Enhanced semantic memory in a case of highly superior autobiographical memory

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Abstract
Highly superior autobiographical memory (HSAM) is characterised by the ability to recall personal events, dates, and news events from long-term memory with profound detail and accuracy. Anecdotes from these individuals suggest that retrieval of rich autobiographical detail is automatic, and often intrusive rather than effortful. We created two novel experiments to objectively verify whether retrieval of information reflects serial or parallel processing in a case of HSAM (R.S.), who has a self-reported superior memory for two sources of personally relevant information: (a) the ability to name days of the week for any given calendar date since the year 2000; and (b) the ability to remember the entire text, practically word-for-word, of the seven Harry Potter books. RS and 10 age-matched controls, who were also aficionados of the Harry Potter series, were presented with pairs of calendar dates or sentences and asked, “Which date came earlier in the week?” or “Which sentence came earlier in the book?” Items within a pair varied in the proximity to one another in time. RS correctly identified earlier calendar dates and sentences with near perfect accuracy, and her reaction time was not impacted by the temporal distance between items. Controls were unable to identify earlier calendar dates and their accuracy and reaction time was dependent on the temporal distance of items. Structural magnetic resonance imaging (MRI) comparing RS with a normative dataset found no significant differences in any memory-related brain regions. Our findings suggest that HSAM memory retrieval for stored information largely reflects parallel processing, rather than a temporal-based system. We also discovered that RS has superior memory for semantic information, boosted by reportedly attaching autobiographical memories to these details. This unusual HSAM phenomenon may hold further clues to creating strong and lasting memories, which appear to be uniquely rich in detail.

Key Words: Highly superior autobiographical memory (HSAM); autobiographical memory; episodic memory; memory retrieval; self-referential processing.

1. Introduction

The nature of memory has been a mystery since the classic amnesia patient HM who, following bilateral medial temporal surgery for intractable epilepsy, was unable to retain new memories (Scoville & Milner, 1957). HM played a crucial role in the development and influence of the single case approach within cognitive neuropsychology. The mirror contrast of HM's classic amnesia is *highly superior autobiographical memory* (HSAM; also known as hyperthymesia), where daily events are rarely forgotten. HSAM is characterised by an extraordinary ability to remember personal experiences, sometimes over decades. This highly accurate and detailed recall is thought to be due to involuntary encoding, re-living, and recollection unaided by the emotional salience of events (Santangelo *et al.,* 2018), savant abilities or the purposeful use of mnemonic strategies (LePort *et al.,* 2017; Mazzoni *et al.,* 2019). For example, an individual with HSAM might be able to tell you the day of the week on which a specific date fell, and details of what happened on every day of their life since childhood. Despite this, HSAM individuals are not immune to false memories (Patihis *et al.,* 2013) and are not superior learners, performing at an average level on cognitive tests unrelated to autobiographical memory (LePort *et al.,* 2012, 2017; Parker *et al.,* 2006). Anecdotes of individuals with HSAM suggest that retrieval of rich autobiographical detail is automatic, and often intrusive (LePort *et al.,* 2012; Parker *et al.,* 2006; Ally *et al.,* 2013), rather than effortful (Robinson *et al.,* 1997). It has been noted that internal or external cues will often lead to the automatic retrieval of information. Indeed, this is a fundamental process of memory not specific to HSAM. What is highly unusual about HSAM is the abundance of detailed autobiographical information available to be prompted in the absence of substantial effort (LePort *et al.,* 2012).

The reason for the highly accurate, enriched and effortless retrieval seen in HSAM is thought to be a unique consolidation process. The underlying mechanism of this process remains speculative and has sparked recent theoretical discussion. One theory suggests that retrieval in HSAM is rooted in obsessively driven, habitual rehearsal of memory details associated with high rates of obsessive-compulsive behaviours shown to be statistically indistinguishable from those of the obsessive-compulsive disorder (OCD) patient population (LePort *et al.,* 2012; LePort *et al.,* 2016). Habitual rehearsal is thought to be passive, without the intention of improving memory. Some HSAM individuals reportedly rely on thinking about the events of a particular day and compare them to what occurred 1 or 5 years earlier to help them fall asleep. However, it is unlikely that HSAM ability is based on explicit rehearsal, given the amount of time and effort that would be required to recall every life event from middle childhood with such enriched detail (Foer, 2011; LePort *et al.,* 2016). Thus, consolidation of autobiographical memories in HSAM is argued to be incidental (LePort *et al.,* 2016). Despite this, the existence of HSAM individuals who do not exhibit obsessive-compulsive tendencies appears to reduce the generalisability of this theory, and indicates that HSAM is not unequivocally driven by obsessive/compulsive-related mechanisms.

Unique memory consolidation in HSAM may also be a product of enhanced self-referential processing; where information related to the self is remembered better than non-self-referential information (Betz & Skowronski, 1997; Klein, 2012; Palombo *et al.,* 2018; Symons & Johnson, 1997). Palombo and colleagues (2018) have recently speculated that normal neural mechanisms within the default mode network (Shulman *et al.,* 1997; Raichle *et* *al.,* 2001) that support self-referential processing are enhanced in HSAM. This reasoning appears logical given that individuals with HSAM display a bias toward their own personal experiences. Furthermore, proposed mechanisms of unique consolidation may not be mutually exclusive; a heightened bias toward self-referential (i.e., autobiographical) information that modulates enhanced memory in HSAM may be strengthened by the obsessive and passive rehearsal of information that appears to be common in the majority of these individuals (LePort *et al.,* 2016; Palombo *et al.,* 2018).

Neurobiological investigations have provided further insight into the mechanisms that underlie HSAM. Where previous studies have demonstrated evidence of increased volume for memory-related brain regions in HSAM (i.e., parahippocampal gyrus, amygdala, insula, intraparietal sulcus, the putamen and caudate, inferior and middle temporal gyri and temporal pole; Ally *et al.,* 2013; DeMarco *et al.,* 2021; LePort *et al.,* 2012; Mazzoni *et al.,* 2019), recent investigations indicate that HSAM can occur in the absence of major morphological brain differences (Santangelo *et al.,* 2018, 2020). Therefore, more evidence is required to understand the relationship between volumetry of the brain and HSAM. Functional magnetic resonance imaging (fMRI) in young adults with HSAM have shown greater blood oxygen level-dependent (BOLD) brain activity and connectivity in ventromedial and dorsomedial prefrontal cortices, the hippocampus and the temporo-parietal junction when retrieving personal memories, relative to controls (Santangelo *et al.,* 2018). During the access phase, HSAM individuals also show greater BOLD activation in posterior regions typically associated with memory reliving (precuneus and visual cortex, angular and supramarginal gyri, posterior cingulate cortex), where mental imagery related to the reactivation of sensory information occurs (Folkerts *et al.,* 2018; Santangelo *et al.,* 2021; Xue, 2018). The profound accuracy in recalling past experiences in HSAM may, therefore, be associated with an increased sense of reliving and self-referential processing associated with increased posterior brain activation (Raichle, 2015; Folkerts *et al.,* 2018).

As autobiographical memories are self-reported and intrinsically personal, they can be very difficult to verify. Many studies have focused on a participant's mental representation of autobiographical episodes rather than their historical occurrence in the material world, thereby making it impossible to differentiate between "true" and "false" memories (Gardner *et al.,* 2012; Johnson & Raye, 1981). This is particularly important when considering HSAM individuals are equally susceptible to memory reconstruction of emotionally salient and neutral information at the time of recall when compared with controls, and therefore possess a normal level of misremembering that is likely an ordinary part of human memory (Patihis *et al.,* 2013). Furthermore, available literature has described the structure of memory retrieval in HSAM as following a parallel (automatic) processing pattern without experimental manipulation of temporal load factors. Automatic retrieval in HSAM has been classified based on overall reaction time rather than differentiating between recall of events that are *close* versus *distant* in time. No study has measured the latter in HSAM.

