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► To cite this version:

Joanna Gautier, Mohamad El Haj. Eyes don't lie: Eye movements differ during covert and overt autobiographical recall. *Cognition*, 2023, 235, pp.105416. <10.1016/j.cognition.2023.105416>. <hal-04230854>

HAL Id: hal-04230854

<https://hal.science/hal-04230854v1>

Submitted on 9 Oct 2023

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Short title: eye movements and covert recall

Eyes don't lie: eye movements differ during covert and overt autobiographical recall

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Abstract

In everyday life, autobiographical memories are revisited silently (i.e., covert recall) or shared with others (i.e., overt recall), yet most research regarding eye movements and autobiographical recall has focused on overt recall. With that in mind, the aim of the current study was to evaluate eye movements during the retrieval of autobiographical memories (with a focus on emotion), recollected during covert and overt recall. Forty-three participants recalled personal memories out loud and silently, while wearing eye-tracking glasses, and rated these memories in terms of mental imagery and emotional intensity. Analyses showed fewer and longer fixations, fewer and shorter saccades, and fewer blinks during covert recall compared with overt recall. Participants perceived more mental images and had a more intense emotional experience during covert recall. These results are discussed considering cognitive load theories and the various functions of autobiographical recall. We theorize that fewer and longer fixations during covert recall may be due to more intense mental imagery. This study enriches the field of research on eye movements and autobiographical memory by addressing how we retrieve memories silently, a common activity of everyday life. More broadly, our results contribute to building objective tools to measure autobiographical memory, alongside already existing subjective scales.

Keywords: Autobiographical memory; Covert recall; Eye movements; Mental imagery

1.1. Introduction

A student's eyes drift off as they remember their last summer night at the beach while sitting on the bus on their way to class. A teacher's gaze shifts as they share an embarrassing experience of the first course they taught ten years ago with their new colleague. Across the globe and throughout the ages ((Wang, 2004), human beings have thought and talked about their personal past: this is thought to be a feature specific to our species (Conway, 2005). However, few studies have considered the silent modality of autobiographical memory, as it is difficult to access without relying on speech. Our study aims to compare thinking and talking about the past through eye-tracking.

Thinking and talking about the past relies on autobiographical recall. Autobiographical memory refers to memories of experiences linked to our personality and our past (Conway, 2005). Reliving specific events involves a strong subjective experience of mental time travel as well as intense phenomenological experience (Tulving, 2002), notably through mental images, which are a defining element of the reliving experience (Rubin & Berntsen, 2003). Mental imagery refers to the ability to construct, inspect, and manipulate images in the mind's eye, in the absence of external stimuli (Kosslyn, 1994). These images are recalled from memory either voluntarily or involuntarily [that is, triggered by external events or internal associations (Pearson & Westbrook, 2015)]. Mental images are strongly involved in autobiographical memory: Conway & Pleydell-Pearce (2000) suggest that they facilitate recall as they accelerate the research process within the hierarchical structure of autobiographical memory. Supporting this assumption, neuropsychologists have established a link between retrograde amnesia and degraded mental imagery capacities (e.g., (Ogden, 1993) while the neuroanatomy research field has highlighted significant activation of visual areas during autobiographical recall (Conway, 2005; Gilboa, 2004; Viard et al., 2007). Taken together, mental imagery plays a crucial role in autobiographical memory. As eye movements may mirror mental imagery during memory retrieval (Bone et al., 2019; Noton & Stark, 1971), eye-tracking is starting to be used as one of the various ways to evaluate autobiographical memories.

Evaluating autobiographical memories (as opposed to controlled events in a laboratory) provides an ecological approach to achieve a fuller understanding of memory as we use it in our everyday lives. Autobiographical memory is mainly studied through methods which necessitate subjective ratings by the scorer, such as the Autobiographical Memory Interview

(Kopelman et al., 1989) or the Test Episodique de Mémoire du Passé Autobiographique (Piolino et al., 2003). As a complementary approach, recent studies are seeking to establish objective measures of cognitive processes such as recollective experience, notably via eye-tracking. While the involvement of eye movements in the encoding (e.g., Henderson et al., 2005; Loftus, 1972) and retrieval (e.g., Brandt & Stark, 1997; Johansson & Johansson, 2014) of memories has been clearly established using laboratory approaches, new research is being led regarding their involvement in the retrieval of real-life memories. In a princeps study, El Haj et al. (2014) recorded the eye movements of 40 healthy young adults in two conditions: autobiographical recall (experimental condition) or counting out loud (control condition). Results showed a significantly lower number of fixations and a significant increase in the number, amplitude, and duration of saccades during autobiographical recall. These eye patterns were interpreted as an attempt of the visual system to search (via saccades) and explore (via fixations) the mental representations of memories, stocked in the form of mental images: autobiographical recall may thus activate a visual treatment of information (El Haj et al., 2014). Additionally, Armson et al. (2021) found that the number of internal details that were retrieved during autobiographical recall predicted the number of fixations per minute realized by their participants. The impact of emotional memories on eye movements has also been studied, even though the relationship between these two elements remains unclear. While El Haj et al. (2017) found that memories elicited by emotional words (e.g., happy, sad, angry) triggered more fixations, shorter fixations, more saccades, and saccades with a wider amplitude (compared to memories elicited by neutral words), Janssen et al. (2021) found no difference in eye movement characteristics between neutral and emotional word-cued memories. Despite these differences, all these studies have demonstrated that autobiographical recall influences eye movements. Other research has highlighted how eye movements influence autobiographical recall. Lenoble et al. (2019) studied the way fixations influence this process by asking participants to retrieve an autobiographical memory while fixating a cross. Results showed that the retrieved memories contained fewer mental images and fewer spatial and temporal details and took longer to retrieve. Thus, maintaining a fixation may prevent participants from making the saccades necessary for the memory's reconstruction, or at least the recuperation of mental images which facilitate recall (El Haj & Lenoble, 2018).

