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Drawing promotes memory retention in a patient with sleep-related anterograde amnesia

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Abstract
Drawing is a powerful tool to enhance memory in healthy participants and patients with probable dementia. Here, we investigated whether the drawing effect could extend to patient CT, a young woman with severe anterograde amnesia. Following surgery for a midline tumor involving her septum pellucidium and extending down into her fornices bilaterally, CT experienced a severe case of sleep-related amnesia. She can remember information encountered throughout the day, but when waking up in the morning or following a nap she forgets information learned prior to sleep. Here, we tested CT and 21 age-matched controls in a 3-day within-subjects design, during which participants encoded words by either drawing or writing them down. Memory for encoded words was tested in two conditions that each followed a 12-h delay, once after a night of sleep, and once after 12 h of wake. Despite her severe memory impairment, CT showed a drawing effect that was comparable to controls in both sleep and wake conditions. Whereas CT's memory for written words was consistently impaired relative to controls, her memory for drawn words was at the lower control range following a waking delay and above chance following a sleep delay. We suggest that amnesic patients may benefit from the drawing effect due to the recruitment of brain regions outside of the hippocampal system for encoding and consolidation. Furthermore, in control participants, sleep benefited memory for written words, but not for drawn words, suggesting that sleep preferentially consolidates memories that are more dependent on the hippocampal system.

Keywords Sleep · Drawing · Drawing effect · Memory · Amnesia · Fornix

Introduction

Drawing is a powerful tool to enhance memory. It has been shown to be more effective than other mnemonic techniques, including semantic elaboration, visualization, writing, and tracing information (Fernandes et al., 2018). A variety of studies have demonstrated that drawing improves recall and recognition memory in both younger adults (Meade et al., 2019; Wammes et al., 2016, 2018a) and older adults (Meade et al., 2018). The process of drawing a word necessitates elaborating on the meaning of the word, performing the motor action of drawing, and looking at the completed picture. Thus, it is thought that the integration of semantically elaborated, motoric, and visual traces can explain why drawing benefits memory (Fernandes et al., 2018). In one study, drawing was associated with better source memory, suggesting that drawing facilitates memory encoding by creating a stronger connection between the encoded word and the encoding context, leading to benefits in later retrieval (Wammes et al., 2018a).

In addition to its ability to enhance memory in healthy populations, drawing has also been shown to be effective as a mnemonic device in those with memory disorders resulting from dementia. In one study, 28 patients with probable dementia living in a long-term care facility were asked to either draw or write 60 words (Meade et al., 2020). Both recall (Experiments 1 and 2) and recognition performance (Experiment 2) were higher for words that were drawn compared to those that were written. The mechanism for this drawing benefit may be the fact that drawing recruits visual areas of the brain that are relatively preserved in earlier stages of dementia. Specifically, drawing has been

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found to evoke activity in primary visual processing regions, lateral occipital cortex, parietal sites, and precentral gyrus (Fan et al., 2020), as well as the cerebellum, somatosensory regions, motor regions, frontal regions, and the dorsal visual stream (Gowen & Miall, 2007; Griffith & Bingman, 2020; Planton et al., 2017; Schaer et al., 2012). Furthermore, recent findings suggest that memory for drawn relative to written information involves reactivation of visual imagery and motor planning regions including the cuneus, premotor, and supplementary motor areas (Roberts et al., 2024). Individuals with dementia show relatively preserved activity in posterior regions including the occipital lobe during a visual memory task, despite reduced activity in medial temporal regions (Golby et al., 2005). This observed pattern of intact brain activity alongside their superior memory for pictures relative to words (Ally et al., 2009) suggests preserved perceptual fluency in individuals with dementia (Ally, 2012; Embree et al., 2012). As such, drawing is arguably a highly effective encoding technique for those with memory impairments who have relatively preserved functioning in brain regions responsible for visual perceptual processing.

In the present study, we sought to determine whether the benefits of drawing on memory could be extended to another patient group: those with severe anterograde amnesia. We had the opportunity to work with CT – a kind, bright, and friendly young woman with a unique case of amnesia. In March 2020, at 16 years old, CT underwent surgery to remove a brain tumor that was directly above both fornices and appeared to invade the right fornix. CT emerged from the surgery with severe anterograde amnesia, with her last stable episodic memory reported as the moment that the anesthesia mask was fitted to her face. Remarkably, CT's family reported that she could remember things throughout the day, but when she woke up in the morning or following a nap she would still expect to be in the hospital, forgetting all the information that she had learned prior to sleep. In a previous study, we found that CT was not able to recall any details about a TV episode that she watched prior to a nap; in fact, she indicated that she had never heard of the TV show in the first place. In contrast, following an equivalent period of wake, she remembered much of the episode, recalling critical details about the plot and the characters from the show (Matorina et al., 2023). However, CT performed worse than all controls even after 100 min of being awake, suggesting that although sleep disproportionately impairs CT's memory, her memory is not fully intact over periods of wake. As further evidence of her severe sleep-related memory deficit, CT could not recall a single autobiographical episodic memory from the time period after her surgery if that memory was separated by a period of sleep. MRI scans in CT revealed that the impact to CT's brain was limited to the right fornix and midsection of the corpus callosum, with hippocampal volumes intact (Matorina et al., 2023). Given that drawing recruits posterior brain regions involved in visual perceptual processing that are preserved in CT, we predicted that CT would benefit from drawing as an encoding strategy relative to writing.

We were further interested in whether drawing could help CT retain memories over both a night of sleep and extended waking delay. We tested CT and age-matched control participants on memory for words that had either been drawn or written. The task took place over 3 days and included both a 12-h delay that involved sleep and a 12-h delay during which participants stayed awake. Memory was tested using a remember/know/new (RKN) design to capture differences in remembering contextual information ("Remember") and a recognition-based signal without context ("Know") between CT and controls. We used this design because in our past work with CT (Matorina et al., 2023) we observed that sometimes she had the familiar sense that an event had previously occurred without being able to recollect any details from the event. We predicted that drawing could help CT retain memory over a 12-h waking delay. We also predicted that memory performance would be worse in CT relative to controls following a period of sleep, but that drawing would preserve some memory function in CT following sleep.