Here, we devised two novel experimental memory tasks to investigate the structure of memory representations in RS, a young woman with HSAM. RS has vivid autobiographical memories that apparently arise automatically. At the same time, she describes her memories as being organised sequentially, so that to retrieve an event she mentally "scans" an ordered structure starting from the earliest memory and continuing to more recent memories until the correct entry is found, akin to scanning a mental timeline (Price & Mattingley, 2013). Our two novel tasks were based on information for which RS has a self-reported superior memory, the advantage of this being that the *content* of her memory can be objectively verified. The first source of her superior memory involved being able to name days of the week for any given calendar date since the year 2000 (e.g., "What day was it on 2 March 2002?" Answer: Saturday). The second involved her seeming ability to remember the entire text, practically word for word, of the seven books of the Harry Potter series by J.K. Rowling. Although this information is factual and 'semantic' in nature, RS nevertheless has personal memories associated with both: in 2000 she began marking off each day of the week on a calendar, and she has specific personal memories associated with reading the Harry Potter series. We compared RS's performance with ten age-matched controls who were also aficionados of the Harry Potter series. If RS's memory retrieval involves a parallel process, then the length of time between two calendar dates or two Harry Potter sentences should not affect her retrieval accuracy or speed. Alternatively, the gap in time between different dates and sentences should affect her performance if she "scans" her memories from earliest to latest, suggesting her memory representations are organised sequentially. In addition, to add to the available evidence of structural brain changes in people with HSAM, we conducted an exploratory 3T MRI scan to quantify structural changes in RS compared with a normative dataset.

2. Materials and Methods

In this section we report how we determined our sample size in the control group, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

2.1 Participants

2.1.1 RS

RS, a right-handed 31 year-old female, was identified as presenting with highly superior autobiographical memory (HSAM) in 2011 by Stark and colleagues at the University of California, Irvine. She graduated from high school with 12 years of education. Comorbid conditions diagnosed during her lifetime include autism spectrum disorder (ASD), obsessive compulsive disorder (OCD), generalised anxiety, depression, and post-traumatic stress disorder (PTSD). She is treated with clomipramine, olanzapine, escitalopram and regular psychotherapy with good effect. Although never formally employed, she does not report being occupationally disabled, as she frequently spends time blogging and writing articles, participating in research, and public speaking, the latter for which she receives financial compensation. RS continues to live with her mother, stepfather, and younger siblings, with all of whom she has close relationships.

At age 21, RS became aware that her personal experience of constantly re-living memories was unusual. She subsequently contacted researchers to participate in studies, including the current investigation, at 29 years. Like many other individuals with HSAM, RS's recall of past events appears profoundly rich in episodic detail, including associated tastes, smells, emotions, interactions with others, as well as more trivial details that others would likely forget (e.g., weather conditions). As mentioned above, RS has a self-reported superior memory for two types of semantic information: she has marked off calendar dates since the year 2000 and apparently remembers the entire text from all seven Harry Potter novels. Consistent with the defining feature of HSAM, RS reports having personal memories attached to both sources of information. She once recalled being home sick from school and sitting in the bedroom of her aunt's house reading the second Harry Potter book and, after reading a quote from Dumbledore, her headache and nausea briefly subsided. Similarly, RS reports that when she is presented with a calendar date, she "senses" the effect it has on her emotions before memories related to the day that she crossed it off on her calendar come "flooding in".

We initially verified her HSAM status using methodology originally established by previous work (LePort *et al.,* 2012, 2017; Parker *et al.,* 2006; see Gibson *et al.,* 2022 for examples of RS's specific screening questions). We also conducted a neuropsychological assessment to rule out any contribution of other factors to her superior autobiographical memory. RS performed at an average level across most cognitive domains assessed, including intelligence, episodic memory, language, attention, and executive function. Areas of difficulty were in social perception and memory for faces, which is unsurprising given her autism diagnosis. RS's full neuropsychological assessment scores are provided in Supplementary Note 1.

2.1.2 Controls

RS was tested against ten healthy individuals (2 males, 8 females), in accordance with sample size convention for previous case studies (e.g., Cheviet *et al.,* 2021; Ilardi *et al.,* 2021; Robinson *et al.,* 1998, 2004, 2005, 2006). Controls were closely matched for age (M = 25.6, SD = 5.64, range = 20 to 36 years), and selected based on their familiarity with the Harry Potter books (i.e., they must have read the entire series at least once). Testing was conducted at the University of Queensland Neuropsychology Research Clinic. RS and controls provided informed written consent to participate in this study, which was approved by The University of Queensland Human Research Ethics Committee. Participants were reimbursed with a gift voucher ranging from $20 to $25.

2.2 Experiment 1: Calendar Dates

2.2.1 Stimuli and Procedure

During the experiment participants viewed two calendar dates (DD/MM/YYYY) presented above and below each other, in the centre of a computer screen (see Figure 1b). Participants were instructed to read each date and were asked "Which date is earlier in the week?", with responses given by saying either 'A' (corresponding to the first presented date) or 'B' (corresponding to the second presented date). Monday was designated as the first day of the week, and Sunday the last day of the week. To determine the reaction time (i.e., the time between the last date being read and when an answer was given), participants were asked to read each date aloud. Once an answer was given, the experimenter (who was blind to the correct answer for each trial) proceeded to the next trial using a standard computer keyboard. The experiment was administered using Microsoft PowerPoint (2018) on a Dell desktop computer. Accuracy was emphasised as more important than speed, although participants were to give their best guess if unsure. To ensure participants successfully understood the task, three practice trials were administered. The experiment took approximately 60 minutes to complete.

One date pair was presented within each trial, with a total of 60 trials presented. Stimuli varied on temporal distance, year position and time period, as illustrated in Figure 1a. For temporal distance, the stimuli were divided into 31 Close and 29 Distant date pairs. A Close pair consisted of two dates extracted from the start and end of one month, and a Distant pair consisted of two dates extracted from the start of one month and the end of the second month, exactly 7 months apart. The start of a month was defined as the first 7 days of the month, and the end of a month was defined as the last 7 days of the month. For each trial, dates were paired depending on their location within the defined period. For example, for a Close pair the first date within the first 7 days in January would be paired with the first date within the last 7 days of the same month. An example of a Distant pair would be the third date in May paired with the third-last date in November, exactly 7 months later. Note that all dates from the month of February were excluded when selecting Close stimuli, as both dates within a pair would land on the same day of the week.

For year position, 30 pairs were from the Start of the year (i.e., first three months), and 30 pairs were from the End of the year (i.e., last three months). Trials comparing dates 3 March vs. 27 March and 3 October vs. 27 October are examples of Close pairs extracted from the Start and End in the year, respectively. Conversely, trials comparing dates 2 February vs. 26 August and 3 June vs. 27 December are examples of Distant pairs extracted from the Start and End of the year, respectively. Finally, stimuli were extracted from three different time periods, specifically, the years 2005, 2010, and 2015. There were 19 trials for dates from 2005, 21 trials for 2010 dates and 20 trials for 2015 dates. Presentation of stimuli was counterbalanced across temporal distance, year position and time period. To avoid dates from earlier in the week being consistently presented as option ‘A’ – and vice versa for dates later in the week - date order was counterbalanced within each individual trial. Figure 1 (A,B) shows a schematic illustration of how the variables were derived, and an example trial.