While the above-mentioned research has demonstrated that eye movements are implicated in autobiographical recall, most of the recall conditions in these studies are similar: participants were invited to recall a personal memory out loud (i.e., overt recall). However, recalling

memories is also done daily within our own thoughts (i.e., covert recall): not all memories are talked about. Bluck & Alea (2009) revealed that regardless of age or gender, people report thinking about the past more than talking about it, hence making covert recall an important object of study in autobiographical memory. In the specific field of eye movements and autobiographical recall, Janssen et al. (2021) have asked participants to think about a memory, but the intention of the study was not to explore the specificities of covert recall. They notably studied the differences in eye movements during access and elaboration of neutral and emotional memories. Interestingly, as mentioned above, Janssen et al. (2021) obtained different eye movement characteristics than El Haj et al. (2017). Their experimental design was similar (autobiographical recall using the same emotional cue-words, recording of the same variables), to the exception that El Haj et al. (2017) used overt recall while Janssen et al. (2021) used covert recall. In light of these divergent results, one may wonder if sharing a memory triggers different eye movements, and thus a different reliving experience. Talking, and the cognitive effort that comes with it (i.e., making the memory intelligible for our interlocutor by structuring it, respecting a certain chronology of events, etc.), could also impact our eye movements and our ability to explore the past. The objective of this study will be to explore the potential differences in eye movement characteristics and memory characteristics between covert and overt recall.

To the very best of our knowledge, across disciplines, no studies have taken an interest in the potential differences between covert and overt recall. Neuroanatomical studies using covert recall (for an example, see Svoboda et al., 2006) and overt recall (Gilmore et al., 2021) identify a similar neural activation during autobiographical memory, such as the default mode network. This network includes areas involved in mental imagery and eye movements, such as the temporo-parietal junction, responsible for saccadic control (Rawley & Constantinidis, 2009); the precuneus, activated during mental imagery (Rubin, 2005); and the posterior cingular cortex and the retrosplenial cortex, involved in visual and spatial treatment (Buckner et al., 2008; Svoboda et al., 2006). Overt recall also activates the left mid-insula and bilateral aspects of somato-motor cortex and the paracentral lobule, reflecting speech production (Gilmore et al., 2021; Gracco et al., 2005). However, no neuroanatomical or neuropsychological study has focused on specifically comparing covert and overt autobiographical recall.

In this study, our first objective was to explore the potential differences in eye movements and memory characteristics during covert and overt recall of autobiographical memories. Our second aim was to assess the potential differences between sharing an emotional memory out

loud (i.e., overt recall) and recalling it silently (i.e., covert recall) by adding an emotional variable (i.e., using neutral or emotional words to cue memories). Indeed, covert recall brings to light the notion of intimacy and, potentially, a modulation in emotional regulation. Furthermore, we chose to conduct separate analyses for positive and negative memories. In previous studies (El Haj et al., 2017; Janssen et al., 2021), no difference was made between the memories triggered by positive and negative word cues: they were grouped as emotional memories. However, positive memories have been shown to contain more sensorial and contextual details than both negative and neutral memories (D'Argembeau et al., 2003). We thus expected that positive, negative, and neutral memories would trigger different eye movement patterns. Lastly, we explored the associations between eye movement characteristics and memory characteristics (retrieval time, emotional intensity, mental imagery).

1.2. Method

1.2.1 Participants

This study included 43 young undergraduate and graduate students (including 30 women, *mean* age = 20.81 years, *SD* age = 2.48), from Nantes University (France). Informed consent was obtained in accordance with the Declaration of Helsinki. All participants were native French speakers. Participants were healthy, between the ages of 18 and 30, had no history of psychiatric or neurologic disease, traumatic brain injury, or use of medication affecting cognition. We controlled any disease or condition affecting eye patterns (e.g., nystagmus, strabismus). Participants with contact lenses or glasses were however included, as this factor does not affect eye movement detection. Because the study dealt with memory function, we controlled the participants' memory performance, by assessing verbal episodic memory using a French validation (Van der Linden et al., 2004) of the Grober & Buschke (1987) test. Participants were invited to retain 16 words, each describing an item belonging to a different semantic category. After a 20-second distraction phase, they were invited to retrieve as many words as possible, in the order that they wished, with the maximum score being 16 points. The mean score of the participants was 12.71 (*SD* = 1.73). Based on this evaluation, we excluded one participant from the original sample, as they performed 1.6 *SD* below the norms (Van der Linden et al., 2004). Two participants were excluded due to calibration difficulties because of the wear of false eye lashes. Three participants were excluded due to low pupil algorithm detection confidence (i.e., we were not able to obtain satisfactory pupil detection due to various parameters such as the shape of the eye). Lastly, one participant wished to withdraw from the

experiment. After excluding these participants from our 50 volunteers, the final sample was of 43 participants. This final sample size was determined a priori using G*Power (Faul et al., 2007). Calculation was conducted for ANOVA within repeated measures as our experimental design involved two conditions (nature of the cue word and recall condition). Sample size calculation was also based on 95% power, an estimated probability of making a Type I error as .05, and a medium effect size of 0.25 (Cohen, 1992). This calculation recommended a sample of 43 participants to achieve sufficient power.

1.2.2 Material

Eye movements were recorded using the Pupil Labs oculomotor eye-tracking glasses (Kassner et al., 2014) and Pupil Capture software (Kassner et al., 2014). Pupil Labs is an eye-tracking system which uses infrared illumination, with a gaze position accuracy of $< 0.1^\circ$ and a 200 Hz sampling rate. Eye movements were then processed and analyzed using Pupil Player (Kassner et al., 2014). Memories were triggered by neutral, positive or negative cue words (i.e., “city”, “happy”, or “sad”) which were chosen to fit the material used in previous research (El Haj et al., 2017; Janssen et al., 2021).

1.2.3. Procedure

The experiment took place in a quiet room on the Nantes University campus. The blinds were closed, and the luminosity of the room remained the same during the whole experiment. Participants were informed that they were going to take part in a study involving memory and vision in general but were not informed of the relation between autobiographical memory and eye movements, nor about our hypotheses, until the end of the experiment, so as not to influence their performance. Prior to the experiment, the software was calibrated by asking participants to look at Pupil Capture’s pupil calibration marker, which was printed on an A4 sheet of white paper, attached to a white wall. They were asked to fixate the calibration marker for ten seconds, then to continue fixating it while slowly rotating their head clockwise and counter clockwise. This enabled to make sure data would be of sufficient quality even in the case of light head movement during the experiment. The calibration marker was placed on five different areas of the wall (one point at the center of the wall where the gaze naturally sits when the head is straight, and four at the extremities of the natural gaze: top left, top right, far right, bottom left) so as to ensure quality recordings and removed after calibration. During the calibration, we

aimed for a pupil detection confidence index $> .80$ (0 being an absence of pupil detection and 1 referring to a high certainty regarding pupil detection), in accordance with the recommended guidelines of Pupil Labs. Calibration was considered satisfactory when the visual angle error of our data was less than 1° .