Methods

Participants

Patient CT

CT's case is described extensively in Matorina et al. (2023). In brief, CT initially presented at 16 years old with a 3-year history of persistent headaches. In March 2020, she started to experience nausea and was admitted to the hospital. MRI scanning at the hospital revealed a midline lesion in the septum pellucidum that involved the fornices. CT was taken for surgery, where a trans-callosal sub-total excision was carried out using neuro-navigation. The surgical team reported that they achieved 70% debulking of the tumor and elected to not go any further due to concerns regarding impact on memory. Immediately post-operatively, CT displayed significant anterograde memory deficits.

CT's family contacted the research team in 2021 when she was 17 years old, about 1 year after her surgery. Her family indicated that she could successfully complete her school assignments if she worked on them all in one session with no periods of sleep in between. However, if she took a nap or slept at night, she would forget the assignment and any progress she had made up until that point. CT would wake up in the morning or following a nap expecting to be in the hospital directly after surgery. However, she was able to remember things throughout the day if she did not

sleep. Over time, around June 2022, we learned that CT's expectation to be in the hospital upon waking up gradually went away, although she did not appear to have any new long-term memories.

In a previous study, we tested CT on a standardized neuropsychological battery, conducted an autobiographical interview (Levine et al., 2002), and collected T1- and diffusion-weighted MRI scans (Matorina et al., 2023). On the neuropsychological assessments, she performed well on tests of visual attention and task switching, on an assessment of visual scanning, perceptual speed, and motor memory, and on an assessment of recent memory. However, she performed poorly on a verbal learning and memory task and on delayed recall in a visuospatial memory task (see Online Supplementary Materials (OSM)). Her results on the autobiographical interview indicated that CT has anterograde amnesia with no retrograde amnesia. Fornix tractography with fixel-based analysis metrics (Dhollander et al., 2021) revealed impact to the right fornix, beginning from the column and extending through the body and crus. We also observed evidence of the trans-callosal surgical approach's impact on the mid-anterior corpus callosum. Finally, volumetric analyses revealed that her hippocampus was intact.

On our demographics questionnaire, CT indicated that her first language is English and that she speaks both English and French. She is right-handed, wears glasses, and is not color-blind. She has a family history of Alzheimer's disease or other related dementias (onset at age 85 years). CT scored 3 on the Pittsburgh Sleep Quality Index (PSQI; scores below 5 are considered to be "good" sleepers; Buysse et al., 1989). She scored 57 on the Morningness-Eveningness Questionaire (MEQ; Horne & Östberg, 1976, intermediate morningness-eveningness type). Her family assisted with filling out the PSQI and MEQ questionnaires because the questions related to frequency of events in the last month.

Controls

Previous studies have typically recruited groups of around ten control participants for single-case studies (King et al., 2004; Vallat-Azouvi et al., 2009). In order to balance our sleep-first and wake-first counterbalancing order (described below), we aimed to recruit approximately ten control participants per counterbalancing order. We anticipated a high attrition rate due to the number of sessions per participant (four sessions in 3 days). For this reason, we over-recruited and anticipated around 20 participants in the final sample. A total of 36 age-matched control participants were recruited through the University of Toronto (via department listservs, research communities, and social media).

Participants were included if they met the following criteria to ensure regular sleep patterns: (1) no history of sleep disorders, (2) an MEQ score between 31 and 69 to exclude extreme chronotypes (Horne & Östberg, 1976), and (3) drinking three or fewer servings of caffeine per day. Fifteen participants were excluded for the following reasons: not completing all four phases of the experiment ($n = 8$), following instructions incorrectly ($n = 3$), needing a translator for presented words ($n = 1$), experimenter error with assignment ($n = 1$), and memory performance indicating either extremely poor memory or a misunderstanding of the task instructions ($n = 2$). We decided to exclude these two obvious outliers because they made fewer than two "Remember" responses to old items during the test phase. Given memory performance of healthy young participants in past work (e.g., Wammes et al., 2018a), we did not expect healthy participants to forget almost all of the words they had written and drawn from only 12 h prior. We think that the participants either misunderstood the Remember/Know/New instructions or that their memory performance was highly abnormal. Our final sample size consisted of 21 participants.

Control participants reported their gender identity as male ($n = 7$), female ($n = 12$), and non-binary or genderfluid ($n = 1$) with a mean age of 18.75 years ($SD = 1.02$ years). Participants were all right-handed and reported their race as East/Southeast Asian ($n = 9$), South Asian ($n = 6$), White ($n = 4$), Middle Eastern ($n = 3$), and Central Asian ($n = 1$), with the ability to select multiple race categories. One participant did not complete the demographics questionnaire.

All participants gave written informed consent, which was approved by the University of Toronto Ethics Board. Participants were compensated either with $10–$15/h (depending on where they were recruited) or with course credit.

Materials

One hundred and twenty words were selected from the verbal labels for Snodgrass images (Snodgrass & Vanderwart, 1980) to ensure that all words could be drawn. Words ranged in frequency from 2.89 to 5.41 ($M = 3.99$, $SD = .57$) using the wordfreq Python library (Speer et al., 2018), in length from three to 12 letters, ($M = 5.71$, $SD = 1.98$), and in number of syllables from one to four ($M = 1.76$, $SD = .86$). All words were common nouns of objects from everyday life (e.g., table, apple, bird). There were two different stimulus assignment lists to ensure that the same words were not always in the sleep or wake condition. Out of the larger list of words, 15 were assigned to each condition (e.g., drawn words for sleep encoding in assignment 1, written words for wake encoding in assignment 2). Thirty words (15 drawn, 15 written) were encoded in each of the sleep and wake conditions. Thirty new words were used as lures in the test phase for each condition. Both targets and lures were drawn from the larger list of words that were all common nouns of objects from everyday life. Full word lists are provided in the OSM.