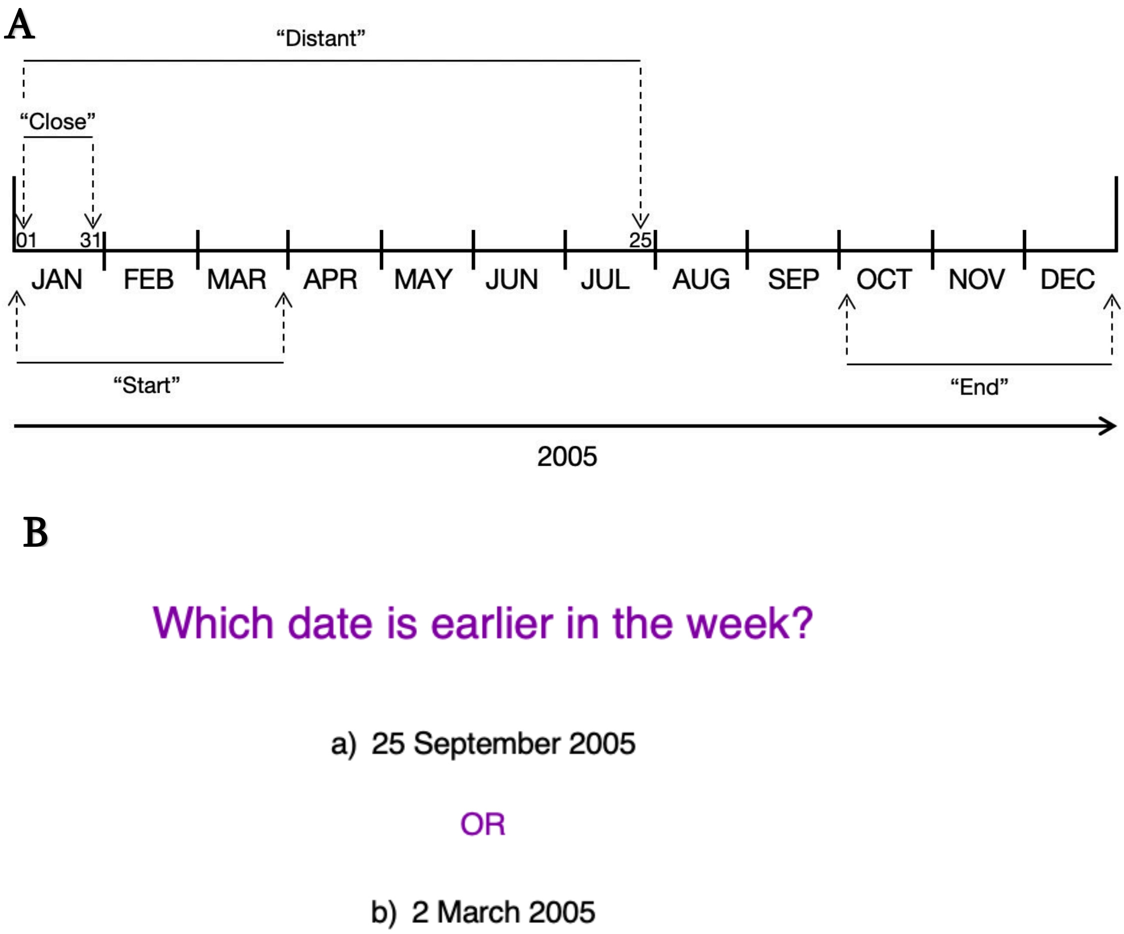

Figure 1. Schematic of the Calendar Dates task (Experiment 1) and an example trial. **(A)** Illustration of how the variables were derived for the Calendar Dates task, with specific examples of Close and Distant dates and Year Position (Start and End); **(B)** Example trial from the Calendar Dates task.

Lastly, all trials were randomly sampled by using a random number generator for each participant. The strategies used by controls to determine which date came earlier in the week were noted. To ensure that participants could not use probability matching to correctly guess the answer, the proportion of correct trials was assessed based on whether they were extracted from the start or the end of a month. For instance, if there were a significantly higher number of correct dates that were from the start of a month versus from the end of a month, participants could consistently choose the earlier date option as a strategy. Analysis confirmed that the earlier of the two dates appeared in only 57.14% of overall trials. Trials were also divided by position at the start of a month and the end of a month, and results revealed that 53% of trials extracted from the start of a month came earlier in the week.

2.3 Experiment 2: Harry Potter

2.3.1 Stimulus and Procedure

Participants viewed two sentences presented above and below each other, in the centre of a computer screen. These sentences were quotes or narrative text extracted from the third Harry Potter novel ("Harry Potter and the Prisoner of Azkaban"; Rowling, 1999). Participants were to read aloud each sentence and asked "Which sentence came earlier in the book?", then provided their answer by saying either 'A' (corresponding to the first sentence) or 'B' (corresponding to the second sentence). Once an answer was given, the experimenter (who was blind to the correct answer for each trial) proceeded to the next trial using a standard computer keyboard. As in Experiment 1, stimuli were presented using Microsoft PowerPoint (2018). Accuracy was emphasised over speed, but participants were encouraged to guess if unsure. It was also emphasised that all trials were from only one book in the series, but participants were still naïve to the book in question. To ensure participants successfully understood the task, two practice trials were administered.

One sentence pair was presented within each trial, with a total of 30 trials presented. Stimuli varied on temporal proximity and book position. For temporal proximity, the stimuli were divided into 14 Close and 16 Distant sentence pairs and were chosen from a pool of 86 sentence pairs (54 Close, 32 Distant). A Close pair consisted of two sentences extracted from the start and end of a double-page within a single chapter, and a Distant pair consisted of two sentences extracted from the start and end of the same chapter. Both conditions were operationalised in this way to avoid participants correctly guessing the answer based on storyline progression. For book position, half (i.e., 15) of the pairs were from the Start of the book (i.e., first three chapters), and the other half were from the End of the book (i.e., last three chapters). Stimulus order was counterbalanced across temporal proximity and book position. To avoid sentences written earlier in the book being consistently presented as option 'A' – and vice versa for sentences later in the book - sentence order was counterbalanced within each individual trial. Figure 2 shows an example trial from the task.

Sentences within a pair were matched on word length and content (i.e., number of main characters mentioned). A series of pairwise *t*-test comparisons were conducted to verify correct matching of these factors. The results revealed no significant difference in word length between Close and Distant pairs (p = .902). Similarly, word length of sentences extracted from the Start of the book did not significantly differ from sentences extracted from the End of the book (p = .797). There was no significant difference in the number of main characters mentioned in Close sentence pairs, when compared with Distant sentence pairs (p =.375). Significantly more main characters were mentioned in sentence pairs from the End of the book (M = 1.25) than from the Start of the book (M = 1.08, t = -2.17, p < .050). Therefore, when selecting the final stimuli, we ensured that each sentence extracted from the Start and End of the book only mentioned one main character.

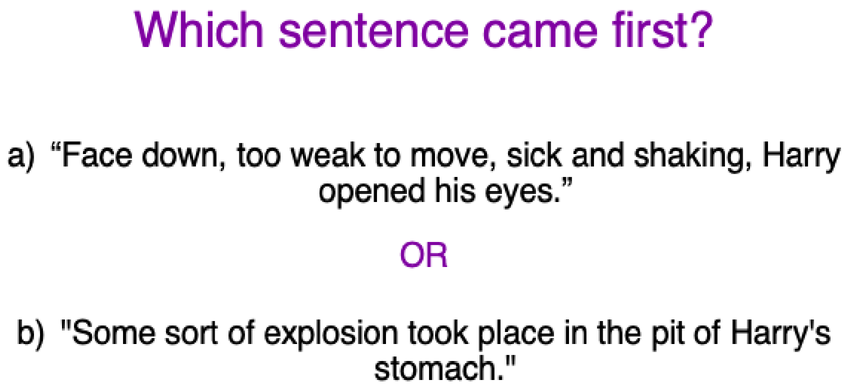

Figure 2. Example trial from the Harry Potter task (Experiment 2).

2.4 Design

Both experiments used a within-groups factorial design and assessed two independent variables consisting of accuracy (percentage of correct responses) and reaction time (RT) in seconds. Experiment 1 (Calendar Dates) measured three independent variables: Temporal Distance (Close vs. Distant), Year Location (Start vs. End) and Time Period (2005 vs. 2010 vs. 2015). Experiment 2 (Harry Potter) measured two independent variables: Temporal Proximity (Close vs Distant) and Book Position (Start vs End).