During the experiment, participants were seated at an approximate distance of 50 cm from the white wall and were free to explore all parts of it (see Figure 1). The participants wore Pupil Labs eye-tracking glasses and were invited to perform the two experimental conditions: “talking” and “thinking”. In the talking condition, participants were invited to recall various memories from the past out loud. They were to recall two memories from a neutral cue word (i.e., “town”), two memories from a positive cue word (i.e., “happy”) and two memories from a negative cue word (i.e., “sad”). In the thinking condition, participants were asked to recall the same six memories from the past in silence, in the privacy of their own mind. We chose to ask the participants to recall the same memories in each condition in order to ensure that both memories were comparable and to verify that the memories recalled in the thinking condition were indeed episodic autobiographical memories. The order of the conditions was counterbalanced across participants. Within the conditions, the three recall tasks (i.e., “town”, “happy” and “sad”) were not randomized, as we noticed during the study’s pretest that recalling the negative memory in first or second place could negatively influence the choice of the neutral and/or positive memory. When participants were assigned to start with the thinking condition, they were informed that later they would need to recall them out loud and were invited to select their memories accordingly. Prior to the recall, participants were informed that the event selected had to have been experienced personally and had to be precise and specific (e.g., when and where the event occurred, what they were doing, who was present and what their feelings were). In accordance with previous research (El Haj et al., 2014, 2017; Janssen et al., 2021; Lenoble et al., 2019), they were informed that they had two minutes to reminisce each event, allowing them to structure the event accordingly. As access (i.e., time spent searching for a memory to retrieve) and elaboration (i.e., time spent revisiting and exploring the selected memory) of a memory trigger different eye movements (Janssen et al., 2021), and bearing in mind that elaboration is associated with an increased activity of the visual cortex (Daselaar et al., 2008), the recording was only launched during the elaboration phase. Participants were thus invited to indicate when they had selected a memory to explore, so the experimenter could start the recording.

Figure 1. Photo of the experimental setup of the study.



At the end of each autobiographical recall, participants were invited to rate its mental imagery according to the statement “I can see it in my mind” on a five-point scale (1 = I have no images, 2 = I have a few hazy images, 3 = The images are somewhat clear, 4 = The images are clear, 5 = The images are extremely clear, as clear as in real life). They were also invited to rate the emotional accuracy with which they had experienced their memory, according to the statement “I am experiencing the emotions that I had experienced at the time”, on a five-point scale (1 = Not at all, 2 = A little, 3 = Moderately, 4 = A lot, 5 = Extremely). Both of these scales replicated items of the Autobiographical Memory Questionnaire (Rubin et al., 2003).

1.2.4. Variables and data processing

This study included two independent variables: recall condition (i.e., covert vs. overt recall) and emotional nature of the memory (i.e., neutral vs. positive vs. negative cue word). The dependent variables were eye movement characteristics (i.e., fixation count, fixation duration, saccade count, saccade duration, and blinks) and memory characteristics (i.e., mental imagery ratings, emotional intensity ratings, and retrieval duration).

Pupil Capture’s fixation detection plugin was adjusted so as to detect fixations between 150 and 900 ms of duration (i.e., an eye movement which lasted for less of 150 ms or more than 900 ms could not be considered a fixation). These bounds were chosen in accordance with various studies indicating that fixations related to cognitive processes tend to be of this length (while fixations linked to visual analysis tend to be shorter) (for a review, see Galley et al.,

2015). Saccades were not detected via Pupil Capture and were calculated afterward, by considering that any eye movement that was not labeled as a fixation or a blink was a saccade. As participants did not always use the two minutes which were allocated to revisit their memory, we calculated ratios for fixation, saccade, and blink count: these refer to the number of fixations, saccades, and blinks per minute. Average fixation and saccade duration were expressed in milliseconds. Lastly, after verifying (via Student's *t* tests) that eye movement and memory characteristics of both memories recalled (i.e., the two neutral, positive and negative memories) were not significantly different, we averaged the data obtained for the first and second memory of each condition.

1.3. Results

1.3.1 Eye movement characteristics

As the data was not always normally distributed and did not necessarily respect sphericity conditions (which are prior conditions to conducting ANOVAs), eye movement characteristics were examined with Friedman tests, which had recall condition (overt vs. covert recall) and emotional nature (neutral vs. positive vs. negative memories) as the independent variables. The effect size was measured with Kendall's *W* coefficient of concordance and was interpreted according to Cohen's guidelines (1992). For descriptive statistics, see Table 1. For a schematic representation of the results, see Figure 2.

Table 1. Mean, median and standard deviation of the eye movement characteristics for memories elicited with neutral, positive and negative words, during overt and covert recall.

	Overt recall			Covert recall		
	<i>Neutral</i>	<i>Positive</i>	<i>Negative</i>	<i>Neutral</i>	<i>Positive</i>	<i>Negative</i>
Fixation count	100.3 (21.7)	103 (22.2)	102 (24.1)	86.6 (23.6)	87.1 (23.9)	87.8 (24.7)
	94.6	96.7	104	78	78.4	79.1
Fixation duration	487 (159)	465 (150)	465 (135)	662 (171)	648 (166)	641 (171)
	483.1	480.8	468.4	663.2	673.4	655.5