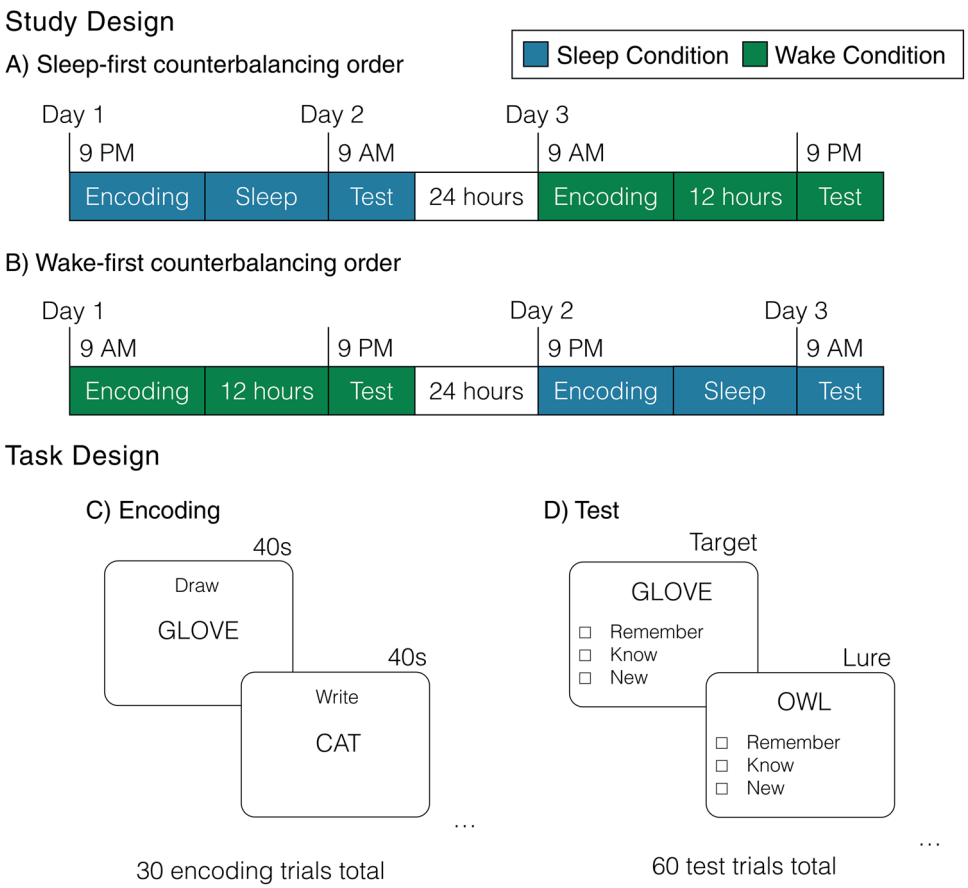

Fig. 1 Study and task design. Participants were randomly assigned to one of two counterbalancing orders, either (**A**) sleep-first or (**B**) wake-first, which involved four phases (two encoding, two test) distributed over 3 days. CT was assigned to the sleep-first order. (**C**) During each of the two encoding phases the encoding manipulation (draw vs. write) was randomly intermixed across 30 trials (15 drawn, 15 written). (**D**) Following a period of either sleep or wake, participants were tested on 60 words (30 previously encoded, 30 new) using a Remember/Know/New procedure

Participants also completed the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1995). In this questionnaire, participants answered 16 questions on a 5-point scale about how vividly they can imagine familiar people, places, and scenes. Items are scored between 1 (most vivid) and 5 (least vivid) leading to scores between 16 and 80.

Procedure

All participants completed four phases (two encoding, two test) over 3 days. There were two counterbalancing orders. The procedure for the sleep-first counterbalancing order (Fig. 1A) involved an encoding phase on Day 1 at 9 p.m., a test phase on Day 2 at 9 a.m., an encoding phase on Day 3 at 9 a.m., and a test phase on Day 3 at 9 p.m. The procedure for the wake-first counterbalancing order (Fig. 1B) involved an encoding phase on Day 1 at 9 a.m., a test phase on Day 1 at 9 p.m., an encoding phase on Day 2 at 9 p.m., and a test phase on Day 3 at 9 a.m. CT was assigned to the sleep-first order. We chose to randomize control participants to complete either the sleep-first or the wake-first order because controls would remember the first session and were likely to perform better on the second session. If all controls completed the sleep session first, they might all perform better on the wake condition, confounding the effect of sleep. Ten control participants completed the sleep condition first and 11 completed the wake condition first. CT completed all sessions at home. Control participants completed the sessions at the University of Toronto St. George campus. In the sleep condition, control participants were asked to estimate how many hours they slept the night before the beginning of the test phase. Control participants self-reported that they slept a mean of 5 h and 40 min (*median* = 6 h, *SD* = 104 min) before the sleep condition test. CT's family reported that she had a usual night of sleep, which was approximately 9 h.

The task was displayed on a lab computer using the Gorilla Experiment Builder (Anwyl-Irvine et al., 2020). Encoding procedures followed those described in Meade at al. (2020). All instructions were presented on-screen in English and participants were given the opportunity to ask

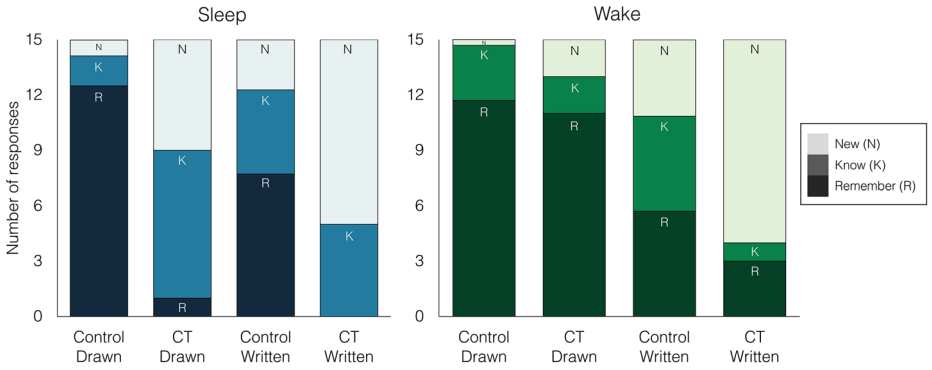

Fig. 2 Remember, know, and new responses for CT and controls. The number of each response type is shown for drawn and written words in both sleep and wake conditions. Darker colors at the bottom of each bar indicate "Remember" (R) responses, lighter colors in the middle indicate "Know" (K) responses, and the lightest colors at the top indicate "New" (N) responses. Comparing CT's performance across conditions, she responded "Know" to more drawn items than written items following a 12-h delay that included sleep and responded "Remember" to more drawn items than written items following a 12-h waking delay. Critically, CT responded "Remember" to one drawn word after a period of sleep, suggesting evidence of memory recollection. This is the first empirical evidence of CT recalling a rich memory after a period of sleep. CT did not respond "Remember" to any written words after a period of sleep

