our developmental sample with a 2014 study examining the effects of different forms of dementia on the retrieval of both recent and remote autobiographical memories (Irish et al., 2014). Compared to controls, individuals with both frontotemporal dementia and Alzheimer's dementia showed reduced FA in both the CB and UF, while FA of semantic dementia patients was only diminished in the UF. Additionally, they found that CB microstructure correlated strongly with both recent (within one year) and remote (1-50 years old) memories, whereas the UF solely related to remote memories. Beyond the age range and clinical diagnoses, there are several important differences between this study and our own: all the memories used for our study were relatively recent (within 6 months). Given our age range (four to seven years), many of our participants would not be able to recall autobiographical events beyond this time frame (Bauer & Fivush, 2014). Also of note is that Irish and colleagues utilised the autobiographical interview designed by Levine and colleagues (2002). This task compares use of internal (episodic) and external (non-episodic) details in descriptions of autobiographical events. We used a different interview style and coding scheme (Cleveland & Reese, 2005; Jack et al., 2009), selected due to its frequent use in developmental samples. Other studies using variants of the Levine coding scheme in young adults or older adults have reported that fornix and inferior longitudinal fasciculus microstructure (Hodgetts et al., 2017), or fornix, CB, and UF microstructure (Memel et al., 2020) relate to autobiographical memory.

Most recently, a study by Clark et al. (2022) looked at the association between autobiographical memory and limbic white matter integrity, with conduction velocity as their primary metric of interest. The parahippocampal (ventral) cingulum correlated with autobiographical recall whether measured via conduction velocity or FA. Interestingly, the dorsal cingulum, along with the uncinate and fornix, did not show any relation to memory retrieval. Due to our inability to analyze the parahippocampal cingulum using AFQ, it is challenging to reconcile some of these results with our own. In contrast to these findings, we were able to identify a link between microstructure of the dorsal cingulum and autobiographical recall. However, their ability to relate autobiographical memory with several measures of cingulum microstructure is generally promising.

Conclusions

The studies by Memel et al. (2020) and Clark et al. (2022) both suggest a role for the CB in autobiographical memory. Our study is unique in that we extend the previous work to a developmental population. Based on Bubb and colleagues' (2018) model of subdivisions, our significant nodes are primarily located within the retrosplenial CB. As mentioned previously, this implicates cortical areas such as the medial parietal lobe and retrosplenial cortex in this process of autobiographical retrieval. Both areas have been linked to important facets of autobiographical memory, such as scene construction, episodic recall, and memory vividness. The role of scene construction is particularly interesting when combined with the results of Memel et al. (2020), in which the cingulum was linked with spatiotemporal details during recollection of autobiographical events. Taken together, these findings suggest a critical role for this subsection of the CB in autobiographical memory across the lifespan.

This is also supported by Bubb, Metzler-Baddeley, and Aggleton's review on the CB, in which they suggest an important function for the tract in scene construction involving spatial memory tasks when using allocentric cues. Inability to transfer spatial information between allocentric and egocentric perspectives after cingulum lesions may also be related to that tract's role within the default mode network. As discussed earlier, the DMN is strongly implicated in abstract thought, including perspective-

taking (via theory of mind), self-referential thinking, and reminiscing about past events. These functions of the DMN may support the development of autonoetic consciousness, an essential component of autobiographical memory according to Tulving. This may be particularly critical during early-middle childhood, when individuals are still developing theory of mind, and consequently the ability to switch between different points of view. In sum, our findings suggest that the cingulum bundle may have an important role in changing perspectives while maintaining a sense of self during scene construction. The development of these distinct but connected abilities are instrumental in the maintenance and retrieval of autobiographical memories.

Furthermore, the lack of relation between UF microstructure and memory elaborations adds to the somewhat mixed literature regarding the role of the UF in autobiographical recall. Leport (2012), Irish (2014), and Memel (2020) all found some relation between the UF and autobiographical memory. Leport and Irish's work, in particular, hints at a unique role in the recall of remote memories, which we were unable to assess due to the inherently limited remoteness of memories in a developmental population. Once it reaches full maturity in adulthood, perhaps this tract mediates recall of specific event elements, such as information relating to individuals or semantic content, spanning a longer time period.

Limitations and future directions

There are several limitations in the behavioural data used for this analysis. First, we have yet to explore the role of parental engagement in the Autobiographical Interview. Maternal reminiscing style is known to influence autobiographical memory development in early-middle childhood (Haden, 1998; Cleveland & Reese, 2005; Fivush, 2011; Wu & Jobson, 2019). Follow-up analyses may explore the link between parental engagement and number of autobiographical details recalled across all four stories, as well as in stories recounted to the experimenter.

Second, we failed to account for memory age during data collection. For some of the events chosen by parents, an approximate date was used in lieu of the exact date, due to uncertainty on the part of the parents. Furthermore, we did not consider the distribution of elected memories across the time range. As a result, a majority of the events discussed in this dataset took place within one or two months of their visit to Temple. While we found no relation between memory age and number of elaborations in the current study, future studies should aim to collect four events occurring at distinct time points, with more precision regarding the specific date of each event.

There are also limitations in our neuroimaging data. First, our interpretation of findings is speculative because very little is known about the functionality of the cingulum bundle during early-middle childhood (Bubb et al., 2018). Our interpretation is based largely on studies focused on the DMN and a small number of adult studies. Second, we were not able to examine the fornix and parahippocampal cingulum in this study, because it is not included in the AFQ default library. The fornix has been closely associated with long term memory for decades due to a robust literature from non-human animals and a small number of compelling human lesion studies that link the fornix to spatial memory and more traditional forms of episodic memory such as object-location memory (Gaffan, 1994), delayed recall (Calabrese et al., 1995), and some types of conditioning (Benear et al., 2020). Additionally, work from our group has shown that the fornix is associated with performance across a wide range of episodic and semantic memory tasks in children (Hoffman et al., 2022). However, this prior work did not assess autobiographical memory. Whether the fornix plays an any role in autobiographical memory is unknown. Although rare individuals who have fornix damage do not have retrograde amnesia (Benear et al., 2020), two diffusion imaging studies have reported that microstructural variation in the fornix accounts for some variance in autobiographical memories in adults (Hodgetts et al., 2017 and Memel et al., 2020). Future researchers may wish to use probabilistic tractography with appropriate software to examine the role of this tract in children's autobiographical memory.

Summary

There is very little research on the white matter correlates of autobiographical memory, and even less among individuals in early childhood. We believe that this project provides novel findings regarding the link between white matter microstructure and autobiographical memory during this underexplored stage of life. By early childhood, the dorsal cingulum shows a strong association with autobiographical memory, regardless of age and verbal intelligence.

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Data availability statement

Diffusion imaging and autobiographical memory data has been made available via Open Science Framework (https://osf.io/9DV5Q/).

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