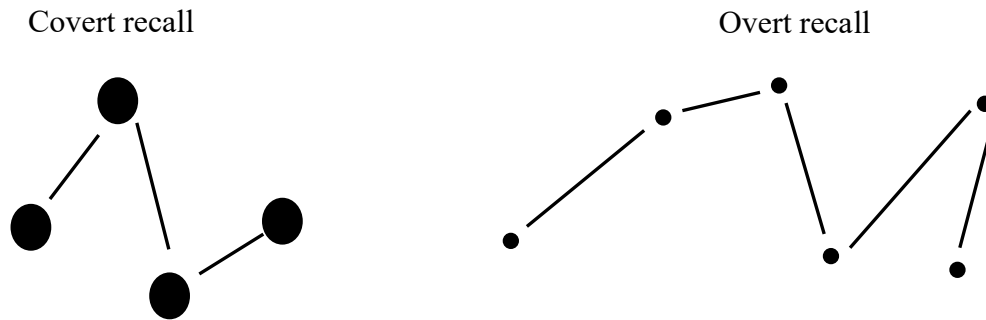
Saccade	99.3 (21.7)	102 (22.2)	103 (24.1)	85.6 (23.6)	86.1 (23.9)	86.8 (24.7)
count	93.6	95.7	101	77	77.4	78.1
Saccade	141 (99.3)	141 (84.0)	149 (105)	77.3 (64.4)	71.9 (41.3)	97.9 (89.1)
duration	112.6	114.9	120.1	57.1	62.1	60.7
Blinks	26.8 (11.8)	28.4 (11.5)	26.9 (10.7)	14.7 (10.6)	15.2 (10.6)	14.3 (10.3)

Note. Fixation, saccade, and blink counts are expressed as a ratio per minute, and fixation and saccade duration are expressed in milliseconds.

Order of presentation: **mean** (*standard deviation*) median

The number of fixations per minute was higher during overt recall than during covert recall: $\chi^2(1) = 45.959, p < .001, W = 0.434$. The emotional nature of the memory had no impact on the number of fixations per minute: $\chi^2(2) = 2.344, p = 0.310, W = 0.023$. Overt recall produced shorter fixations than covert recall: $\chi^2(1) = 77.263, p < .001, W = 0.795$. The emotional nature of the memory had no impact on the number of fixations per minute: $\chi^2(2) = 1.919, p = 0.383, W = 0.026$. Overt recall produced more saccades per minute than overt recall: $\chi^2(1) = 45.959, p < .001, W = 0.434$. The emotional nature of the memory had no impact on the number of saccades per minute: $\chi^2(2) = 2.344, p = 0.310, W = 0.023$. Overt recall produced longer saccades than covert recall: $\chi^2(1) = 43.886, p < .001, W = 0.520$. The emotional nature of the memory had an extremely weak effect on saccade duration: $\chi^2(2) = 6.065, p = 0.048$, but $W = 0.078$. Given the weakness of the effect size, we decided to realize Conover's pairwise comparisons post-hoc. After applying a Bonferroni correction, no difference was found regarding saccade duration for the three emotional conditions: $t_{\text{neutral-positive}}(213) = .442, p_{\text{neutral-positive}} = 1.000$; $t_{\text{neutral-negative}}(213) = 1.139, p_{\text{neutral-negative}} = 0.768$; $t_{\text{positive-negative}}(213) = 0.697, p_{\text{positive-negative}} = 1.000$. It seems therefore reasonable to consider that the emotional nature of memory had no significant impact on saccade duration. Lastly, overt recall produced significantly more blinks than covert recall: $\chi^2(1) = 49.554, p < .001, W = 0.455$. The emotional nature of the memory had no impact on the number of blinks: $\chi^2(2) = 0.227, p = 0.893, W = 0.003$.

Figure 2. Schematic representation of eye movement characteristics during covert and overt recall.



Note. Dots represent fixations and lines represent saccades. Bigger dots represent longer fixations while longer lines represent longer saccades.

1.3.2 Memory characteristics

Memory characteristics were examined with repeated-measures ANOVAs and Friedman tests (depending on the nature of the distribution), that had recall condition (overt vs. covert recall) and emotional nature of the memory (neutral vs. positive vs. negative) as the independent variables (for descriptive statistics, see Table 2).

As data regarding the subjective scales measuring emotional accuracy and mental imagery was not normally distributed, Friedman tests were used.

Overt recall led to less emotional accuracy than covert recall: $\chi^2(1) = 8.225, p = .004, W = 0.154$. The emotional nature of the memory also had an impact on emotional accuracy: $\chi^2(2) = 54.292, p < .001, W = 0.405$. Pairwise comparisons were led and revealed that neutral and emotional memories (regardless of their nature, i.e. positive or negative) produced significantly different emotional accuracy scores: after applying a Bonferroni correction, $t_{\text{neutral-positive}}(208) = 2.663, p_{\text{neutral-positive}} = .025$; $t_{\text{neutral-negative}}(208) = 3.002, p_{\text{neutral-negative}} = .009$; $t_{\text{positive-negative}}(208) = .339, p_{\text{positive-negative}} = 1.000$. Similar results were observed regarding mental imagery.

Overt recall produced less intense mental imagery than covert recall: $\chi^2(1) = 24.429, p < .001, W = 0.338$. The emotional nature of the memory had an impact on mental imagery: $\chi^2(2) = 18.457, p < .001, W = 0.157$. Pairwise comparisons were led and revealed no significant difference between emotional conditions after applying a Bonferroni correction ($t_{\text{neutral-positive}}$

(213) = 1.882, $p_{\text{neutral-positive}} = 0.184$; $t_{\text{neutral-negative}}$ (213) = 1.122, $p_{\text{neutral-negative}} = 0.789$; $t_{\text{positive-negative}}$ (213) = 0.760, $p_{\text{positive-negative}} = 1.000$).

Retrieval duration data was normally distributed, after winsorizing the only outlier (which corresponded to the only person who used the full two minutes to recall the memory) by replacing its value with the second highest value of the data set. Regarding retrieval duration (see Figure 3 for a visual representation of the results), there was no main effect of the recall condition: $F(1,42) = 1.032$, $p = .315$. However, there was a main effect of emotion: $F(2,42) = 28.023$, $p < .001$, $\eta^2 = 0.077$; and an interaction effect : $F(2,42) = 61.035$, $p < .001$, $\eta^2 = 0.168$. For neutral and positive memories, memory duration was longer during overt recall. However, for negative memories, memory duration was longer during covert recall.