any questions. During encoding, 30 words were presented in a randomized order for each participant with encoding trial types (drawing and writing) randomly intermixed (Fig. 1C). Participants were told that they would see words on-screen one at a time. On each trial, a word was presented in the center of the screen for 40 s with the encoding condition (draw or write) at the top of the screen. Depending on the prompt at the top of the screen, they were asked to either write the word repeatedly on a sheet of paper or draw a picture of what the word represented. They were instructed either to continue writing the word or continue adding detail in the drawing until time was up. To account for memory deficits in CT and the fact that the draw versus write instructions changed from trial to trial, we included the following instructions at the top of the screen: "Please draw or write the bold word according to the prompt". At the end of the 40 s, participants heard a 500-ms tone that prompted them to stop the task and flip over the sheet of paper. They also saw written reminders to do this on screen.

At test, participants were shown 60 words individually and asked to respond "Remember", "Know", or "New" to each word. Half of the words were the words they had seen at encoding; half of the words were new lures. They were asked to respond "Remember" if the word on-screen reminded them of something specific that happened when they were first writing or drawing. This could have been something that happened in the room, or something they were thinking at the time, or any mental images that they formed. They were asked to respond "Know" if they were certain that they recognized a word from the first part of the experiment, but they did not remember anything specific about drawing or writing it. They were asked to respond "New" if they did not remember seeing the word before. Each trial only progressed once the participant made a selection. The experimenter was positioned next to the participant and was available to provide clarifications throughout the experiment. Anecdotally, part-way through one of the test sessions and prior to making a "Remember" response, CT correctly stated the instructions for "Remember" responses and asked if this definition was correct. We are confident that CT understood and retained the instructions throughout. We chose a Remember/Know/New rather than a Remember/Know/Guess or a Remember/Know/Guess/New design because the majority of prior work on drawing had been conducted using the Remember/Know/New procedure (Meade et al., 2018; Wammes et al., 2018a) and we reasoned it would help us compare our results to prior work more easily.

Results

Descriptive analyses: CT demonstrated sleep-related memory loss and drawing benefit in terms of "Remember" and "Know" responses

Remember, know, and new responses for CT and controls are displayed in Fig. 2 and raw scores are given in the OSM. Descriptively, our results support our previous findings that CT displays sleep-related memory loss, such that CT responded "Remember" to many more words in the wake, compared to sleep, condition. Considering differences between drawing and writing, CT responded "Remember" to more drawn items than written items in the wake condition, suggesting that drawing may be preserving memory even across intervals of sleep. Anecdotally, CT has been aware of the distinction between "Remember" and "Know"

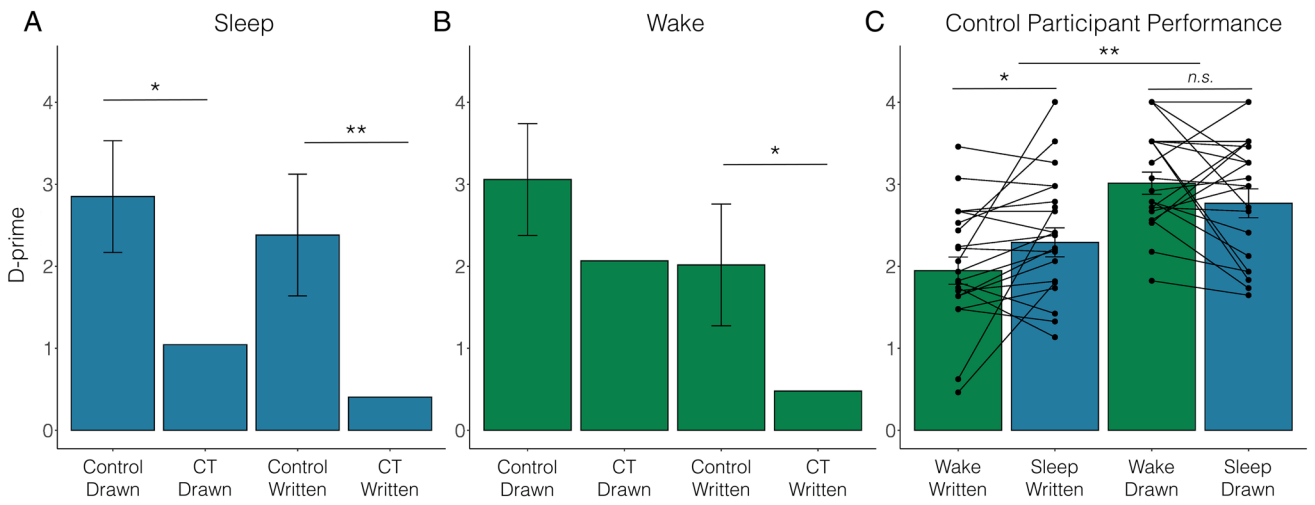

Fig. 3 D-prime for CT and controls. To calculate d-prime, hits were scored as either "Remember" or "Know" responses to old items; misses were scored as "New" responses to old items. (**A**) In the sleep condition, CT's memory was worse than controls for both drawn and written words. (**B**) In the wake condition, CT's memory was worse than controls for written words. (**C**) Control participants had significantly better memory for written words in the sleep compared to wake conditions, with no differences for drawn words. In panels **A** and **B**, brackets depict comparisons between CT and controls on the same encoding condition. In panel **C**, brackets depict comparisons between written and drawn words in each delay condition for control participants (within-subject comparisons connected by lines). Error bars in panels **A** and **B** represent standard deviations. Error bars in panel C represent standard error of the mean,* $p < .05$, ** $p < .01$, *n.s.* = not significant

across all of the tests we have held with her and usually has a conservative threshold for responding "Remember". Critically, in the sleep condition CT responded "Remember" to one drawn word, suggesting evidence of memory recollection. This is the first empirical evidence of CT recalling a rich, explicit memory after a period of sleep. Anecdotally, CT also seemed to display vivid memory for certain drawn items in the wake condition (e.g., laughing at a word that reminded her of a drawing she had made).

