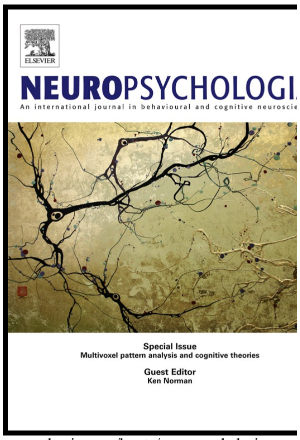

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Personal semantics: Is it distinct from episodic and semantic memory? An electrophysiological study of memory for autobiographical facts and repeated events in honour of Shlomo Bentin

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Abstract

Declarative memory is thought to consist of two independent systems: episodic and semantic. Episodic memory represents personal and contextually unique events, while semantic memory represents culturally-shared, acontextual factual knowledge. Personal semantics refers to aspects of declarative memory that appear to fall somewhere in between the extremes of episodic and semantic. Examples include autobiographical knowledge and memories of repeated personal events. These two aspects of personal semantics have been studied little and rarely compared to both semantic and episodic memory. We recorded the event-related potentials (ERPs) of 27 healthy participants while they verified the veracity of sentences probing four types of questions: general (i.e., semantic) facts, autobiographical facts, repeated events, and unique (i.e., episodic) events. Behavioral results showed equivalent reaction times in all 4 conditions. True sentences were verified faster than false sentences, except for unique events for which no significant difference was observed. Electrophysiological results showed that the N400 (which is classically associated with retrieval from semantic memory) was maximal for general facts and the LPC (which is classically associated with retrieval from episodic memory) was maximal for unique events. For both ERP components, the two personal semantic conditions (i.e., autobiographical facts and repeated events) systematically differed from semantic memory. In addition, N400 amplitudes also differentiated autobiographical facts from unique events. Autobiographical facts and repeated events did not differ significantly from each other but their corresponding scalp distributions differed from those associated with general facts. Our results suggest that the neural correlates of personal semantics can be distinguished from those of semantic and episodic memory, and may provide clues as to how unique events are transformed to semantic memory.

Keywords: Personal semantic memory, Autobiographical facts, Repeated events, Episodic memory, Semantic memory, Autobiographical Memory, ERPs, N400, LPC.

Dedication:

Shlomo was a close friend, even more than a colleague. Our friendship was bashert, a Yiddish term that is associated with meeting your soul-mate and life-partner, though I see no reason why it can’t be extended to friends. We were born about a year apart, I, in 1945, Shlomo, in 1946, in Bucharest. I lived in Ramleh, Israel, as a child, but it took until 1978 for us to meet. I was on my first sabbatical which I chose to spend in Jerusalem, and Shlomo was working on his PhD, while running (unofficially) the EEG laboratory at Hadassah Hospital where I was assigned an office.

We liked and respected each other from the beginning, and we, and our families, grew close to each other, and remain so to this day. Though I was more advanced nominally in my career, it was clear to me that Shlomo surpassed me in knowledge and technical skill, an advantage he never relinquished. He was an indefatigable worker, a generous collaborator and a selfless, caring and wise mentor whose scientific contributions, and those he fostered in his colleagues and trainees, have advanced our field greatly. In recognition of his achievements, he was awarded the Israel Prize in 2012, which delighted and gratified him.

To celebrate his receiving the Israel Prize, Shlomo invited me to give a special lecture in November at the 20th Anniversary of the Interdisciplinary Center for Neural Computation to commemorate his receiving the Israel Prize. In preparing that lecture, I thought it would be appropriate to present the results of a study that used ERPs, a measure that Shlomo began using when I first met him, and that figured prominently in his research throughout his life. Tragically, on July 13, just as his sabbatical year at Berkeley was ending, he was killed there in a vehicular accident while he was riding his bicycle safely. What was to be a celebratory event, turned into a Memorial Lecture. I reminisced about his life, and presented data from an ERP study in which, fittingly, I was a junior collaborator, as I had been in the ERP studies I published with Shlomo. The present paper, a follow-up to that study (Renoult, Davidson et al, 2015), can be considered an addendum to that lecture, and a means for continuing my relationship with Shlomo whom I miss very much.

Morris Moscovitch

Introduction

Declarative memory is typically defined as consisting of two independent systems: episodic and semantic (for reviews see Moscovitch, et al., 2005; Squire, 2004; Tulving, 2002). Episodic memory handles personal and contextually unique events, while semantic memory contains culturally-shared, acontextual factual information. Between these two extremes, however, lie several aspects of declarative memory that share some features with episodic and/or semantic memory, but may be dissociable from them. These aspects of memory are commonly referred to as personal semantics or personal semantic memory. Personal semantics is not well integrated into models of declarative memory and knowledge, in part because it has been little studied. In a recent review (Renoult, Davidson, Palombo, Moscovitch, & Levine, 2012), we noted that personal semantics has been operationalized in four main ways (autobiographical facts, self-knowledge, repeated personal events, and autobiographically-significant concepts). Here we focus on two of these: autobiographical facts and repeated personal events. We examine the event-related potential (ERP) patterns associated with processing of autobiographical facts and repeated personal events, and compare them to episodic and semantic memory.