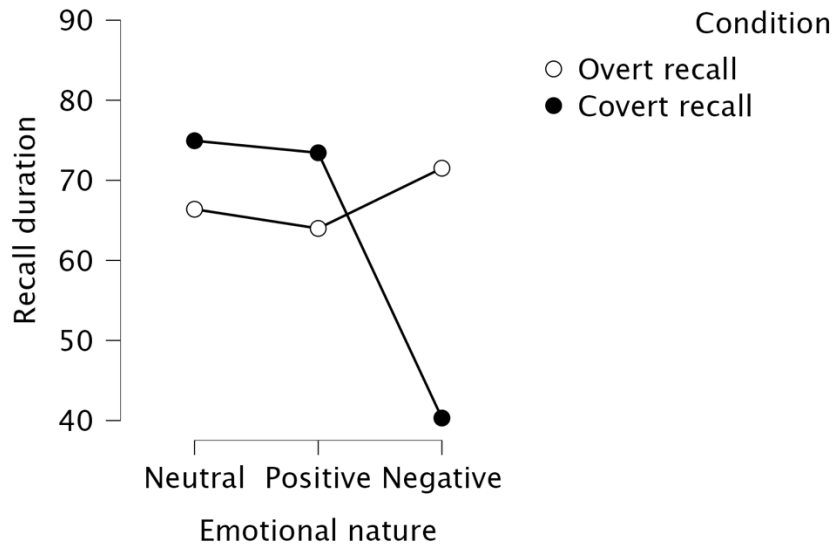
Table 2. Mean, standard deviation and median of the memory characteristics for memories elicited with neutral, positive and negative words, during overt and covert recall.

	Overt recall			Covert recall		
	<i>Neutral</i>	<i>Positive</i>	<i>Negative</i>	<i>Neutral</i>	<i>Positive</i>	<i>Negative</i>
Mental imagery	3.80 (.77) 4.00	4.05 (.69) 4.00	3.72 (.74) 4.00	3.81 (.72) 4.00	4.67 (.53) 5.00	4.47 (.77) 5.00
Emotional intensity	3.17 (.86) 3.50	3.86 (.72) 4.00	3.86 (.94) 4.00	3.19 (1.02) 3.50	4.16 (.924) 4.50	4.47 (.73) 5.0
Retrieval duration	66.4 (27.9) 66.4	64.0 (24.5) 64.0	71.5 (32.5) 71.4	74.9 (32.3) 73.6	73.4 (31.7) 68.8	40.3 (22.9) 35.4

Note. Mental imagery and emotional intensity are rated via a Likert-scale ranging from 1 to 5, and retrieval duration is expressed in seconds.

Order of presentation: **mean** (*standard deviation*) median

Figure 3. Descriptive plot representing autobiographical recall duration in function of the emotional nature of the memory and recall type.



1.3.3 Complementary analyses

We decided to proceed with complementary analyses to explore if memory characteristics could be predictors of eye movement characteristics. Spearman's rho correlation coefficients were calculated to examine the relationship between the ratings of memory characteristics and eye movement variables. There were very few significant correlations found (all correlations matrixes can be found in Annex 1, 2, 3, 4, 5 and 6).

During overt recall of negative memories, mental imagery was negatively correlated with fixation duration ($\rho = -0.41$, $p = .006$) and positively correlated with saccade duration ($\rho = 0.310$, $p = .043$), while emotional accuracy was negatively correlated with the number of blinks ($\rho = -0.324$, $p = 0.034$).

During covert recall of neutral memories, emotional accuracy was negatively correlated with saccade duration ($\rho = -0.352$, $p = .020$), while blink rate was positively correlated with saccade duration ($\rho = 0.652$, $p < .001$).

1.4. Discussion

This study sought to explore the differences in eye movements between overt and covert autobiographical recall, with memories cued by neutral, positive, and negative cue words. Results showed that covert recall led to fewer and longer fixations, as well as fewer and shorter saccades. The emotional nature of the recalled memory had no impact on eye movement

characteristics. Participants characterized covert memories as more emotionally intense and accurate, as well as more vivid in terms mental imagery. The time spent to describe negative memories, compared to neutral or positive memories, was shorter during covert recall, but longer during overt recall.

The first objective of this research was to compare overt and covert recall. While Janssen et al. (2021) used a covert recall condition, they did not compare it to overt recall. Our data (see Table 1 in the Results section) show eye movement characteristics that are relatively similar to those in Janssen et al.'s study. For example, the fixation count during the elaboration of a neutral memory was 93.0 in Janssen et al.'s study and 86.6 in ours. Fixations lasted an average of 628.8 ms in Janssen's study and 662 ms in our own. The saccade count was 95.0 in their study and 85.6 in ours. Our results somehow mirror those of Janssen et al.'s study.

Our findings have demonstrated covert recall triggered fewer and longer fixations, fewer and shorter saccades, and fewer blinks than overt recall. The fewer blinks, longer fixations and fewer fixations observed during covert recall can all be attributed to greater cognitive resources allocated to the task (see Zagermann et al., 2016, for a review). One may link this to intense mental imagery activity: indeed, participants experienced more mental images during covert recall than during overt recall. Furthermore, mental images, which are a crucial part of mental time travel, are maintained mainly by cognitive effort and fade rapidly without it (Kosslyn, 1990). Given the cognitive load implied for speech production, one could argue that during covert recall, the cognitive cost from speech production is alleviated, leading participants to allocate more resources to vivid mental time travel. However, other work has attributed long fixations to a difficult access to memory (El Haj et al., 2021; Lenoble et al., 2019): given the fact that fixation duration is considered as a measure of information processing demand (Zelinsky et al., 2013), it could thus mirror high effort to access the memory (through the search of various information). Although one cannot rule out the theory that in our study, the longer fixations and fewer blinks are linked to more difficult memory access, this does seem unlikely in view of the participants' mental imagery ratings, as they experienced covert recall as more intense in terms of mental imagery. We thus suggest that covert recall is associated with stronger mental imagery (i.e., more vivid mental images), according to objective and subjective measures (that is, eye tracking and participants' ratings of their experience of covert recall). This could make sense as overt recall may not serve the same function as covert recall. While overt recall may imply sharing memories to communicate and reach out to others, covert recall

could indicate an inner exploration and a more intimate experience. Autobiographical memory has been theorized to serve three main functions: a self-function, a social function, and a directive function. The self-function serves to maintain a sense of being the same person over time and providing oneself with knowledge of the person they were in the past, which can be related to the present and the projected future self (Bluck et al., 2005; Conway et al., 2004, 2005). The social function relies on retrieving memories to develop, maintain and enhance interindividual bonds (Alea & Bluck, 2003). The directive function involves retrieving memories to guide present and future thoughts and behavior, or to solve current problems (Bluck et al., 2005; Bluck & Alea, 2002; Cohen, 1998). In our study, while overt recall could serve a social function (which relies mainly on sharing facts with our interlocutor), covert recall could serve a self-function, and more broadly, an intense subjective experience which may trigger more mental images. It would be of interest to elucidate the functions of covert retrieval compared to memories shared with others to verify this assumption and explore its links with eye movements.