Statistical analysis overview

We first compared CT's overall memory on written and drawn items to age-matched controls. We then compared difference scores between drawing and writing in CT and controls to determine whether the magnitude of the drawing effect was different for CT and controls in each condition. We then conducted a trial-by-trial analysis to determine whether CT showed evidence of memory in the various conditions. The d-prime scores were composed of combined "Remember" and "Know" responses to assess overall memory performance. To calculate d-prime, hits were scored as either "Remember" or "Know" responses to old items and misses were scored as "New" responses to old items. Finally, although memory performance for control participants across sleep and wake conditions was not our primary interest in this study, we then conducted analyses on memory performance for control participants across sleep and wake conditions to inform future hypotheses on the role of sleep in consolidating drawn and written information. All analyses were conducted in RStudio version 1.3 (Team, 2020).

CT's d-prime scores were in the lower range of controls for drawn words following a 12-h waking delay, but significantly below controls in other conditions

D-prime scores for CT and controls are given in Fig. 3. To compare CT and controls, we conducted a series of Crawford's modified t-tests, which takes one observation and compares it to a control sample, using the singcar package (Rittmo & McIntosh, 2021). We report t-values and p-values from Crawford's modified t-tests, as well as the point estimate and 95% confidence intervals (CIs) of the effect size for the difference between CT and controls (Z_{CC}), and the point estimate and 95% CIs for estimated percentage of the control population that would obtain a lower score than CT (Crawford et al., 2010). Results are provided in Table 1. In the sleep condition, CT's d-prime score for drawn words was below that of controls, $t(20) = -2.36$, $p = .01$, $Z_{CC} = -2.42$. Her d-prime score for written words was also below that of controls, $t(20) = -2.65$, $p = .008$, $Z_{CC} = -2.71$. In the wake condition, CT's d-prime score for drawn words was not below that of controls, $t(20) = -1.59$, $p = .06$, $Z_{CC} = -1.63$. However, her d-prime score for written words was below that of controls, $t(20) = -2.07$, $p = .03$, $Z_{CC} = -2.12$. These results indicate that in the sleep condition, CT performed worse than controls for both drawn and written items. In the

Table 1 Results for Crawford's modified t-tests

Delay condition	Encoding condition	T-value	Degrees of freedom	P-value	Z_{CC}	Estimated percentage of controls below CT
Sleep	**Draw**	-2.36	20	**.01**	-2.42, 95% CI [-3.27, -1.55]	1.42%, 95% CI [0.05, 6.03]
Sleep	**Write**	-2.65	20	**.008**	-2.71, 95% CI [-3.64, -1.76]	0.77%, 95% CI [0.01, 3.89]
Wake	Draw	-1.59	20	.06	-1.63, 95% CI [-2.28, -0.96]	6.39%, 95% CI [1.14, 16.88]
Wake	**Write**	-2.07	20	**.03**	-2.12, 95% CI [-2.90, -1.33]	2.56%, 95% CI [0.19, 9.12]

Significant differences are indicated in bold. Z_{CC} = the point estimate and 95% confidence intervals of the effect size for the difference between CT and controls

wake condition, CT performed worse than controls for written items but was in the lower range of controls for drawn items.

Drawing effect comparable for CT and controls

We next conducted two additional Crawford's modified t-tests on the difference scores between drawing and writing for each condition to determine whether the magnitude of the drawing effect is comparable for CT and controls. In the sleep condition, CT's d-prime difference score for drawn and written words was not below that of controls, $t(20) = 0.26$, $p = .60$, $Z_{CC} = 0.27$, 95% CI [-0.17, 0.70]. The estimated percentage of the control population that would show a difference score below CT was 60.17%, 95% CI [43.11, 75.85]. In the wake condition, CT's d-prime difference score for drawn and written words was also not below that of controls, $t(20) = 0.72$, $p = .76$, $Z_{CC} = 0.73$, 95% CI [0.24, 1.21]. The estimated percentage of the control population with a difference score below CT was 75.92%, 95% CI [59.60, 88.72]. These results indicate that drawing benefits memory similarly in both CT and controls.

Bias comparable for CT and controls

We also calculated *c*, an index of bias, using the psycho package (Makowski, 2018). This package calculates *c* as the number of standard deviations from the midpoint between the signal and noise distributions. Negative values of *c* signify a bias towards responding "Remember" or "Know", whereas positive values of *c* signify a bias towards responding "New" (Stanislaw & Todorov, 1999). Zero is the neutral point of no bias. *C* is measured in standard deviations, meaning that a *c* value of -0.5 indicates a criterion that is 0.5 standard deviations to the left of neutral. In the sleep condition, CT's *c* score was 0.29 for drawn words and 0.60 for written words. Average *c* scores in the sleep condition for controls were -0.04 ($SD = 0.25$) for drawn words and 0.19 ($SD = 0.45$) for written words. In the wake condition, CT's *c* score was 0.02 for drawn words and 0.82 for written words. Average *c* scores in the wake condition for controls were -0.18 ($SD = 0.27$) for drawn words and 0.34 ($SD = 0.47$) for written words. Crawford's modified t-tests revealed no differences in *c* scores between CT and controls on any condition, $ps > .76$. Overall, both CT and controls' biases were either neutral or more conservative.