Autobiographical facts constitute a set of personal information (e.g., I own a red bicycle; I have a diploma from McGill University), typically detached from its context of acquisition (W.F. Brewer, 1986; W.F. Brewer, 1996; M. A. Conway, 1987; Larsen, 1992; L. Renoult, et al., 2012). These autobiographical facts may form a kind of skeletal CV or autobiography (Warrington & McCarthy, 1988), which, along with some other types of personal semantics such as self-knowledge, likely plays an important role in the maintenance of a sense of self in the present moment and across time (Grilli & Verfaellie, 2015; Prebble, Addis, & Tippett, 2013). Autobiographical facts are the type of personal semantics that is evaluated in the Autobiographical Memory Interview (AMI; Kopelman, Wilson, & Baddeley, 1989), via questions about names of friends and colleagues, names of schools, addresses where one has lived, etc. The neural correlates of autobiographical facts were compared to general facts and unique events in a series of functional neuroimaging studies by Maguire and collaborators using a sentence verification paradigm (Maguire & Frith, 2003; Maguire, Henson, Mummery, & Frith, 2001; Maguire & Mummery, 1999; Maguire, Mummery, & Buchel, 2000; Maguire, Vargha-Khadem, & Mishkin, 2001). These studies showed overlap between these three types of memory in a left lateralized network, including the medial prefrontal cortex, lateral and medial temporal lobe and temporoparietal junction. The left hippocampus was more active for unique events than for the other types of memory (Maguire & Frith, 2003; Maguire & Mummery, 1999; Maguire, Vargha-Khadem, et al., 2001), whereas the left temporoparietal junction was more active for autobiographical than general facts (Maguire & Frith, 2003; Maguire & Mummery, 1999). In addition, the left medial prefrontal cortex and retrosplenial cortex showed a graded decreasing pattern of activity from unique events to autobiographical facts to general facts (Maguire & Frith, 2003; Maguire & Mummery, 1999; Maguire, Vargha-Khadem, et al., 2001).

Memories of repeated events can be viewed as constellations of separate but similar episodes. During retrieval, one would not remember a single episode, but rather the common characteristics from across the series of similar events (Neisser, 1981), similar to a personal schema (Ghosh & Gilboa, 2014). Accordingly, these memories are characterized by reduced temporal specificity, personal significance, emotionality, and detail as compared to memories of unique episodes (Addis, Moscovitch, Crawley, & McAndrews, 2004; Holland, Addis, & Kensinger, 2011; Levine, et al., 2004). However, in contrast to semantic memories, both memories of unique and repeated events have a spatial organization, that gives them their "basic context" (Rubin & Umanath, 2015). Barsalou (1988) was perhaps the first to report that a large proportion of the content of autobiographical memories concerns repeated or summarized events (e.g., I brought my brother to school every day that winter; We would always eat that cake at Thanksgiving). This seminal study and the work of Conway and colleagues suggest that repeated events play an important role in autobiographical memory retrieval, particularly to access unique episodes (M. A. Conway, 2005; M. A. Conway & Pleydell-Pearce, 2000). Despite their prevalence and importance in autobiographical memory, memories for repeated events have rarely been studied. Compared to memories of autobiographical facts (e.g., My dog is named Rex), these memories have greater contextual specificity (e.g., I used to walk Rex in "Parc La Fontaine" when I lived in Montreal) and would typically involve a 1st person rather than a 3rd person type of recall (Renoult et al., 2012). As instances of memory for events, they are likely to be less static or permanent than memories of autobiographical facts (Warrington, 1986), but perhaps not as dynamic and perceptually specific as memories of unique events (e.g., I remember where Rex slipped his leash this morning). Indeed, a relative stability or slow updating (Wagenaar, 1992) of memories of repeated events would facilitate their privileged interactions with life stories and the conceptual self (M. A. Conway, 2005; M. A. Conway & Pleydell-Pearce, 2000; see also McAdams, 2001; Neisser, 1988). Studying repeated events may provide some insight into how unique events may be transformed to facts (Winocur & Moscovitch, 2011).

Neuropsychological (St-Laurent, Moscovitch, Levine, & McAndrews, 2009; Tulving, Schacter, McLachlan, & Moscovitch, 1988) and neuroimaging findings (Addis, McIntosh, Moscovitch, Crawley, & McAndrews, 2004; Addis, Moscovitch, et al., 2004; Ford, Addis, & Giovanello, 2011; Holland, et al., 2011; Levine, et al., 2004) have shown substantial overlap in the neural correlates of unique and repeated events, notably in the medial temporal lobe (including the hippocampus) and the anteromedial prefrontal cortex, but also a number of differences. The parahippocampal gyrus and temporoparietal junction were found to be more active on the right for unique events and on the left for repeated events (Addis, Moscovitch, et al., 2004; Levine, et al., 2004). Moreover, repeated events were associated with greater lateral parietal cortex activity (BA 39 and 40) as compared to unique events (Holland, et al., 2011; Levine, et al., 2004) or general facts (Levine, et al., 2004). Activation in the hippocampus was sometimes found to be greater for unique than repeated events (Ford, et al., 2011; Holland, et al., 2011), but not always (Addis, McIntosh, et al., 2004; Addis, Moscovitch, et al., 2004; Levine, et al., 2004). Interestingly, in the study of Holland et al. (2011), in which the initial construction of memories was contrasted with their subsequent elaboration, greater hippocampal involvement for unique than repeated events was found only during the construction phase. This selective activation may explain why differential hippocampal involvement for unique as compared to repeated events has not been found in other studies using specific retrieval cues, as the presence of these cues may eliminate the need for a construction phase. Finally, in Levine et al. (2004), in which memories for repeated events were compared to both unique events and general facts, a graded decreasing pattern of activity from unique events to repeated events to general facts was observed in left anteromedial and ventrolateral prefrontal cortex, left premotor cortex and right retrosplenial cortex (see also Ford, et al., 2011). This graded pattern of activation is reminiscent to that observed in the studies of Maguire et al. using autobiographical facts, which suggests that both types of personal semantics (autobiographical facts and repeated events) can trigger intermediate degrees of neural activity in a common declarative memory network, while also involving distinct neural correlates.