The hypothesis that covert recall may trigger more mental images must be interpreted with caution as very few correlations were found between subjective ratings and eye movement characteristics. One explanation for the lack of correlations may be a ceiling effect for mental imagery ratings. Indeed, as an example, the average rating for positive and negative memories during covert recall was 4.67 and 4.77 respectively, with 5 being the highest rating possible. This ceiling effect could have annihilated correlations. It could be due to the lack of finesse of our mental imagery scale, or even due to a rating bias between the participants. Some participants indeed expressed a degree of difficulty to evaluate how clear their mental images were, or if one memory was particularly more vivid than another. Future research should be led with more precise tools to clearly statute if intense phenomenological experience leads to a direct variation in eye movement patterns. The way we evaluated mental imagery is indeed one of the limitations of our study. Another explanation for the absence of correlation across experimental conditions could be the variety of memories recalled between participants, which do not necessarily contain equal imagery. This limitation could be challenged in future work by staging naturalistic events and exploring the eye movement characteristics triggered by retrieval (similarly to what Armson et al. did in 2021). Finally, another possibility for absence of correlations may be individual differences in autobiographical memory, which we did not control in our experiment. A study by Armson et al. (2021) showed that eye movements could predict the number of internal details recalled, but only for individuals with high trait

autobiographical memory (that is, individuals which experience episodic memories more vividly than others). Some participants within our sample could have had low trait autobiographical memory and thus present a less evident relationship between memory, mental imagery, and eye movements. Despite these limitations, our results indicate marked differences in covert and overt recall and contribute to a new field of research. Future studies could explore the involvement of spatial eye movement measures, such as saccade amplitude or fixation dispersion. One could also compare the involvement of mental imagery during covert and overt recall using neuroimaging as a complementary approach to eye tracking and studying participants' subjective experiences, so as to achieve better understanding of the intimate experience of autobiographical memory.

The second aim of this research was to take an interest in emotional memories, to explore their potential effect on eye movement characteristics. Although emotional cue words led participants to perceive memories as more intense emotionally and more vivid compared to memories triggered with neutral cue words, this did not transpire in the eye movement characteristics. This part of our study could be seen as a replication of the studies conducted by El Haj et al. (2017) and Janssen (2021). While El Haj et al. (2017) found that participants produced more fixations and saccades but had a shorter average fixation duration during emotional rather than neutral autobiographical memories, Janssen et al. (2021) did not find any significant differences when comparing both conditions. To explain the differences between these two previous studies, one could argue that El Haj et al. (2017) used overt recall while Janssen et al. (2021) used covert recall, as we know now that they produce different eye movements. Another explanation for the differences between the two previous studies could be that the eye movement characteristics of memories triggered by positive and negative cue words were averaged in both studies. As positive and negative memories seem to lead to different recollective experiences (D'Argembeau et al., 2003), we chose to differentiate them for the statistical analyses. However, no difference was found in eye movement characteristics. In the case of our study, like Janssen et al. (2021), we found no difference in the number of saccades or fixations, nor a difference in fixation duration, between emotional and neutral autobiographical memories, regardless of the recall method. It is unclear why we found these contrasting results. One possibility could be strong inter-individual and intra-individual differences in the chosen autobiographical memories. For example, for some people, positive and negative memories can be so integrated in their life story (for example, their parents divorcing when they were young) that they do not engender as much emotional intensity when

revisited. Moreover, one could argue that there is no such thing as a neutral memory. When asked to find a memory in relation to the word “city”, many people talked about a vacation with friends or family, which is typically a happy memory. Others may relate stories about harassment or aggression, which are strongly negatively connoted. These observations are in line with previous research, which has found that many memories elicited by neutral cue words are emotional (El Haj et al., 2016). This is not surprising as autobiographical memory is intimately associated with emotion (Conway, 2005). This represents a strong bias in the comparison between supposedly “neutral” and “emotional” memories and reinforces the necessity to use staged naturalistic events to control the memories which are explored by participants whilst maintaining an ecological approach. To conclude this section on emotion, it appears fixations and saccades are not yet the characteristics of choice to study the emotional experience of autobiographical recall. Pupil dilation could be considered as it is linked to emotion (Bradley & Lang, 2015), but recent studies have found that recalling neutral and emotional memories triggers similar pupil dilation (El Haj et al., 2019; Janssen et al., 2021), for similar reasons to the ones we have stated. Thus, eye tracking does not seem to be precise enough to study emotion during autobiographical recall. Techniques such as electrodermal activity (also known as galvanic skin response) combined with subjective ratings seem more appropriate (see Salgado & Kingo's work in 2019).

While eye movement characteristics do not seem to be the most appropriate tools to study emotion and autobiographical memory, our results show that memory characteristics can be an indicator of emotional experience. One interesting finding is related to the time spent recalling the memory. While neutral and positive memories were explored for a similar duration during covert and overt recall, this was not the case for negative memories. People spent more time talking about negative memories than neutral or positive ones but spent less time thinking about negative memories compared to neutral or positive ones. These results cannot be explained by the fact that we asked participants to recall the same memories during covert and overt recall (which could have produced a repetition effect), as we counterbalanced the order of the conditions. In this study, sharing negative memories with an experimenter could have produced emotional regulation and led to more time spent on the event, as talking about emotion has been proven to regulate it (Matejka et al., 2013; Pasupathi, 2003). Indeed, many participants started crying during negative overt recall (but not during negative covert recall), and the former could be associated with emotional regulation (Bylsma et al., 2019). Additionally, the fact that

people spent less time thinking about negative memories compared to positive or neutral ones may be interpreted as avoiding “going too deep” into a painful memory.