CT's memory was above chance for both drawn and written words after 12-h waking delay, but only for drawn words after a 12-h sleep delay in trial-by-trial analysis

Next, to determine if CT displayed evidence of above-chance memory in the various conditions, we conducted single-sample t-tests for all of CT's trials against chance. Trials were scored as correct (given a value of 1) if she responded "Remember" or "Know" to old items or "New" to new items. Trials were scored as incorrect (given a value of 0) if she responded "New" to old items or "Remember" or "Know" to new items. New items were not subdivided into drawing and writing, so the same new items were included in drawn and written words for each condition (i.e., the same 30 new words are in Sleep Drawn and Sleep Written). Therefore, each condition had a total of 45 trials (15 old and 30 new). Chance was 0.5 because on any given trial, CT had two response options in our combined metrics – "Remember" or "Know" to indicate oldness or "New" to indicate newness. We report t-values and p-values from one-sample t-tests, as well as Cohen's *d* as a measure of effect size using the lsr package (Navarro & Navarro, 2022). Trial-by-trial accuracy scores for CT are given in Fig. 4. In the sleep condition, CT scored above chance on drawn items, $t(44) = 3.5$, $p = .001$, $d = 0.52$, but not written items, $t(44) = 2.00$, $p = .05$, $d = 0.30$. In the wake condition, CT scored above chance on both drawn items, $t(44) = 7.15$, $p < .001$, $d = 1.07$, and written items, $t(44) = 2.35$, $p = .02$, $d = 0.35$. Thus, CT showed reliable memory performance for both conditions after a 12-h waking delay, but only for drawn words after a 12-h delay including sleep.

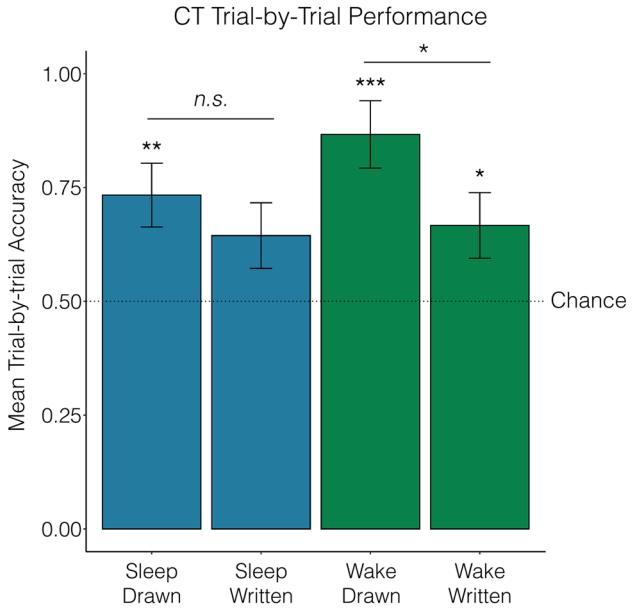

Fig. 4 CT's mean trial-by-trial accuracy. Correct responses were counted as either "Remember" or "Know" responses to old items or "New" responses to new items. Incorrect responses were counted as either "New" responses to old items or "Remember" or "Know" responses to new items. Correct trials were scored as 1 and incorrect trials were scored as 0. Asterisks depict comparisons of mean performance in each condition relative to chance performance of 0.5. In the wake condition, CT scored above chance on both drawn and written words and her accuracy for drawn words was significantly higher than written words. In the sleep condition, CT scored above chance on drawn but not written words. Error bars indicate standard error of the mean, * $p < .05$, ** $p < .01$, *** $p < .001$, *n.s.* = not significant

CT showed a drawing effect following waking delay in trial-by-trial analysis

To determine if CT performed differently on writing and drawing, we also conducted independent-samples t-tests on CT's responses for drawn and written items in sleep and wake conditions, respectively. In the sleep condition, there were no significant differences between drawn and written words, $t(88) = 0.90$, $p = .37$. However, in the wake condition, CT's accuracy for drawn words was significantly higher than written words, $t(88) = 2.28$, $p = .02$. These results indicate clear evidence for a drawing effect in CT following wake. Following sleep, she numerically showed better performance for drawn words but the benefit from drawing was likely overpowered by her sleep-related memory deficits.

VVIQ scores were comparable for CT and controls and did not predict accuracy

The mean VVIQ score for controls was 34.19 ($SD = 8.80$). CT's VVIQ score was 40. Higher VVIQ scores indicate poorer visual imagery. To compare VVIQ scores between CT and controls, we conducted a Crawford's modified t-test that revealed no differences, $t(20) = 0.63$, $p = .73$, $Z_{CC} = 0.65$, 95% CI [0.17, 1.12], indicating that CT did not have an impairment in visual imagery relative to controls. The estimated percentage of the control population with a VVIQ score below CT was 73.31%, 95% CI [56.67, 86.76]. Given that the ability to form vivid mental images might lead to enhanced memory encoding, we also conducted a regression to test whether VVIQ predicted memory performance. VVIQ did not predict d-prime, $b = -0.02$, $SE = 0.02$, $t(20) = -1.01$, $p = .32$.

CT's drawing quality was comparable to controls

We rated drawing quality in both CT and control participants using the rating scheme from Meade et al. (2020). Each drawing was rated as either (1) "Unidentifiable" indicating that the drawing does not represent what it is meant to represent or represents any other item, (2) "Low Quality" indicating that the drawing contains relevant features, but the target word could not be identified from the drawing, and (3) "High Quality", indicating that the target word could be easily determined from the drawing. Two independent raters rated all images. We calculated ICC values using the psych package (Revelle, 2020). The ICC value was .63, indicating moderate reliability (Koo & Li, 2016). Drawing quality ratings per drawing were averaged between raters. Both CT and controls had high-quality drawings ($M_{CT} = 2.97$, $SD_{CT} = 0.13$, $M_{controls} = 2.89$, $SD_{controls} = 0.34$). To compare drawing quality between CT and controls, average drawing quality scores per participant were computed. A Crawford's modified t-test revealed that CT's drawing quality was not different from that of controls, $t(20) = 0.51$, $p = .69$, $Z_{CC} = 0.52$, 95% CI [0.06, 0.97]. The estimated percentage of the control population with a drawing quality score below CT was 69.08%, 95% CI [52.20, 83.39].

Sleep preferentially consolidated written words in control participants

D-prime scores for individual controls across encoding condition (draw vs. write) and delay condition (sleep vs. wake) are visualized in Fig. 3C. To compare control participants' memory for drawn and written items across conditions, we fit a linear mixed effects model using the lme4 (Bates, 2010) and lmerTest (Kuznetsova et al., 2017) packages. A model was fitted with a random slope for delay condition (sleep vs. wake) and encoding condition (draw vs. write), as well as a random intercept for each participant. Delay condition (sleep vs. wake) and encoding condition (draw vs. write) were contrast coded (sleep = 1, wake = -1; draw = 1, write = -1). Interactions were probed with simple effects using the emmeans package (Lenth et al., 2019). We report beta estimates, standard error, degrees of freedom, t-values, and p-values. A model summary is given in Table 2.