2.5 Data Analysis

Both experiments utilised a two-alternative forced choice paradigm, where participants were presented with two items within a trial, and answers were deemed either ‘correct’ or ‘incorrect’. Therefore, the binomial test was used to assess accuracy. To do this, we solved the linear equation:

$$P(B = k) = \binom{n}{k} p^k (1-p)^{n-k}.$$

Where n is the number of trials within a condition, k is the number of successes, p is the probability of success for a single trial, and $P(B = k)$ refers to the binomial probability of obtaining a specific number of successes on a specific number of trials that is required to achieve accuracy significantly above chance (50%), $p < .050$. For Experiment 1 (Calendar Dates), statistical analysis of reaction time results were not conducted because controls were unable to perform the task (i.e., they were all at chance level). For Experiment 2 (Harry Potter), due to the high variability in RTs for controls, performing a series of modified *t*-tests to detect any significant differences was not viable. Therefore, additional analyses were carried out by integrating measures of RT and accuracy (proportion of errors; PE) into a single measure in order to inspect the speed-accuracy balance for RS and controls. The linear integrated speed accuracy score (LISAS) has been shown to be the most valid and reliable method of measuring speed-accuracy trade-off, when compared with previously proposed integrated measures (Vandierendonck, 2017; 2018). LISAS is expressed as the following equation:

$$\text{LISAS} = \text{RT}_c + \text{PE} \times \frac{\text{S}_{\text{RT}}}{\text{S}_{\text{PE}}}.$$

Where RT_c is the average correct RT, PE is the proportion of errors, S_{RT} is the standard deviation of the correct RTs, and S_{PE} is the standard deviation of PE. All of these values were calculated per condition. If PE and/or S_{PE} are 0, LISAS is equal to RT_c. Note that PE is weighted by the ratio of the two standard deviations. This ensures that any differences of standard deviation in the RT_c scores are weighted equally as differences of standard deviation in the PE scores, so that when RT_c and PE effects are opposite, they balance each other out. Therefore, LISAS is considered a balanced combination of speed and accuracy and can be interpreted as RT adapted for the number of incorrect responses.

2.6 Magnetic Resonance Imaging

RS was imaged using a 3T whole-body scanner (PRISMA, Siemens Healthcare, Erlangen, Germany). We acquired a 2D TSE sequence (TR: 8460ms, TE: 67ms, FA: 150°, FoV: 192mm, voxel size of 0.5 x 0.5 x 1.0mm^3 ; up-sampled in k-space to 0.3 x 0.3 x 1.0mm^3 Turbo factor of 13; TA: 4:24) three times (totalling approximately 13 minutes) and a prototype MP2RAGE (WIP 900c, Variant VE11C; Marques *et al.,* 2010) with an isotropic resolution of 0.8mm^3 (TR / TE / TIs = 4000ms / 2.9ms / 700ms / 2220 ms, TA: 6:04). All TSEs were pre-processed by resampling to 0.3mm isotropic, bias field corrected using N4 (ANTs Version: 2.3.0; Tustison *et al*., 2010), and non-linearly registered to one another using the method described in Shaw and colleagues (2019) in order to boost signal-to-noise ratio and increase segmentation reliability.

Data were anonymised and defaced using pyDeface (Gorgolewski *et al*., 2017) and volumetric data were extracted using VolBrain (Manjón *et al.,* 2016). Segmentation of cortical and subcortical structures (excluding the hippocampus) were computed using the Vol2Brain pipeline, and hippocampus subfield segmentation was computed using HIPS (Romero *et al.,* 2017). Data (volume in mm^3) for RS were referenced against normative bounds of the IXI dataset, which contains 600 normal subjects covering a majority of the adult lifespan (Manjón *et al.,* 2016). No part of the study procedures or analyses was pre-registered prior to the research being conducted.

3. Results

3.1 Experiment 1: Calendar Dates

Overall mean accuracy for determining the earlier date within a week was 90% for RS (SD = 0.30) and 50% for controls (ranging from 43% to 55%; SD = 0.50). Overall median reaction time was 17.12 s for RS (SD = 7.01) and 1.24 s for controls (ranging from 0.51 to 18.85 s; SD = 10.64). Controls responded quickly because they were only able to guess on this task, unlike RS who deliberated carefully and was correct on 9 out of 10 trials. Cumulative binomial probabilities were calculated to determine whether RS and controls performed significantly above chance (50%) on the task. While RS performed above the 60%

accuracy required to be significantly above chance ($p = .046$), controls both collectively and individually could not do the task.

Cumulative binomial probabilities revealed that to perform significantly above chance, RS and controls needed to achieve above the following: 65% accuracy for Close pairs ($p = .035$), 66% for Distant pairs ($p = .031$), and 63% for pairs from the Start and End of the year ($p = .049$). Only RS met this level of accuracy across Temporal Distance (87% for Close and 93% for Distant) and Year Position (87% for Start and 93% for End), compared with controls (48% for Close, 53% for Distant, 51% for Start and 49% for End pairs). For Time Period, RS was significantly above chance for 2005 items (95% accuracy with 68% benchmark; $p = .032$), 2010 items (90% accuracy with 67% benchmark; $p = .039$), and 2015 items (85% accuracy with 70% benchmark; $p = .021$). Collectively, controls did not perform significantly above chance for any condition within Time Period (50% accuracy for 2005, 53% for 2010, and 48% for 2015). At an individual level, 1 out of 10 controls performed significantly above chance for dates from 2010 (71% accuracy). Figure 3 (A-C) shows the binomial accuracy results, and Figure 4 (A-C) shows median RTs for RS and controls (individual and pooled data).