As well as having theoretical implications by contributing to understanding real-life memory, this study also has clinical implications. Indeed, by underlining that covert recall triggers specific eye movements and could facilitate memory access, we confirm that eye tracking is an interesting tool for evaluating memory function in specific populations, such as infants or patients with neuropsychological, psychiatric or neurodegenerative conditions, who do not necessarily have access to verbalization. An interesting lead for future research would be to investigate the nature of eye movements during covert recall in populations who have trouble verbalizing and are known to have degraded autobiographical memory, such as people with Alzheimer’s disease. If similar eye patterns are observed between “healthy” participants and these patients, this could mean that some memories are still stocked but are simply impossible to verbalize. Furthermore, this study could contribute to understanding the processes behind therapies which use eye movements to treat various psychological conditions such as post-traumatic stress disorder. Eye movements during memory retrieval have been shown to reduce memory vividness and emotional activation (Barrowcliff et al., 2004; Jeffries & Davis, 2013) and are being used in therapies such as Eye Movement Desensitization and Reprocessing therapy (EMDR; Shapiro, 1989) or Brainspotting (Grand, 2013). EMDR is based on the adaptive information model (Shapiro, 2018). According to this model, the memory of a traumatic event is stored in an unprocessed and maladaptive form, making it unable to connect with other memories which enable adaptive information. EMDR allows the accessing of the traumatic memory and facilitates its processing, bringing it to an adaptive resolution, through alternate horizontal eye movements. In Brainspotting, it is suggested that the direction in which people stare affects the way they feel. During therapy, the objective is to identify the “brainspot”, i.e., the visual point which appears to promote the processing of the traumatic memories. While these approaches have globally shown their efficacy (D’Antoni et al., 2022), more studies are needed to understand the true functioning of these approaches, as the concrete implication of eye movements is still questioned (for a review, see Landin-Romero et al., 2018). In these studies, the differences between covert and overt retrieval will need to be considered.

1.5. Conclusions

In this study, we showed that thinking about a memory produces significantly different eye movement patterns than when talking about a memory. We theorize that this is due to a more intense reliving experience, as more cognitive resources are allocated to memory retrieval. These findings contribute to suggesting that eye tracking could be a reliable and ecological tool to comprehend and measure autobiographical memory in everyday life, when sharing memories with others or, as we saw in this study, when retrieving memories privately. Our results more generally contribute to a blooming field which links the hippocampal and the oculomotor system together. Both systems have the same phylogenetic age and are structurally and functionally connected (Ryan & Shen, 2020), leading eye movements to play a key-role in encoding, maintaining, and as we saw in our study, retrieving memories. Our eyes move, not only to capture sensory visual information, but also to bring our memories to the surface whether to connect with oneself or with others.

Compliance with ethical standards

Funding: This research was supported by the Etoile Montante program (Pays de la Loire, France).

Conflict of interest: The authors have no financial or proprietary interests in any material discussed in this article.

Ethical approval: All procedures performed in this study were in accordance with the ethical standards of the institutional research committee (Nantes University, IRB number: IORG0011023) and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent: All participants were fully informed about the procedure of the study and gave their formal consent to participate.

Availability of data and material: The datasets generated during and/or analyzed during the current study are not publicly available as to guarantee participants' anonymity but are available from the corresponding author on reasonable request.

Credits

Joanna Gautier: Conceptualization; Methodology; Formal Analysis; Investigation; Resources; Data Curation; Writing – original draft; Writing – reviewing and editing.

Mohamad El Haj: Regular supervision and feedback at each step of the research; Writing - reviewing and editing.

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Appendices

Appendix 1. Correlation matrix between eye movement characteristics and memory characteristics during overt recall of a neutral memory.

Spearman's Correlations

Variable		fix/min TA-N	sac/min TA-N	Duration fix TA-N	Duration sac TA-N	Blinks TA-N	Emotion TA-N	Imagery TA-N	Time TA-N
1. fix/min TA-N	Spearman's rho	—							
	p-value	—							
2. sac/min TA-N	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. Duration fix TA-N	Spearman's rho	-0.815	-0.815	—					
	p-value	< .001	< .001	—					
4. Duration sac TA-N	Spearman's rho	0.186	0.186	-0.655	—				
	p-value	0.231	0.231	< .001	—				
5. Blinks TA-N	Spearman's rho	-0.133	-0.133	0.213	6.040e-4	—			
	p-value	0.392	0.392	0.170	0.997	—			
6. Emotion TA-N	Spearman's rho	-0.114	-0.114	-0.067	0.184	-0.121	—		
	p-value	0.473	0.473	0.675	0.244	0.446	—		
7. Imagery TA-N	Spearman's rho	-0.132	-0.132	0.095	-0.052	3.071e-4	0.236	—	
	p-value	0.400	0.400	0.545	0.742	0.998	0.132	—	
8. Time TA-N	Spearman's rho	0.093	0.093	-0.036	-0.066	-0.036	0.085	-0.009	—
	p-value	0.552	0.552	0.819	0.673	0.817	0.593	0.954	—

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.

Appendix 2. Correlation matrix between eye movement characteristics and memory characteristics during overt recall of a positive memory.

Spearman's Correlations

Variable		fix/min TA-P	sac/min TA-P	Duration fix TA-P	Duration sac TA-P	Blinks TA-P	Emotion TA-P	Imagery TA-P	Time TA-P
1. fix/min TA-P	Spearman's rho	—							
	p-value	—							
2. sac/min TA-P	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. Duration fix TA-P	Spearman's rho	-0.861	-0.861	—					
	p-value	< .001	< .001	—					
4. Duration sac TA-P	Spearman's rho	0.097	0.097	-0.484	—				
	p-value	0.536	0.536	0.001	—				
5. Blinks TA-P	Spearman's rho	-0.060	-0.060	0.051	0.125	—			
	p-value	0.702	0.702	0.745	0.422	—			
6. Emotion TA-P	Spearman's rho	0.017	0.017	-0.076	-0.038	-0.168	—		
	p-value	0.915	0.915	0.630	0.810	0.283	—		
7. Imagery TA-P	Spearman's rho	0.127	0.127	-0.022	-0.125	-0.053	0.196	—	
	p-value	0.418	0.418	0.891	0.426	0.738	0.209	—	
8. Time TA- P	Spearman's rho	-0.060	-0.060	0.149	-0.248	-0.020	0.063	0.181	—
	p-value	0.703	0.703	0.338	0.109	0.901	0.687	0.245	—

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.

Appendix 3. Correlation matrix between eye movement characteristics and memory characteristics during overt recall of a negative memory.

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.