Despite a renewed interest in personal semantics in recent years (Grilli & Verfaellie, 2014, 2015; Martinelli, Sperduti, & Piolino, 2012), only a handful of studies have compared personal semantics to both semantic and episodic memory. It is thus still unclear whether the neural correlates of personal semantics can be distinguished from those of semantic and episodic memory. Similarly, whether personal semantics is a unified construct or whether different forms, such as autobiographical facts and repeated events, have distinct neural bases, still remains to be determined. One might conceive of these aspects of memory as falling along a continuum of abstraction from the personal/contextually unique to the general/acontextual (see Figure 1). However, as no studies to our knowledge have directly compared memories of repeated events and autobiographical facts, the evidence is essentially indirect. In our review on personal semantics (Renoult et al., 2012), we noted that current evidence suggests greater similarity in the neural correlates of general and autobiographical facts as compared to unique events, and greater similarity of repeated and unique events, as compared to general facts. For example, in neuropsychological studies, autobiographical and general facts are often preserved together while episodic memory is impaired (Hirano, Noguchi, Hosokawa, & Takayama, 2002; Levine, et al., 1998; McCarthy, Kopelman, & Warrington, 2005; Oxbury, Oxbury, Renowden, Squier, & Carpenter, 1997; Viskontas, McAndrews, & Moscovitch, 2000) or impaired together while episodic memory is relatively preserved (Eslinger, 1998; Hodges, Patterson, Oxbury, & Funnell, 1992). Similarly, equivalent patterns of impairment of unique and repeated events along with preserved semantic memory have been described (St-Laurent, et al., 2009; Tulving, et al., 1988; see also Grilli and Verfaellie, 2015). However, a crucial factor in these comparisons is that the different types of memory are often measured in distinct tests that are not matched in task difficulty/demands (e.g., when comparing memory for facts and events in the AMI). Moreover, as no previous studies to our knowledge have directly compared autobiographical facts and repeated events, it is thus unclear whether they differ.

Insert Fig. 1 about here

The goal of the present study was to compare the neural correlates of processing of unique events, repeated events, autobiographical facts, and general facts in the same experiment. At least two methodological problems have to be solved to carry out such comparisons. First, when comparing these forms of memory, one is confronted with a qualitative gap between facts and events (L. Renoult, et al., 2012): Tasks investigating the neural correlates of unique events (episodes) often rely on detailed remembering and re-experiencing, which is associated with long response times from participants (approximately 5-10s per trial; M. A. Conway, Pleydell-Pearce, Whitecross, & Sharpe, 2002; Svoboda, McKinnon, & Levine, 2006). This is quite different from tasks that require retrieval of semantic facts, for which reaction times are often between 0.8-1.5s (Chang, 1986). A convincing comparison of memory for facts and events would ideally require comparable task demands as evidenced by similar response times.

Second, investigating personal memories often involves conducting pre-experimental individual interviews to create relevant stimuli. This complicates the execution and interpretation of the research in several ways: At the very least, it requires the use of different materials for each participant. It also creates ambiguity as to the precise content of memory retrieval, because it is difficult to be sure that participants are remembering the target personal events during testing and not recollecting their recent pre-experiment interview (Cabeza & St Jacques, 2007). One solution to this problem is to use materials that have an appropriate level of generality/commonality across participants, so that it is possible to measure personal forms of memories without using idiosyncratic materials or conducting pre-experimental interviews. One such design has recently been used in an intracranial EEG (ECoG) study by Foster, Dastjerdi, and Parvizi, (2012). These authors contrasted the response of neurons in the posteromedial cortex (which includes the posterior cingulate cortex, retrosplenial cortex, and precuneus) during autobiographical retrieval and arithmetic calculation. The autobiographical conditions used a sentence verification task that compared autobiographical facts ("self-semantic condition"; e.g., I read books often), unique events ("self-episodic condition", e,g., I read a book this week), and self-knowledge (e.g., "I am a quiet person"). Focusing on event-related changes in high-gamma power (70-180Hz), the authors observed a maximal increase in power during retrieval of unique events, a smaller increase for autobiographical facts, and a minimal response for self-knowledge. The onset of these responses ranged between 400 and 750ms after stimulus presentation. Electrodes responding maximally to unique events were found close to the splenium of the corpus callosum, including the retrosplenial cortex (see also Dastjerdi, et al., 2011). Interestingly, the retrosplenial cortex was one of the brain regions showing a graded decreasing pattern of activity from unique events to autobiographical facts to general facts in Maguire et al. fMRI studies (Maguire & Frith, 2003; Maguire & Mummery, 1999; Maguire, Vargha-Khadem, et al., 2001), and from unique events to repeated events to general facts in Levine et al. (2004).

In the present study, we adapted Foster et al.'s (2012) sentence verification paradigm to compare for the first time the neural correlates of memory for unique event, repeated events, autobiographical facts and general facts. An important advantage of the sentence verification paradigm to investigate autobiographical memory is that it is often associated with similar reaction times across conditions, making a comparison of their neural correlates less clouded by any behavioral differences (Maguire & Frith, 2003; Maguire, Henson, et al., 2001). As in Forster et al. (2012), rather than relying on individual-specific material obtained in pre-test interviews, we used statements with an appropriate level of generality/commonality to allow participants to retrieve relevant personal or general memories. Like these authors, we took advantage of the excellent temporal resolution of electrophysiological recordings. To study how personal semantics compares to semantic and episodic memory, we focused on the N400 and the late positive component (LPC) of event-related potentials (ERPs), which have been reliably associated with semantic processing (reviewed in Kutas & Federmeier, 2011) and episodic recollection (reviewed in Wilding & Ranganath, 2012), respectively. As we describe below, these ERP components have the advantage of being robust indexes of declarative memory operations, relatively independently of the type of paradigm used or of the type of cognitive strategies adopted by the participants.

The N400 is a negative deflection which develops between 200 and 500 ms after stimulus onset, with maximal amplitude at centro-parietal electrode sites, and frequently exhibits a right-sided maximum (Kutas & Federmeier, 2011). This ERP component has been studied in a variety of tasks relevant to semantic memory, such as lexical decision, semantic categorization, sentence verification and concreteness decisions (Renoult, in press). However, several studies have shown that the N400 can be elicited in tasks that do not rely on attention to semantic relations, such as tasks using masked primes and very short stimulus-onset asynchronies (SOA; Deacon, Hewitt, Yang, & Nagata, 2000; Kiefer, 2002; Misra & Holcomb, 2003; Schnyer, Allen, & Forster, 1997) or even during various sleep stages (Brualla, Romero, Serrano, & Valdizan, 1998; Ibanez, Lopez, & Cornejo, 2006; Perrin, Bastuji, & Garcia-Larrea, 2002). Neuropsychological studies report that left temporal and temporo-parietal lesions produce significant reductions in N400 amplitude, a pattern that is associated with comprehension deficits, but have no effect on the amplitude of late parietal components (Friederici, Hahne, & von Cramon, 1998; Hagoort, Brown, & Swaab, 1996; Swaab, Brown, & Hagoort, 1997).