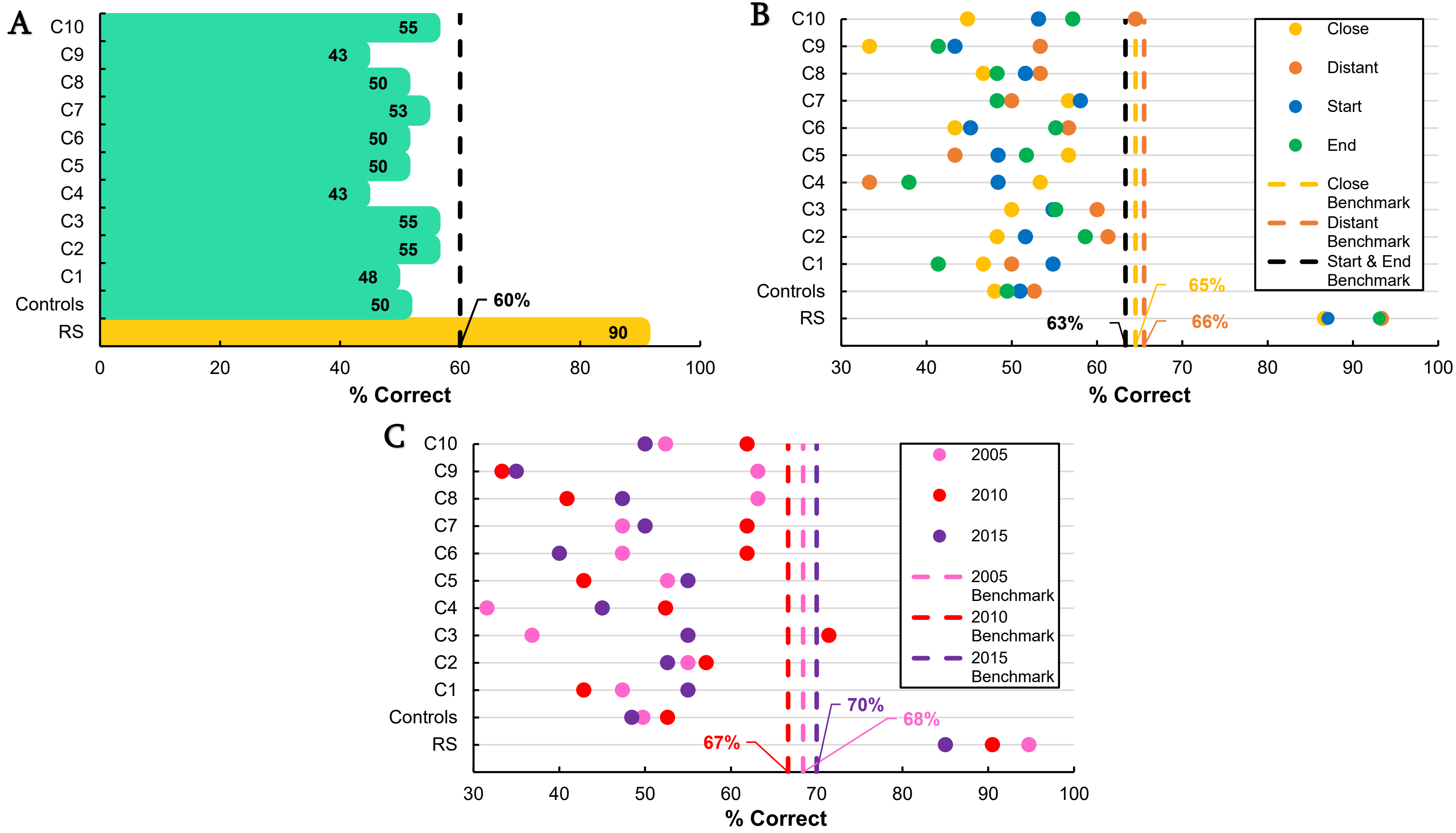

Figure 3. Binomial accuracy results on the Calendar Dates task (Experiment 1) for RS and controls (collectively and individually). Results are presented overall (A), for Temporal Distance and Year Position (B), and for Time Period (C).

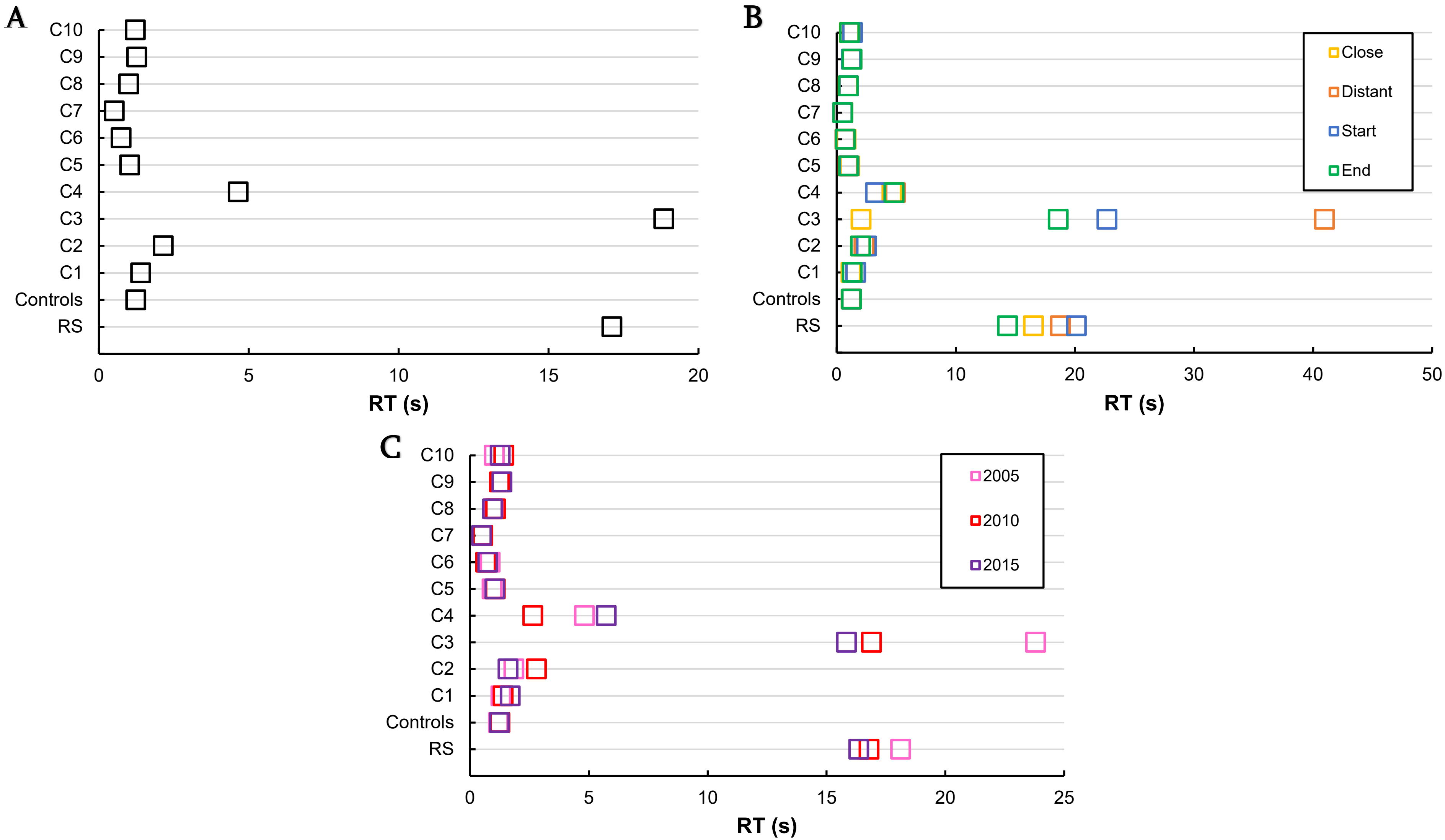

Figure 4. Median RTs in seconds for RS and controls (collectively and individually) on the Calendar Dates task (Experiment 1). Results are presented overall (A), for Temporal Distance and Year Position (B), and for Time Period (C).

3.1.1 Documented Retrieval Strategies

RS noted that she would relate certain dates within a trial to a personal or well-known event (e.g., birthdays, public holidays) and then calculate the answer by adding or subtracting the number of years between the remembered event and the item. For instance, if RS was presented with "7 January 2015", she would recognise that as her sister's birthday – which fell on a Sunday in 2018 – and subtract four days from Sunday to get Wednesday. She would then gauge the probability of the second date within the pair being earlier or later than Wednesday. For all trials, RS repeated the date aloud to herself after initially reading it to remember her calculated answers. Controls either employed the same strategy as RS, used mathematical strategies, or guessed, although none of these strategies permitted above chance performance.

3.2 Experiment 2: Harry Potter

Overall mean accuracy in detecting the earlier sentence within the book was 97% for RS (SD = 0.18) and 71% for controls (ranging from 57% to 83%; SD = 0.45). Cumulative binomial probabilities revealed that to perform significantly above chance, RS and controls needed to achieve above the following: 63% overall (p = .049) and 73% for both Temporal Proximity and Book Position (ps = .042). RS performed significantly above chance overall (97%), for Close (94%) and Distant (100%) pairs, and for sentences from the Start (100%) and End (93%) of the book. Collectively, controls performed significantly above chance overall (71%), for Distant pairs (76%) and for sentences from the Start of the book (74%), but not for Close pairs (67%) and sentences from the End of the book (69%). At an individual level, 8 out of 10 controls performed significantly above chance overall, 5 out of 10 were above chance for Close pairs, 6 out of 10 were above chance for Distant pairs, and 3 out of 10 controls were above chance for pairs from the Start and End of the book. Overall median RT was 0.90 s for RS (SD = 1.90) and 1.50 s for controls (ranging from 0.76 to 4.85 s; SD = 3.09). Linear integrated speed accuracy scores (LISAS) were compared with the original mean correct RT across each group to highlight the extent of speed-accuracy trade-offs for controls. Note that the LISAS values for RS always equalled her mean correct RT score (see Section 2.5 for further elaboration). Collectively, lower accuracy performances for controls led to slower reaction time scores overall and across Temporal Proximity and Book Position, compared with RS. Figure 5 (A,B) shows binomial accuracy results for the Harry Potter task, and Figure 5 (C,D) shows LISAS results for RS and controls (individual and pooled data).