Spearman's Correlations

Variable		fix/min TA-NEG	sac/min TA-NEG	duration fix TA- NEG	Duration sac TA- NEG	Blinks TA- NEG	Emotion TA-NEG	Imagery TA-NEG	Time TA- NEG
1. fix/min TA-NEG	Spearman's rho	—							
	p-value	—							
2. sac/min TA-NEG	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. duration fix TA- NEG	Spearman's rho	-0.859	-0.859	—					
	p-value	< .001	< .001	—					
4. Duration sac TA- NEG	Spearman's rho	-0.189	-0.189	-0.274	—				
	p-value	0.225	0.225	0.076	—				
5. Blinks TA-NEG	Spearman's rho	-0.136	-0.136	0.150	0.072	—			
	p-value	0.384	0.384	0.335	0.646	—			
6. Emotion TA-NEG	Spearman's rho	0.063	0.063	-0.055	0.018	-0.324	—		
	p-value	0.689	0.689	0.728	0.908	0.034	—		
7. Imagery TA-NEG	Spearman's rho	0.290	0.290	-0.410	0.310	-0.078	0.064	—	
	p-value	0.059	0.059	0.006	0.043	0.619	0.685	—	
8. Time TA-NEG	Spearman's rho	-0.180	-0.180	0.080	0.067	0.028	-0.125	-0.214	—
	p-value	0.248	0.248	0.608	0.667	0.860	0.424	0.168	—

Appendix 4. Correlation matrix between eye movement characteristics and memory characteristics during covert recall of a neutral memory.

Spearman's Correlations

Variable		fix/min TH-N	sac/min TH-N	duration fix TH-N	Duration sac TH-N	Blinks TH-N	Emotion TH-N	Imagery TH-N	Time TH-N
1. fix/min TH-N	Spearman's rho	—							
	p-value	—							
2. sac/min TH-N	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. duration fix TH-N	Spearman's rho	-0.934	-0.934	—					
	p-value	< .001	< .001	—					
4. Duration sac TH-N	Spearman's rho	0.227	0.227	-0.515	—				
	p-value	0.143	0.143	< .001	—				
5. Blinks TH-N	Spearman's rho	0.010	0.010	-0.173	0.652	—			
	p-value	0.949	0.949	0.266	< .001	—			
6. Emotion TH-N	Spearman's rho	-0.107	-0.107	0.198	-0.352	-0.212	—		
	p-value	0.494	0.494	0.204	0.020	0.172	—		
7. Imagery TH-N	Spearman's rho	-0.052	-0.052	0.103	-0.060	-0.079	0.389	—	
	p-value	0.739	0.739	0.509	0.702	0.616	0.010	—	
8. Time TH- N	Spearman's rho	0.104	0.104	-0.041	-0.178	0.193	-0.115	-0.159	—
	p-value	0.507	0.507	0.794	0.252	0.213	0.464	0.308	—

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.

Appendix 5. Correlation matrix between eye movement characteristics and memory characteristics during covert recall of a positive memory.

Spearman's Correlations

Variable		fix/min TH-P	sac/min TH-P	duration fix TH-P	Duration sac TH-P	Blinks TH-P	Emotion TH-P	Imagery TH-P	Time TH-P
1. fix/min TH-P	Spearman's rho	—							
	p-value	—							
2. sac/min TH-P	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. duration fix TH-P	Spearman's rho	-0.869	-0.869	—					
	p-value	< .001	< .001	—					
4. Duration sac TH-P	Spearman's rho	0.236	0.236	-0.521	—				
	p-value	0.127	0.127	< .001	—				
5. Blinks TH-P	Spearman's rho	0.018	0.018	-0.116	0.555	—			
	p-value	0.909	0.909	0.458	< .001	—			
6. Emotion TH-P	Spearman's rho	0.074	0.074	0.076	-0.172	-0.122	—		
	p-value	0.637	0.637	0.626	0.271	0.435	—		
7. Imagery TH-P	Spearman's rho	-0.025	-0.025	0.036	-0.050	-0.116	0.489	—	
	p-value	0.872	0.872	0.821	0.752	0.458	< .001	—	
8. Time TH- P	Spearman's rho	0.240	0.240	-0.166	-0.041	0.130	0.117	0.145	—
	p-value	0.121	0.121	0.287	0.792	0.405	0.454	0.352	—

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.

Appendix 6. Correlation matrix between eye movement characteristics and memory characteristics during covert recall of a negative memory.

Spearman's Correlations

Variable		fix/min TH- NEG	sac/min TH-NEG	duration fix TH- NEG	Duration sac TH- NEG	Blinks TH- NEG	Emotion TH-NEG	Imagery TH-NEG	Time TH- NEG
1. fix/min TH-NEG	Spearman's rho	—							
	p-value	—							
2. sac/min TH-NEG	Spearman's rho	1.000	—						
	p-value	< .001	—						
3. duration fix TH- NEG	Spearman's rho	-0.907	-0.907	—					
	p-value	< .001	< .001	—					
4. Duration sac TH- NEG	Spearman's rho	0.239	0.239	-0.551	—				
	p-value	0.122	0.122	< .001	—				
5. Blinks TH-NEG	Spearman's rho	0.047	0.047	-0.241	0.586	—			
	p-value	0.764	0.764	0.119	< .001	—			
6. Emotion TH-NEG	Spearman's rho	-0.015	-0.015	-0.022	0.134	0.013	—		
	p-value	0.926	0.926	0.889	0.393	0.937	—		
7. Imagery TH-NEG	Spearman's rho	0.140	0.140	-0.169	0.162	0.029	0.380	—	
	p-value	0.371	0.371	0.278	0.298	0.853	0.012	—	
8. Time TH-NEG	Spearman's rho	0.030	0.030	0.045	-0.215	0.125	-0.053	0.038	—
	p-value	0.849	0.849	0.775	0.165	0.422	0.737	0.808	—

Note. “TA” refers to the talking condition, i.e. overt recall. “TH” refers to the thinking condition, i.e. covert recall. “N” refers to neutral memories, “P” refers to positive memories and “NEG” refers to negative memories. “Fix-min” refers to the fixation count per minute. “Sac/min” refers to the saccade count per minute. “Duration fix” refers to fixation duration, while “saccade fix” refers to saccade duration. “Blinks” refers to the blink count per minute. “Emotion” refers to the emotional accuracy rating scale, from 1 to 5. “Imagery” refers to the mental imagery rating scale, from 1 to 5. “Time” refers to retrieval duration of the memory.