The LPC, also known as the 'parietal old-new effect' or 'parietal EM (episodic memory) effect', is a positive deflection that develops between 400 and 800ms after stimulus onset with maximum amplitude at posterior parietal sites and frequently exhibiting a left-sided maximum. It is considered to be a reliable index of episodic recollection (Friedman & Johnson, 2000; Rugg & Curran, 2007; Voss & Paller 2008; Wilding & Ranganath, 2012). This ERP component is sensitive to the "true memory status" of an item: old items wrongly categorized as new and new items wrongly categorized as old both elicit LPC amplitudes similar to new items (R. J. Johnson, Kreiter, Russo, & Zhu, 1998; Smith, 1993; Wilding, Doyle, & Rugg, 1995). Similarly, equivalent LPC amplitudes are found no matter whether participants responded truthfully or deceptively in a task (R. J. Johnson, Barnhardt, & Zhu, 2003; Tardif, Barry, Fox, & Johnstone, 2000). Amnesic patients with bilateral lesions of the hippocampus show preserved N400 effects but an absence of LPC effects (Addante, Ranganath, Olichney, & Yonelinas, 2012; Duzel, Vargha-Khadem, Heinze, & Mishkin, 2001; Olichney, et al., 2000), consistent with the role of this ERP component in episodic memory.

In addition to N400 and LPC, we also considered the frontal N400 (FN400; also known as the mid-frontal old-new effect, Rugg & Curran, 2007). Like the N400, FN400 is a negative deflection which develops between 300 and 500 ms after stimulus onset, but unlike the N400, FN400's maximal amplitude is usually at frontal/ fronto-central sites. The functional significance of this ERP component is still debated, with some investigators contending that it reflects familiarity-based recognition (reviewed in Curran, Tepe, & Piatt, 2006; Rugg & Curran, 2007), but others proposing that it instead reflects conceptual priming (Voss, Lucas, & Paller 2012), similar to the centro-parietal N400 (Voss & Federmeier, 2011) . We included relevant frontal sites in our N400 analyses to explore the potential presence of FN400 and generate hypotheses about its role.

So far, very few ERP studies of autobiographical memory have been conducted, and those that were did not distinguish among the four categories we have reviewed, making the results open to different interpretations. In one of these studies, Johnson, Simon, Henkell, and Zhu (2011) used short autobiographical statements and showed modulations of the LPC for statements that were congruent with participants' personal experiences (see also Hu, Bergstrom, Bodenhausen, & Rosenfeld, 2015 for similar effects interpreted as P300 modulations), thus showing that this ERP component can be evoked by autobiographical in addition to (non-personal) laboratory material. This was confirmed in a study by Renoult et al. (2015), in which the LPC was found to be increased for famous names that were associated with autobiographical episodes by the participants. Importantly, results from this study also illustrate that this ERP component is sensitive to the most automatic aspects of episodic retrieval, as the presence of associated episodes was only assessed after the experiment, and was thus incidental to task performance. In another ERP study, Watson, Dritschel, Obonsawin, and Jentzsch (2007) asked participants to evaluate the self-relevance of affective words, and observed increased N400 amplitudes for stimuli that were discrepant with participants' self-concept (i.e., positive words rated as non-self-referential, or negative words rated as self-referential; see also Fields & Kuperberg, 2015). Other ERP studies have looked at the impact of self-relevance on neural activity, typically by comparing one's own name with other names (Folmer & Yingling, 1997; Muller & Kutas, 1996; Tacikowski & Nowicka, 2010), but also by comparing one's date of birth with another date (Ganis & Schendan, 2012), owned versus unowned objects (Miyakoshi, Nomura, & Ohira, 2007) or statements in the second and third person (i.e., “you” versus “he” or “she”; Fields & Kuperberg, 2012). These studies have typically reported increased amplitude of the LPC for self-relevant material (Ganis & Schendan, 2012; Miyakoshi, et al., 2007; Muller & Kutas, 1996), but also increased amplitude of the P300 component (or P3b; Folmer & Yingling, 1997; Tacikowski & Nowicka, 2010). Previous research has consistently demonstrated that P300 and LPC are distinct components (Duzel & Heinze, 2002; Friedman, 1990; Herron, Quayle, & Rugg, 2003; Rugg & Nagy, 1989; Smith & Guster, 1993), even though they may involve partly overlapping neural generators in the medial temporal lobe, including the hippocampus (Halgren, et al., 1995; Smith, et al., 1990; Smith, Stapleton, & Halgren, 1986). Self-relevant material indeed elicits activity in recollection related neural networks (Morel, et al., 2014; Viskontas, Quiroga, & Fried, 2009), but also more broadly in the fronto-parietal network also associated with P300 generation (Tacikowski, et al., 2011). Modulations of the N400 have not always been reported in these studies of self-relevance, and when they were, self-relevance was sometimes associated with an increased (Muller & Kutas 1996) or a decreased amplitude (Ganis & Shendan, 2012). Note that some of these studies may have failed to identify N400 modulations as such because they used multiple presentations of the same stimuli (e.g., one’s own name), which results in the N400 peaking substantially earlier than usual (e.g., Renoult & Debruille, 2011; Renoult, Wang, Calcagno, Prévost, & Debruille, 2012). Nonetheless, as self-relevant material could activate both personal semantics and episodic memory, modulations of both the N400 and the LPC would be expected. Even though sensitivity of the LPC to episodic autobiographical retrieval has been clearly established (Johnson et al., 2011; Renoult et al., 2015), modulation of the N400 to personal in addition to general semantics still needs confirmation and could help clarify whether personal semantics is simply a subcomponent of semantic memory or involves partly distinct neural correlates (Renoult et al., 2012).