3.2.1 Documented Retrieval Strategies

RS attributed delayed response times to interference due to similarities in content between some items and sentences from other books within the series (e.g., she recalled similarities between a specific sentence pair presented and a sentence that appears in Chapter 16 of the fourth novel). Neither RS nor controls reported using a strategy, stating that they "either knew it or they guessed". RS correctly guessed the source of the text immediately during the practice. Similarly, of the 8 (out of 10) controls who were questioned, 7 correctly guessed the book either during practice or on Trial 1 of the main task. Only one control did not guess the correct Harry Potter novel the from which the sentences were extracted. To ensure this did not impact the findings, we excluded this control participant from the group data across all variables and found no differences in the pattern of results (see Supplementary Note 2 for analysis results).

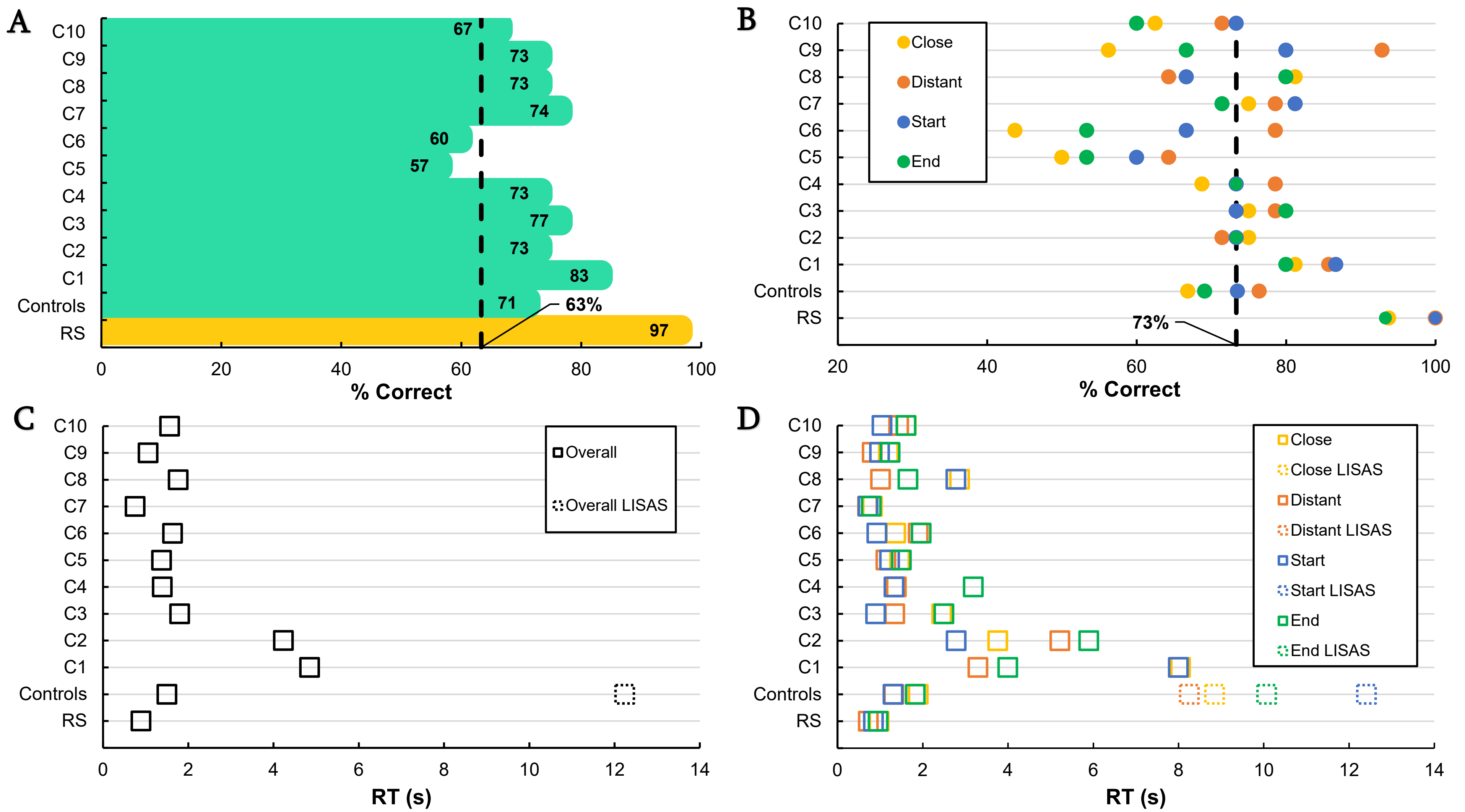

Figure 5. Harry Potter (Experiment 2) accuracy and reaction time results for RS and controls (collectively and individually). Binomial accuracy results are presented overall (A) and for Temporal Proximity and Book Position (B). Comparisons between correct RT in seconds and LISAS results are presented overall (C) and for Temporal Proximity and Book Position (D).

3.3 MRI results

Absolute volumes for each region of interest (ROI) were computed and then corrected (i.e., normalised) by dividing by the intra-cranial volume (ICV; Table 1). Normalised volumes were referenced against expected limits (95%) from the IXI dataset of volume as a function of age and sex for each ROI (Table 1). We also referenced cortical thickness values for all ROIs against normative values. No volumes or cortical thickness values deviated from normative ranges, including the hippocampal subfields (Figure 6).

Table 1

RS Brain Volumes for Regions Of Interest (ROI) Previously Associated With HSAM

ROI	Absolute Volume (cm^3)	Normalised Volume (%)	Normative value range (%)
Amygdala	2.369	0.164	0.116-0.171
Anterior insula cortex	9.291	0.643	0.522-0.755
Posterior insula cortex	5.332	0.369	0.274-0.430
Putamen	10.260	0.710	0.524-0.755
Inferior temporal gyrus	23.334	1.615	1.405-2.011
Middle temporal gyrus	29.156	2.017	1.827-2.487
Temporal pole	18.742	1.297	1.053-1.597
Whole hippocampus	4.731	0.3274	0.28-0.42
Caudate	9.595	0.664	0.445-0.665
Precuneus	23.149	1.602	1.421-1.766

Note. Absolute volumes were normalised by dividing by intra-cranial volume, and were compared with normative ranges for individuals matched for age and sex with RS.