We found a significant effect of encoding condition, b = 0.38, SE = 0.06, $t(20)$ = 5.91, $p < .001$, such that memory for drawn items was better than for written items. We also found a significant interaction between encoding condition and delay condition, b = -0.14, SE = 0.04, $t(20)$ = -3.52, p = .002. Follow-up contrasts indicated that there was a significant difference between sleep and wake conditions for written items, b = -0.37, SE = 0.16, $t(32.7)$ = -2.30, p = .03, such that memory scores for written items were better following sleep rather than wake, but there were no differences for drawn items, b = 0.21, SE = 0.16, $t(32.7)$ = 1.31, p = .20. These results indicate that for control participants, sleep preferentially consolidated written, rather than drawn, items.

Discussion

CT is a patient who developed severe anterograde amnesia following impact to the mid-anterior corpus callosum and the right fornix, beginning from the column but extending through the body and crus. Our previous results demonstrated that sleep differentially and profoundly impaired her memory (Matorina et al., 2023). In the present study, we investigated whether the drawing effect would rescue some of her memory deficits. Indeed, we show that the magnitude of the drawing effect was comparable for CT and controls, demonstrating that drawing can mitigate memory deficits even in severe anterograde amnesia. Whereas CT's memory for written words was consistently impaired relative to controls, her memory for drawn words was at the lower range of controls following a waking delay and above chance following a sleep delay. Moreover, she showed some evidence of recollection for drawn words – the first empirical observation of episodic memory recall after sleep in this patient. Overall, we demonstrate that drawing can be an effective encoding technique for patients with damage to the hippocampal system.

Drawing is thought to benefit memory through the integration of a motoric memory trace that involves manually producing the image, a pictorial memory trace from visually observing the image, and a memory trace that is elaborated based on deciding how to draw an item (Fernandes et al., 2018) – all of which leads to a rich, highly detailed memory (Wammes et al., 2018a). Critically, the integration of these different memory traces may engage memory networks outside of the hippocampal system. CT's brain damage is localized to the fornix and corpus callosum, preserving regions that have been previously associated with drawing, including the primary visual processing regions, lateral occipital cortex, parietal sites, and precentral gyrus (Fan et al., 2020), as well as the cerebellum, somatosensory regions, motor regions, frontal regions, and the dorsal visual stream (Gowen & Miall, 2007; Griffith & Bingman, 2020; Planton et al., 2017; Schaer et al., 2012). We suggest that the recruitment of these preserved brain regions through drawing at encoding strengthens memory, even in the case of an impaired hippocampal system. This is consistent with previous findings demonstrating that populations who have impaired hippocampal function, such as older adults (Meade et al., 2018) and those with probable dementia (Meade et al., 2020), benefit from drawing words at encoding. However, along with Levi et al. (2024), this work provides the first evidence that the drawing effect can be extended to amnesic patients with damage to regions in the hippocampal system.

In our previous study with CT, we showed that she exhibited sleep-related amnesia, such that her memory after long periods of wake was partially impaired but her memory after sleep was almost completely impaired (Matorina et al., 2023). We speculate that these impairments may arise due to disruption of endogenous hippocampal replay processes

Table 2 Results for linear mixed effects model testing the role of delay condition (sleep vs. wake) and encoding condition (draw vs. write) on memory performance in control participants

Predictor					
Random effects	Variance	Standard deviation			
Participant	0.24	0.49			
Delay condition	0.06	0.25			
Encoding condition	0.05	0.23			
Residual	0.14	0.37			
Fixed effects	b	Standard Error	Degrees of freedom	T-value	P-value
Encoding condition	0.38	0.06	20	5.91	**<.001**
Delay condition	0.04	0.07	20	0.58	.57
Encoding condition* Delay condition	-0.14	0.04	20	-3.52	**.002**

Significant effects are indicated in bold. b = beta estimates

that occur during sleep and are thought to underpin memory consolidation (Paller et al., 2020). We reasoned that CT may be able to encode memories in her hippocampus when she is awake, but during sleep the coordination between the hippocampus and the cortex is disrupted by damage to her fornix, making the memories no longer retrievable. Here, we see that CT's memory for drawn items is above chance after a period of sleep, suggesting that the consolidation trajectory for drawn items may be partially distinct from other episodic memories. Engaging the cortex and creating multiple memory traces that are well integrated through drawing may help to better consolidate memories and enhance subsequent retrieval, even when hippocampally-mediated recall and consolidation is disrupted.

The present work also provides evidence for the preferential consolidation of memory for written words, rather than drawn words, during sleep in control participants. Prior work has shown that human hippocampal replay prioritizes weakly encoded items during subsequent rest (Schapiro et al., 2018). One possible explanation for our results is that due to the drawing effect, written words were more weakly encoded compared to drawn words, leading to prioritized replay and consolidation during sleep. Future work could vary encoding time (e.g., 40 s to draw a word or 2 min) and then test immediate memory for various drawn items to determine whether memory strength impacts sleep-dependent consolidation. Another possible explanation is that memory for written words is more hippocampally dependent (i.e., less distributed compared to memory for drawn words) and sleep plays a preferential role in the consolidation of hippocampally dependent memories. A sleep-related dissociation between more and less hippocampally dependent memories has been found in a prior study that pharmacologically modulated sleep spindles. In this study, increased sleep spindles predicted enhanced verbal memory but did not impact motor learning (Mednick et al., 2013). The authors suggested that the verbal task was more hippocampally dependent and thus benefited more from sleep spindles as a result of hippocampal replay. The drawing task may be partially distinct from motor memory tasks in that although it is thought to include a motoric memory trace, it may also include a pictorial memory trace and an elaborative memory trace. One study that investigated consolidation of a combined motoric and elaborative memory trace found that making gestures related to the content of a lecture improved memory for the lecture only at 2–3 days following encoding (Cherdieu et al., 2017), suggesting that delays of several days may be necessary to observe memory benefits for tasks that involve the integration of memory traces, possibly because these memories are stronger in the first place. Future work could investigate the role of sleep in memory for drawn and written words with an additional delayed memory test after several days.