To overcome the ambiguity of the nature of the memories probed in the previous studies, we examined how ERPs in the time windows of the N400 and the LPC would differ for responses to unique events, repeated events, autobiographical facts, and general facts. On the one hand, we hypothesized that the two types of personal semantics conditions, autobiographical facts and repeated events, by their self-relevance, should elicit modulations of the LPC, but that maximum amplitudes would be produced by the unique events condition, as this ERP component is particularly sensitive to retrieval from episodic memory (Wilding & Ranganath, 2012). On the other hand, as neuroimaging studies show an overlap in the neural substrates of autobiographical and general facts, we hypothesized that autobiographical facts would modulate the N400, but that maximum N400 amplitudes would be associated with general facts, knowing the sensitivity of this component to retrieval from semantic memory (Kutas & Federmeier, 2011). Finally, even though no prior study to our knowledge has compared the neural correlates of autobiographical facts and repeated events, we hypothesized that these two types of personal semantics would differ, with repeated events being more similar to unique events (essentially modulating the LPC; Rubin & Umanath, 2015) and autobiographical facts more similar to general facts (essentially modulating the N400; Renoult et al., 2012).

Methods

Participants

Twenty-seven right-handed participants (12 men) completed the Sentence Verification Task. They were aged between 18 and 31 years old (mean age: 23.56 ± 3.64), and with mean years of education of 15.59 ± 1.91. They had normal or corrected-to-normal vision. They were recruited through posters displayed on the campus of the University of Ottawa or word of mouth. Exclusion criteria included a history of head injury with loss of consciousness longer than 5 min, and other neurological or medical conditions known to compromise brain function, and active substance abuse. All participants signed an informed consent form approved by the Research Ethics Board of the University of Ottawa. Participants were compensated $15 per hour of participation.

Experimental Tasks

We adapted the sentence verification paradigm used by Foster et al. (2012). We replaced the “self-judgment” and “math” conditions with repeated events and general facts conditions. We modified the “self-episodic” and “self-semantic” conditions to create our unique events and autobiographical facts conditions: the original sentences were edited and new sentences were added to obtain a total of 67 sentences by condition (compared to 48 in the original study; see Appendix). In Foster et al. (2012), the “self-episodic” and “self-semantic” conditions differed only in their temporal specificity: only the former included specific temporal markers. We kept a similar logic in our study and used the same main clauses for the sentences of our 4 experimental conditions (general facts, autobiographical facts, repeated events, and unique events). The conditions differed only in two aspects: 1) The tense changed from past tense for unique events, to present perfect for repeated events, to present for facts (general and autobiographical). The type of awareness associated with semantic memory is indeed thought to be centred in the present, whereas episodic recollection is oriented towards the past (Tulving, 2001, 2002). 2) We added distinct cue words that preceded each condition and gave different degrees of temporal specificity. We used the same number of cues for each condition (6). In the unique events condition, we used specific time cues (Last night, Last week-end, This morning, This week, Today, Yesterday) to promote access to specific instances of events (e.g., "Last week-end, I watered a plant"). In the repeated events condition, we used script-like cues (When at school, When at work, When on the bus, When on vacation, When shopping, When with friends, When alone), and constrained their temporal scope by asking participants to verify sentences by thinking about events that happened repeatedly within the last year (e.g., "When on vacation, I have watered a plant"). In the autobiographical facts condition, we used general time cues (Every day, Often, Rarely, Sometimes, Usually, Very often) for participants to report what is usual for them ("Often, I water a plant"). For the general facts condition, the first-person personal pronoun (I) and the 6 cues were replaced by 6 distinct 3rd person perspectives (Everyone, Few people, Many people, Most people, No one, Some people; see Appendix for list of all sentences), and participants had to report what they thought was generally true for people in their country ("Most people water plants").

The sentences were piloted in each condition to obtain a comparable number of yes and no responses (in other words approximately 33 of each).

Procedure

Participants were seated comfortably in a dimly lit room in front of a computer screen placed 1 m from their eyes. E-Prime 2.0 was used for stimulus presentation. Cue words were displayed for 2s on a single screen, and then each word of the remaining sentence appeared individually for 200ms. The stimuli were presented on the center of a white screen and written in New Courier 12 black font. We intercalated the cues and each of the words with a 200ms white screen. The last word of the sentence appeared for 3s, punctuated with a question mark, at which time participants had 4s to decide whether each sentence was true or false (for themselves for the personal conditions and for most people for the general facts condition) using one of two keyboard keys. Each trial ended with 2s blink screen. When needed, participants took short breaks between blocks.

The 4 different experimental conditions (general facts, autobiographical facts, repeated events, and unique events) were presented in different block of trials, so that participants could maintain a specific mode of processing when verifying the sentences. Four orders for the block presentation were obtained using the Latin Square method, and these were assigned randomly to each participant. Likewise, the order of the sentences was randomized within each block.

EEG Acquisition

The Electroencephalogram (EEG) was recorded with a 63-channel active electrode system (Brain Products GmbH) embedded in a nylon cap (10/10 system extended). An additional electrode was placed under the left eye in order to monitor vertical eye movements (lower EOG). The continuous EEG signal was acquired at a 500 Hz sampling rate using a right mastoid reference. The impedance was kept below 20 kΩ. The high filter was set at 500 Hz and the time constant was 10 s. A vertical EOG was reconstructed offline as the difference between the lower EOG and FP1 activity. A horizontal EOG was constructed by subtracting F7 from F8 activity.

Offline analyses were conducted using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014), two open source toolboxes running under Matlab

7.12 (R2013a, The Mathworks). High- and low-pass filter half-amplitude cutoffs were set at 0.01 and 80 Hz, respectively. An average reference was computed offline and used for all analyses. Before averaging, trials contaminated by excessive artifacts were rejected automatically with a step function (Luck, 2005) with a voltage threshold of ± 100 µV in moving windows of 200 ms and with a window step of 100 ms. Noisy channels were interpolated using the EEGLAB function eeg_interp (spherical interpolation) . This resulted in the following average number of trials per condition: Autobiographical facts: “Yes” responses: 37 ± 5, “No” responses: 29 ± 5; General Facts: “Yes”: 37 ± 6, “No”: 29 ± 6; Repeated Events:“Yes”: 35 ± 8, “No”: 31 ± 9; Unique Events:“Yes”: 25 ± 5, “No”: 41 ± 5.