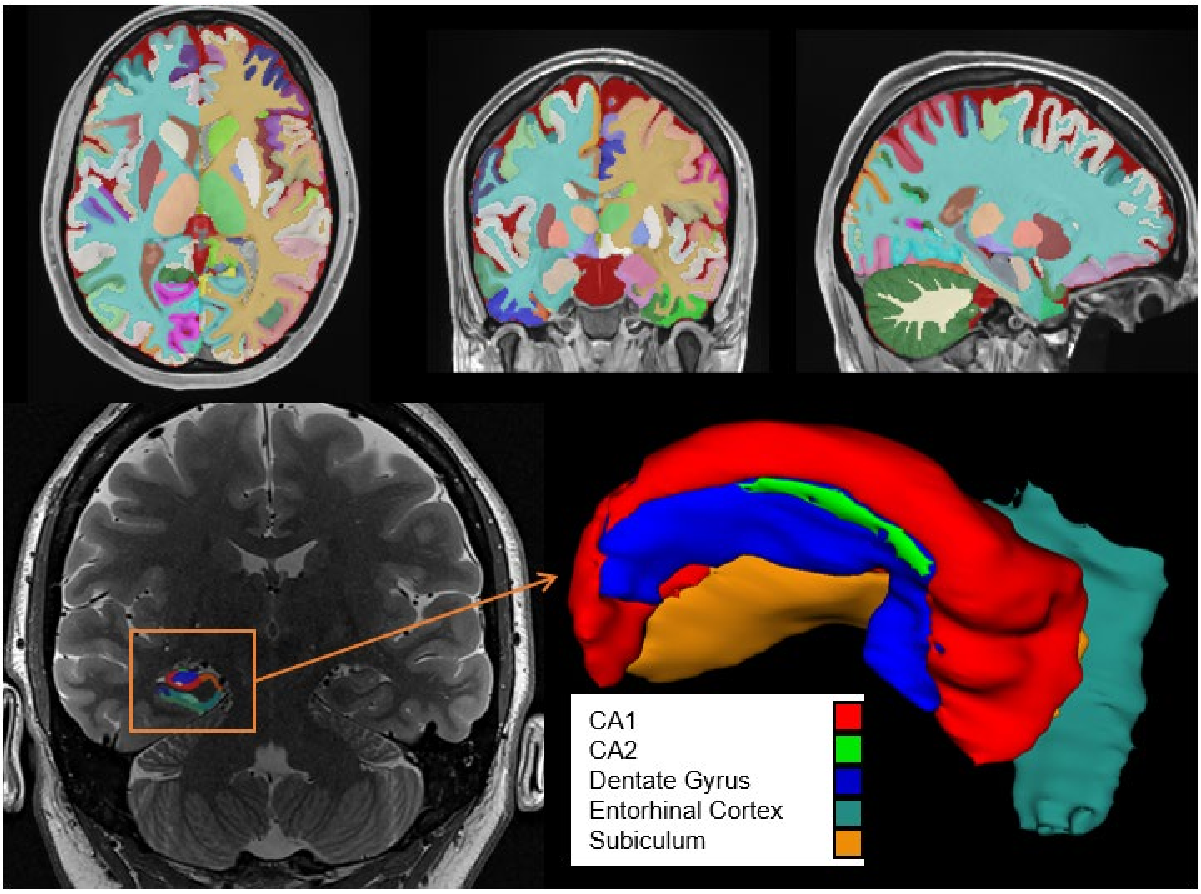

Figure 6. Upper panels: Brain segmentations for RS using the Vol2Brain pipeline for the MP2RAGE scan. No volumetric or cortical thickness differences in expected ROIs were found. Lower left panel: hippocampus segmentation overlaid on TSE scan. Lower right panel: corresponding geometric representation of hippocampus subfield segmentation.

4. Discussion

The present study is the first to experimentally examine the structure of memory representations in a case of highly superior autobiographical memory (HSAM). RS has a self-reported superior memory for two sources of personally relevant information, involving (a) the ability to name days of the week for any given calendar date since the year 2000; and (b) the ability to remember the entire text, virtually word for word, of the seven Harry Potter books. We devised two novel experiments based on this information and varied the length of time between two dates or sentences to determine the impact of temporal constraints on retrieval. The controls were no better than chance in identifying calendar dates (Experiment 1), whereas RS's accuracy was near perfect. The fact that controls happened to respond more quickly in this task reflected the fact that they were merely guessing. In identifying Harry Potter sentences (Experiment 2), controls demonstrated a clear speed-accuracy trade-off and their performance was significantly impacted by the temporal position of sentences within the book. By contrast, RS identified all sentences with high accuracy and speed, irrespective of their temporal distance from one another. Here, for the first time, we objectively established that, rather than reflecting a sequential scanning process, the accuracy and efficiency of RS's memory retrieval is not contingent on temporal proximity of relevant memories.

While our accuracy findings certainly point toward heightened memory retrieval in RS, the variability in her reaction times for determining the temporal order of calendar dates (overall median RT = 17.12 s) versus Harry Potter material (overall median RT = 0.90 s) may indicate differences in the nature of her retrieval. Here we refer to RS's self-reported strategies to help tease this apart. It appears that while retrieval of Harry Potter information occurs immediately without the use of an explicit strategy, her method for retrieving calendar dates is considerably more effortful. She reports the initial retrieval of an attached personal memory on a known date (e.g., her sister's birthday), which she then uses to identify the day of the week that the presented date fell on through a combination of calculation and probability estimation. While this is a relatively laborious process, there may be a level of automaticity in retrieving the initial autobiographical memory associated with a date. This may be unique to RS, as controls rarely reported having access to memories associated with presented dates.

We also discovered that HSAM individuals can have superior memory for non-autobiographical information (in RS's case, calendar dates and Harry Potter content), boosted by reportedly attaching autobiographical memories to these details. For calendar dates, RS reports repeatedly marking off dates on her calendar since she began to "memorise" them in 2000, and indeed in Experiment 1 she seemed to benefit from relating items to personal or well-known events in her lifetime. In addition, she reported frequently re-reading and rehearsing the Harry Potter books in her mind as a relaxation technique when she is anxious or has difficulty sleeping. This is consistent with evidence that HSAM individuals tend to be strongly biased towards information relatable to their own personal narrative (LePort *et al.,* 2012, 2017). In fact, RS herself has recently demonstrated this bias in an investigation of future thinking, a process known to be intrinsically related to remembering the past (D'Argembeau *et al.,* 2010; Schacter & Addis, 2007; Suddendorf & Coballis, 1997, 2007; Tulving, 1985, 2005). She displayed unremarkable future thinking only when there was minimal scope to tie information to her past experiences (i.e., narrative scene construction; Gibson *et al.,* 2022). Enhanced recall of semantic information in the present study may, therefore, be due to the fact that autobiographical significance contributes to the efficiency and strength in memory for non-episodic details.

The present study also aimed to characterise any structural brain anomalies in HSAM. High-resolution structural MRI scans revealed no volumetric or cortical thickness differences between RS and controls within any of the expected ROIs (i.e., hippocampus, amygdala, insula, temporal gyri and pole, subiculum, putamen). While our findings are in contrast to some previous reports of structural changes in memory-related brain regions amongst individuals with HSAM (Ally et al., 2013; DeMarco et al., 2021; LePort et al., 2012; Mazzoni et al., 2019), and more broadly to historic evidence of neuroplastic change in response to superior ability or environmental demands (e.g., larger posterior hippocampal volume in London taxi drivers; Maguire et al., 2000; Schlaug et al., 1995), they are consistent with recent investigations that indicate HSAM can occur in the absence of major morphological brain differences (Santangelo et al., 2018, 2020). While structural investigations have proved instrumental in differentiating pathologic rates of atrophy from normal age-related changes (e.g., Scahill et al., 2003), they are, in this instance, insufficient measures of brain function. Here, we did not assess functional activity in RS's brain and thus cannot link our behavioural findings to dynamic changes in neural activation or functional connectivity. Future research would benefit from these investigations, particularly in the context of recent findings of functional differences during stages of memory retrieval (Santangelo et al., 2018, 2020, 2021) and greater resting-state connectivity between areas within the default mode network (Ally et al., 2013; DeMarco et al., 2021). The insights gained may in turn inform our understanding of the mechanisms behind individual differences in autobiographical memory. Nonetheless, the absence of structural anomalies in RS confirms that HSAM can occur without major morphological brain differences.

The chief finding of this study extends beyond anecdotal reports of parallel memory processing in HSAM (LePort *et al.,* 2016) and directly contrasts with RS's descriptions of her own memory as being organised sequentially. Parallel memory retrieval is often reflected in the recall of personal semantic information (i.e., facts about the self) that does not depend on retrieving particular experiences, but is rather linked to feelings of "knowing" or familiarity (Holland & Kensinger, 2010). On the other hand, recalling personal episodic information requires an individual to re-experience or "relive" an event through the reactivation of perceptual, affective and spatiotemporal details integrated to form a visual representation of that event (Conway, 2001; Rubin & Umanath, 2015). The latter form of retrieval is slowed owing to the mental reconstructive process that occurs, whereas access to personal semantic information occurs rapidly (Conway, 1996; Conway & Bekerian, 1987; Conway & Pleydell-Pearce, 2000). As discussed above, HSAM individuals reportedly attach autobiographical memories to semantic information. Based on our findings, this results in simultaneous and highly accurate retrieval of information unburdened by the temporal proximity of memories. This suggests that the enriched, vivid details associated with these attached memories are more readily available and are re-experienced with much greater efficiency, consistent with recent functional neuroimaging work showing increased BOLD activation of posterior brain regions during memory retrieval in HSAM (Santangelo *et al.,* 2018, 2021). Here our findings create interesting avenues for future experimental investigations, particularly regarding the limits of retrieval efficiency in other HSAM individuals and their association with underlying neural circuitry.