Drawing may benefit memory in people with memory impairments due to the motoric memory trace, pictorial memory trace, elaborative memory trace, or a combination of all three. Previous work in people with memory impairments has shown that they are better able to retain memory for objects that involve a motoric memory trace. Specifically, patients with hippocampal amnesia (Hilverman et al., 2018), transient global amnesia (Hainselin et al., 2014), and Alzheimer's disease (De Lucia et al., 2019) all exhibited better memory when they performed a related action at encoding, a memory enhancement known as the enactment effect (Sivashankar & Fernandes, 2022). However, some work suggests that motor movements that have semantic meaning may be necessary to facilitate learning in both healthy participants (Sivashankar & Fernandes, 2022) and those with amnesia (Voss et al., 2011). For example, when comparing objects that were volitionally studied (through mouse-clicking or using a joystick) versus those that were passively viewed, patients with amnesia did not benefit from volitional study (Voss et al., 2011). Given that drawing is thought to integrate motoric memory traces with both visual and semantic traces, it is possible that the semantically meaningful motoric processing involved in drawing may contribute to memory benefits in those with amnesia.

The pictorial memory trace component of drawing may also be helpful in patients with hippocampal amnesia due to dissociations between verbal and visual memory in this population. For example, Patient FRG showed impaired recall and recognition for verbal material, but had normal performance on a number of recognition tests for visual material, possibly due to her intact perirhinal cortex (Barbeau et al., 2005). However, there are also examples of patients who show the opposite effect. For example, patient RH who had right-sided hippocampal damage performed well on tests of verbal memory but was impaired on memory for some types of visual stimuli, such as pictures of outdoor scenes (Bird et al., 2007). Patient JC, who had bilateral hippocampal damage, was impaired on both verbal and visual stimuli (Bird et al., 2007). The pictorial component of the memory trace during drawing may benefit some patients with amnesia, but not all. It is also plausible that some patients with amnesia, such as RH, may benefit preferentially from writing over drawing.

Patients with medial temporal lobe damage perform poorly on tests of semantic elaboration, which is a key mechanism by which drawing is thought to derive mnemonic benefits (Wammes et al., 2018b). When asked to elaborate on general semantic issues in their past, patients with hippocampal amnesia described issues with limited semantic detail, despite performing well on other semantic processing tasks (Race et al., 2013). Hippocampal amnesics also performed worse than controls on an assessment of the depth and richness of semantic knowledge for highly familiar words (Klooster & Duff, 2015). It remains to be

seen whether the elaboration component of drawing is challenging for patients to leverage for memory gain, or whether the scaffolding provided by drawing helps them overcome deficits in semantic elaboration. Future research can explore whether those with hippocampal system amnesia would also benefit from the elaborative component of drawing in which they are asked to imagine drawing a word, or whether impairments in semantic elaboration may reduce the memory benefits from drawing to-be-remembered items. More broadly, future research could replicate the drawing study in other patients with amnesia and investigate the role of the motoric memory trace, visual memory trace, and elaborative semantic memory trace separately to determine the specific mechanism by which memories may be preserved in this group. Understanding which component is critical to memory retention in amnesics can support the development of other encoding interventions that support more complex and detailed memories. Future studies could also investigate the neural traces of drawn compared to written items following a night of sleep to better understand how drawn items are consolidated over time.

One important point of consideration is whether the drawing benefits in CT would last beyond the relatively short 12-h delay tested in this study and apply to real-life situations. Previous research has found that drawing is more effective than writing in a diary in maintaining details for autobiographical events in both younger and older adults (Tran et al., 2023). Drawing has also been found to be more useful than reading the text or using text-focused strategies (e.g., summarizing) to learn new information (Fiorella & Zhang, 2018). In some cases, support during drawing can also be useful, such as training in how to translate a text into a drawing or feedback on drawings (Fiorella & Zhang, 2018). To be applicable as a memory intervention, future work should test whether the drawing effect in those with memory impairments extends to autobiographical memory and memory for useful information (e.g., upcoming appointments). In addition, it would be beneficial to manipulate the number of times that a stimulus is encoded to determine whether repeated exposures are necessary for enduring memory for drawn items. Testing memory at various delay intervals would also be informative to determine how long the drawing benefits may last. In addition, drawn items may function as an effective memory cue that could be displayed for a certain amount of time following initial encoding to allow for repeated study. Finally, drawing may also function as an effective cue for retrieval, for instance with prospective memory. Drawings may be quicker and more effective than writing in a diary to provide memory aids and cues, and someone with a memory impairment could browse their drawings to determine what they needed to remember to do that day.

In conclusion, we demonstrate that the drawing effect extends to those with severe anterograde amnesia. CT, a patient with mild memory impairments during periods of wake and profound memory impairments following periods of sleep, was consistently impaired relative to controls on her memory for written words. However, CT's memory for drawn words was in the lower range of controls following a waking delay and above chance following a sleep delay. The magnitude of the encoding benefit from drawing was comparable in CT and controls in both sleep and wake conditions. Drawing may be a powerful tool to develop memory interventions for those with hippocampal system damage. CT's memory for drawn items after both sleep and waking delays may be retained due to the recruitment of preserved brain regions outside of the hippocampal system that are associated with drawing, leading to more effective encoding and a distinct consolidation trajectory. Furthermore, in control participants, sleep benefited memory for written words, but not for drawn words, suggesting that sleep is involved in the preferential consolidation of memories that are more dependent on the hippocampal system.

Supplementary information The online version contains supplementary material available at https://doi.org/10.3758/s13421-024-01613-9.

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Data availability Data for this study is available on The Open Science Framework: https://osf.io/9b347/?view_only=2a515086c3894857b88dab76d0849634. The experiment was not preregistered.

Code availability Not applicable.

Declarations

Ethics approval This study was approved by the ethics board at the University of Toronto.

Consent to participate Informed consent to participate in the study was obtained from CT and all control participants included in the study.

Consent for publication Not applicable.

Conflicts of interest The authors have no relevant conflicts of interest.

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