The EEG was segmented into epochs of 1 s (from -200 ms prior to, to 800 ms after the onset of the final words). ERPs were time-locked to the final word of the sentences. The amplitudes of the N400 and the LPC were measured as the mean of all data points between 300 to 500 ms and 500 to 700 ms, respectively. They were measured relative to the mean of all data points in the 200 ms pre-stimulus baseline. Electrode sites were grouped in 5 subsets: a prefrontal subset including FP1/2, AF7/8, AF3/4, a sagittal subset, including Fz, FCz, Cz, and CPz, a para-sagittal subset, including F3/4, FC3/4, C3/4, and CP3/4, a posterior parietal subset including P1/2, P3/4, and PO3/4, and a lateral subset including FT9/10, FT7/8, T7/8, TP7/8, and TP9/10 (see Figure 2).

Insert Fig. 2 about here

Statistical analyses

We ran one repeated-measures ANOVA on mean reaction times (RTs). It had memory type (4; general facts, autobiographical facts, repeated events, and unique events) and response ("yes" and "no") as within-subjects factors. Another repeated-measures ANOVA was run on response proportion (i.e., proportion of "yes"). It had memory type as within-subjects factor.

For ERP data, we ran initial repeated-measures ANOVAs with memory type (general facts, autobiographical facts, repeated events, and unique events), electrode subset (prefrontal, sagittal, para-sagittal, posterior parietal and lateral) and time window (300-500 and 500-700) as within-subject factors. For these ANOVAs, for each subset of electrode, we considered the average voltage measures across electrodes and hemispheres (please note that the sagittal subset of electrodes did not have a hemisphere factor). Subsequent repeated-measures ANOVAs were conducted with memory type, hemisphere (right vs. left) and electrode (3, 4 or 5 electrodes depending on subset) as within-subject factors. The false discovery rate (FRD) correction was applied for all these subsequent ANOVAs (Benjamini & Hochberg, 1995), using q = 0.05. Only "yes" responses were retained for the ERP analyses, as this condition was not associated with reaction times differences between memory types (see below), which allowed a more unbiased comparison of their neural correlates.

The Greenhouse and Geisser (1959) procedure was used to compensate for possible violations of the sphericity assumption associated with the electrode factor, when appropriate. In this case, the original degrees of freedom are reported together with the epsilon (E) and the corrected probability level.

For both behavioral and ERP data, partial eta-squared (η^2) is indicated as a measure of effect size.

Insert Fig. 3 about here

Results

Behavioral data: Reaction Times

Interactions between memory type and response

The repeated-measures ANOVA on mean reaction times revealed no main effect of memory type ($p > .25$) but an interaction between this factor and response ($F_{3,63} = 11.08$, $p < .001$, $\eta^2 = .34$). To further investigate the interaction, we conducted separate repeated ANOVAs for "yes" and "no" responses.

For "yes" responses, there was no main effect of memory type ($p > .25$). Mean reaction times were 1190 ms (± 265) for general facts, 1206 ms (± 243) for autobiographical facts, 1243 ms (±294) for repeated events and 1252 ms (± 266) for unique events (see Figure 3).

For "no" responses, there was a main effect of memory type ($F_{3,63} = 3.67$, $p = .02$, $\eta^2 = .15$). Further analyses showed that negative responses to autobiographical facts (1285 ms ± 275) were faster than to general facts (1374 ms ± 333; $F_{1,26} = 4.52$, $p = .04$, $\eta^2 = .16$) but tended to be slower compared to unique events (1216 ms ± 247; $F_{1,26} = 3.63$, $p = .07$, $\eta^2 = .13$). In addition, negative responses to unique events were faster than to general facts ($F_{1,26} = 10.96$, $p = .003$, $\eta^2 = .3$) and faster than to repeated events (1355 ms ± 336; $F_{1,26} = 8.87$, $p = .006$, $\eta^2 = .25$). No differences were observed between negative responses to general facts and repeated events and between negative responses to autographical facts and repeated events (all $p > .25$).

Analyses of responses for each memory type

The repeated-measures ANOVA on mean reaction times in the general facts conditions revealed a main effect of response ($F_{1,26} = 29.62$, $p < .001$, $\eta^2 = .54$), with faster reaction times for "yes" (mean: 1190 ±265) than for "no" (mean: 1374 ±333) responses. Similarly, for autobiographical facts, reaction times were faster for "yes" (mean: 1206 ±243) than for "no" responses (mean: 1285 ±275; $F_{1,26} = 6.75$, $p = .02$, $\eta^2 = .23$). The same pattern was observed for repeated events with shorter reaction times for "yes" (mean: 1243 ±294) than for "no" responses (mean: 1355 ±336; $F_{1,26} = 14.02$, $p = .001$, $\eta^2 = .36$). However, for unique events, reaction times for "yes" (mean: 1252 ±266) did not differ significantly from "no" responses (mean: 1216 ±247, p = .13).

Behavioral data: Response Proportion

The repeated measures ANOVA on response proportion (i.e., proportion of "yes") revealed a main effect of memory type ($F_{3,63} = 28.19$, $p < .001$, $\eta^2 = .56$). Further analyses showed that the proportion of "yes" responses was lower for unique events (mean proportion: 0.38 ± 0.1) than for autobiographical facts (mean number: 0.55 ± 0.1; $F_{1,26} = 125.44$, $p < .001$, $\eta^2 = .84$), general facts (0.55 ± 0.1; $F_{1,26} = 66.89$, $p < .001$, $\eta^2 = .72$) and repeated events (0.51 ± 0.1; $F_{1,26} = 34.88$, $p < .001$, $\eta^2 = .57$). There was also a trend for a greater proportion of "yes" responses for general facts than repeated events ($F_{1,26} = 3.68$, $p = .066$, $\eta^2 = .13$), but no difference between autobiographical facts and repeated events (p > .19), and between autobiographical and general facts (all p > .25).