Our behavioural findings provide indirect evidence for current theoretical perspectives on the underlying mechanisms of HSAM. RS's apparent attachment of autobiographical memories to semantic information would support enhanced self-referential processing as a likely contributor to unique memory consolidation. In line with the view of Palombo and colleagues (2018), neural activity within the default mode network that supports self-referential processing may be enhanced, allowing HSAM individuals to process mundane information as highly personal. Indeed, HSAM individuals have recently been shown to exhibit stronger posterior medial neural recruitment associated with self-referential processing when accessing their autobiographical memories (Santangelo *et al.,* 2018, 2021). Our findings also give support to further consolidation through passive rehearsal and incidental strengthening of memory traces, given RS's existing OCD diagnosis and reports of rehearsing memorised information (i.e., the Harry Potter books; LePort *et al.,* 2016). It may be that the obsessively driven, habitual rehearsal of details inadvertently boosts the selfrelevance of the information, leading to an enriched memory consolidation and retrieval process. While our findings certainly suggest there is a bias toward personally relevant information that is compulsively rehearsed in HSAM, we are unable to provide direct evidence for this because it is difficult to verify, a common limitation of research investigating autobiographical memory. Further work will be required to test this hypothesis explicitly.

To what extent can RS's HSAM abilities be differentiated from those of savant syndrome? The two phenomena are often associated with enhanced memory recall without the explicit use of mnemonics (Patihis, 2015). However, autistic savants tend to have cognitive deficits in one or more domains (Treffert, 2009), whereas RS performed at an average or higher level across all cognitive domains. RS is also not a "calendar calculator"; she does not possess the rare ability seen in some savants to readily specify the day of the week for dates spanning across centuries (LePort et al., 2012). For RS, the range of dates for which she can readily retrieve the day of the week is limited to dates within her lifetime and, as we have shown here, these dates are associated with vivid personal memories. RS also bears some resemblance to another case of enhanced memory not associated with savant syndrome, patient MM (Brandt & Bakker, 2017), who has the profound ability to remember dates, as well as historical facts, popular culture trivia and sports statistics. Key differences between the cases lie in the autobiographical richness of their enhanced memory retrieval, as MM's abilities appear to be circumscribed to semantic information without the vivid recollection of attached memories (e.g., the weather conditions on the day of a particular historical fact).

Unique memory consolidation in HSAM may also be reinforced by other psychological comorbidities, specifically PTSD and ASD in RS's case. Intrusive and involuntary memory retrieval is a hallmark feature of PTSD, and is assumed to take us out of the present thus provide a sense of continuity across time (Hall *et al.,* 2018; Rasmussen & Berntsen, 2009). The constant influx of information difficult to suppress in HSAM may be reinforced by enhanced neural mechanisms associated with involuntary retrieval of memories (i.e., limbic system, sensory and motor areas, ventromedial prefrontal cortical areas; Bourne *et al.,* 2013; Battaglini *et al.,* 2016; Clark *et al.,* 2016; Hall *et al.,* 2018). RS's ASD may also contribute to her unique memory consolidation and retrieval given her diminished flexibility to shift from her self-perspective and her preoccupation with rehearsal of memories. Not all HSAM individuals have diagnoses of PTSD or ASD (LePort *et al.,* 2012, 2016), however, and so the contribution of these comorbidities may be specific to RS only.

An alternative view is that the intrusive and involuntary retrieval of memories debilitates some HSAM individuals to such an extent that the corresponding impairments in day-to-day functioning mimic psychiatric illness. This is pertinent in RS's case as her comorbid conditions were diagnosed during a period before HSAM was first described. As such, RS's automatic remembering of rich detail may resemble "flashbulb" memories reminiscent of post-traumatic stress disorder. She often feels compelled to rehearse and order memories in her mind to successfully interact with the environment around her. This strategy of coping with the constant influx of memories would likely limit her attentional capacity and, in turn, might impair her ability to socially communicate and interact with others. While it would prove difficult to determine the true source of impaired functioning in some HSAM individuals, future studies including larger samples of subjects should aim to disentangle the contribution of these symptoms in HSAM.

We must be cautious in seeking to generalise the present findings to all individuals with HSAM, as with all single case studies (Persons & Jensen, 2018), and particularly in light of RS's comorbidities. It will be important for future studies to verify the nature of memory organisation in a wider sample of HSAM individuals. We also appreciate the difficulty in determining the true moment of memory retrieval, and the inherent limitation of any study involving reaction time as the proxy measure. Given the accuracy and speed in her responses it is possible that RS was retrieving information prior to finishing reading aloud the sentence pairs. However, it is assumed that individuals require a basic level of comprehension when processing semantic content, and factors such as reading speed must be controlled for, which is the reason reaction time was measured from the end of a participant reading aloud the text. We refer readers to Supplementary Note 3 which compares reaction time data for the total duration of trials (available for RS and 3 controls) to the original data. As expected, the pattern of results does not change.

Notwithstanding these limitations, our novel investigation provides new information on HSAM and sheds light on this rare condition of enhanced memory. HSAM may hold further clues to creating strong and lasting memories, which appear to be uniquely rich in detail. This may be particularly pertinent to individuals with amnestic syndromes (e.g., Alzheimer's disease, mesial temporal lobe epilepsy, Korsakoff syndrome), where remote memories are more resistant to deterioration and more recent memories are rapidly forgotten. By attaching past experiences to information encoded and stored within the short-term – and consequently increasing the richness of detail and feelings of re-experiencing/reliving – primary forgetting may be altered as a result of increased strength and efficiency of content and organisation of these memories. Further research on the influence of autobiographical memories on short-term memory retrieval in individuals with rapid forgetting would be worthwhile.

5. Conclusions

Here we have presented the first experimental investigation of the structure of memory retrieval in a single case of HSAM. Our findings, based on two novel experimental paradigms, suggest that the accuracy and efficiency of RS's semantic memory retrieval is not contingent on temporal proximity of relevant memories and therefore not reflective of a sequential scanning process. Rather, by reportedly attaching unique experiences from her personal narrative, information is seemingly more readily available and retrieved with much greater efficiency. The case of RS highlights the individual differences in information processing that can occur in humans and demonstrates the central role for self-referential processing in HSAM's unique memory consolidation. Clinically, this has important implications for enhancing recollection of events, particularly for those individuals for whom such details are forgotten.

Study Material and Data Availability

Legal copyright restrictions prevent public archiving of the various neuropsychological tests used in this research. These materials can be obtained from the copyright holders in the cited references. The conditions of our ethics approval do not permit public archiving of RS's clinical data as she is the only publicly known case of HSAM in Australia. Qualified researchers seeking access to the data should contact the corresponding author (G.A.R.). Data will be shared with named individuals following completion of a data sharing agreement and approval of the local research ethics committee. Freely accessible experimental material and non-clinical data are available at https://osf.io/gxdt8/.

Credit Author Statement

Lucy Ford: Conceptualisation, Methodology, Investigation, Formal Analysis, Writing – Original Draft; **Thomas Shaw:** Formal Analysis, Writing – Review and Editing; **Jason Mattingley:** Conceptualisation, Methodology, Writing – Review and Editing; **Gail Robinson:** Conceptualisation, Methodology, Writing – Review and Editing, Funding acquisition.

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