Insert Fig. 4 about here

Electrophysiological data

For electrophysiological data, we focused our analyses on "yes" responses for which a memory trace was presumably available to participants. This condition was not associated with reaction times differences between memory types (see above), which allowed a more unbiased comparison of their neural correlates.

To verify that the different types of memory affected the ERP components differently, we conducted an initial analysis including memory type (general facts, autobiographical facts, repeated events, and unique events), electrode subset (sagittal, para-sagittal, posterior parietal, lateral and prefrontal) and time window (300-500 and 500-700). This produced a significant interaction between these three factors ($F_{12,312} = 2.44$, $p = .005$, $\eta^2 = .083$)[1]. Subsequent analyses revealed that the interaction between memory type and electrode subset was significant in both the N400 ($F_{12,324} = 2.31$, $p = .008$, $\eta^2 = .079$) and the LPC ($F_{12,324} = 2.21$, $p = .025$, $\eta^2 = .13$) time windows. We then broke down analyses of memory effects in subsequent 3-way ANOVAs (memory type x electrode x hemisphere) separately for each time window and electrode subset, followed by pairwise comparisons of memory types for the subsets of electrodes for which the main effect of memory type was significant. For all these analyses, we applied correction for multiple comparisons using the false discovery rate (FDR; Benjamini & Hochberg, 1995), with q = 0.05.

Insert Fig. 5 about here

[1] The same analysis on "no" responses produced no significant interaction (*p* = .45).

N400 time window (300 to 500)

The repeated-measures ANOVAs on the mean voltage amplitudes in the N400 time window showed a main effect of memory type (corrected threshold of significance using FDR: q* = 0.04) at sagittal ($F_{3,78}$ = 3.27, p = .033, η^2 = .11), para-sagittal ($F_{3,78}$ = 3.48, p = .028, η^2 = .12), posterior parietal ($F_{3,78}$ = 10.10, p < .001, η^2 = .40), and lateral ($F_{3,78}$ = 4.82, p = .011, η^2 = .15) subsets of electrodes, but not at the prefrontal subset (see Figure 4). In addition, there was an interaction between memory types and the electrode factor at the sagittal subset of electrodes ($F_{9,234}$ = 2.52, p = .039, η^2 = .10). Further analyses showed that the effect of memory type was significant at Cz ($F_{3,78}$ = 4.08, p = .020, η^2 = .13) and CPz ($F_{3,78}$ = 5.42, p = .004, η^2 = .17) but not at Fz and FCz (p ≥.13), illustrating its centro-parietal distribution. Overall, the amplitude of N400 was maximal at CPz followed by Cz for the general facts condition. As illustrated by Figure 5, the N400 had a classic right-centro-parietal distribution for general facts.

To further investigate how memory types differed, we then compared each type of memory in separate repeated-measures ANOVAs for the subsets of electrodes for which the main effect of memory type was significant, using the FDR correction (corrected threshold of significance: q* = 0.02).

Insert Fig. 6 about here

General Facts versus Autobiographical Facts

General facts were associated with more negative amplitudes than autobiographical facts at the sagittal ($F_{1,26}$ = 8.54, p < .001, η^2 = .24) and posterior parietal subsets of electrodes ($F_{1,26}$ = 7.66, p = .014, η^2 = .34; see Figures 4, 6 and 7). In contrast, general facts tended to produce less negative amplitudes than autobiographical facts at the lateral subset ($F_{1,26}$ = 5.73, p = .024, η^2 = .18).

General Facts versus Repeated Events

General facts produced more negative amplitudes than repeated events the posterior parietal subset of electrodes ($F_{1,26}$ = 6.76, p = .020, η^2 = .31; see Figures 4 and 6). A similar effect at the sagittal subset ($F_{1,26}$ = 3.51, p = .036, η2 = .12) did not survive correction for FDR. Over posterior parietal electrodes, the difference between general facts and repeated events appeared more pronounced over the right than the left hemisphere (see Figures 6 and 7B) but the interaction between memory type and hemisphere did not reach the threshold of the corrected level of significance ($F_{1,26}$ = 3.36, p = .05, η^2 = .18).

Conversely, general facts produced less negative amplitudes than repeated events at the lateral subset of electrodes ($F_{1,26}$ = 8.10, p = .008, η^2 = .23). At this subset, there was an interaction between memory type, electrode and hemisphere ($F_{4,104}$ = 3.57, p = .020, η^2 = .12). Further analyses showed that general facts produced less negative amplitudes than repeated events at T7/T8 ($F_{1,26}$ = 5.67, p = .02, η^2 = .17), FT9/10 ($F_{1,26}$ = 9.96, p = .004, η^2 = .27) and at FT7/8 ($F_{1,26}$ = 11.98, p = .002, η^2 = .31; see Figures 6 and 8).

Insert Fig. 7 about here

General Facts versus Unique Events

General facts produced more negative amplitudes than unique events at sagittal ($F_{1,26}$ = 4.76, p = .017, η^2 = .15), para-sagittal ($F_{1,26}$ = 11.15, p = .002, η^2 = .29), and posterior parietal subsets of electrodes ($F_{1,26} = 42.33$, $p < .001$, $\eta^2 = .74$), but less negative amplitudes at the lateral subset ($F_{1,26} = 6.09$, $p = .020$, $\eta^2 = .18$; see Figure 4). At the lateral subset ($F_{4,104} = 3.63$, $p = .017$, $\eta^2 = .12$), an interactions between memory type and electrode was found. Further analyses showed that general facts were associated with less negative amplitudes than unique events at FT9/10 ($F_{1,26} = 10.34$, $p = .003$, $\eta^2 = .27$) and FT7/8 ($F_{1,26} = 10.69$, $p = .003$, $\eta^2 = .28$; see Figure 8).

Autobiographical Facts versus Unique Events

Autobiographical facts were associated with more negative amplitudes than unique events at the posterior parietal subset of electrodes ($F_{1,26} = 8.06$, $p = .012$, $\eta^2 = .35$; see Figure 4 and 7B). In contrast, these memory types did not differ at the sagittal, para-sagittal and lateral subsets of electrodes ($p \geq .22$).

Repeated Events versus Unique Events

Repeated events tended to be associated with more negative amplitudes than unique events at the posterior parietal subset of electrodes ($F_{1,26} = 5.65$, $p = .031$, $\eta 2 = .27$; see Figure 4). However, this effect did not survive correction for FDR. These memory types did not differ at the sagittal, para-sagittal and lateral subsets of electrodes ($p \geq .18$).

Autobiographical Facts versus Repeated Events

Autobiographical facts and repeated events did not differ for any of the subsets of electrodes (all ps > .25).

Insert Fig. 8 about here

LPC time window (500 to 700)

The repeated-measures ANOVAs on the mean voltage amplitudes in the LPC time window showed a main effect of memory type at the posterior parietal subset of electrodes ($F_{3,78} = 6.78$, $p = .001$, $\eta^2 = .31$, see Figure 4). At the sagittal ($F_{3,78} = 3.78$, $p = .021$, η2 = .12) and para-sagittal ($F_{3,78} = 2.71$, $p = .05$, η2 = .15) subsets, similar effects did not survive correction for FDR (corrected threshold of significance: q* = 0.01).

Overall, the amplitude of the LPC was maximal at P1 and PO3 for the unique events condition. As illustrated by Figure 9, the LPC had a classic left posterior-parietal distribution for unique events.

To further investigate how memory types differed, we then compared each type of memory in separate repeated-measures ANOVAs at the posterior parietal subset of electrodes for which a significant effect of memory type was found, using the FDR correction (corrected threshold of significance: q* = 0.025).

Insert Fig. 9 about here

At the posterior parietal subset of electrodes, mean voltage amplitudes in the LPC time window were greater for unique events than general facts ($F_{1,26} = 14.48$, $p = .002$, $\eta^2 = .49$). They were also greater for autobiographical than general facts ($F_{1,26} = 8.04$, $p = .013$, $\eta^2 = .35$) and for repeated events than general facts ($F_{1,26} = 8.27$, $p = .012$, $\eta^2 = .35$; see Figure 4). However, even though LPC amplitudes tended to be more positive for unique than repeated events ($F_{1,26} = 5.36$, $p = .035$, $\eta^2 = .26$), and for unique events than autobiographical facts ($F_{1,26}$ = 3. 41, $p = .046$, $\eta^2 = .18$; see Figures 4 and 10), these effect did not survive correction for

FDR. Finally, the two types of personal semantics (i.e., repeated events and autobiographical facts) did not differ in the LPC time window ($p < .1$).

Insert Fig. 10 about here

Discussion

To our knowledge, this is the first ERP study to compare the neural correlates of personal semantics to both semantic and episodic memory. Using a sentence verification task, we have found that the neural correlates of personal semantics can be differentiated from those of the two main types of declarative memory, episodic (i.e, unique events) and semantic memory (i.e., general facts).

For all types of memory except unique events, true sentences were verified faster than false. When the sentence verification paradigm is used to assess general facts, true statements are generally verified faster than false ones (reviewed in Chang, 1986). A similar effect was observed here for the two types of personal semantics: statements congruent with personal experience were verified faster than were incongruent statements. As in the present study, Conway (1987) observed that true general or personal statements were verified faster than untrue general or personal false statements. Moreover, reaction times to primed general or personal facts were faster than to unprimed general or personal facts. The presence of priming and congruency effects for personal knowledge suggests some similarity in structural organization to general knowledge. Conway (1987) proposed that knowledge of autobiographical facts could be represented along with general knowledge or indexed by it. Interestingly, using similar stimuli as in Conway (1987), Conway and Bekerian (1987) found no priming effects for specific autobiographical experiences, consistent with the absence of difference in reaction time between true and false unique events in the present study. Note, however, that context-specific cues such as "lifetime periods" (e.g., school days) or goal-derived categories ("means to travel to a holiday location") did prime retrieval of memories of unique events (Conway, 1990; Conway & Bekerian, 1987; Reiser, Black, & Abelson, 1985). Taken together, these studies show similarities in the organization of personal and general semantics, and also some differences between the organization of both types of semantics and episodic memory.

Crucially, for true sentences, no difference in reaction times was observed between memory types in the present study. This is important as it ensures that the four types of memory were equated in terms of retrieval demands, thus rendering it unlikely that differences in behavioral performance could have influenced the differences in ERPs.

Our electrophysiological results showed that, as hypothesized, the amplitude of N400 was maximal for general facts. It reached its maximal value at centro-parietal-sites (Cz and CPz), consistent with the typical distribution of this component (Kutas & Federmeier, 2011). N400 amplitude was significantly reduced for autobiographical facts and repeated events and minimal for unique events. The greatest difference between general and autobiographical facts was observed over sagittal electrode sites, whereas the greatest difference between general facts and repeated events occurred at posterior parietal sites. Over lateral sites for which the amplitude of the N400 is typically reduced (e.g., Kutas & Hillyard, 1982), all the personal conditions (autobiographical facts, repeated events, and unique events) produced more negative amplitudes than general facts, especially at fronto-temporal sites (FT7/8, FT9/10). Bearing in mind the poor spatial resolution of the EEG and the absence of source localization, these results are reminiscent of neuroimaging findings of greater activation of brain regions such as the temporal pole and medial frontal cortex for personal forms of memory as compared to general facts (Maguire & Frith, 2003; Maguire & Mummery, 1999; Renoult et al., 2012). In future, our paradigm could be run with fMRI to compare the patterns of activation associated with autobiographical facts, repeated events, and episodic and semantic processing.

As hypothesized, the LPC (or parietal old-new effect; Wilding & Ranganath, 2012), associated with retrieval from episodic memory, reached its maximal values at posterior parietal sites (P1 and PO3) for unique events. At these sites, it was significantly reduced for general facts. These results are in agreement with a recent study by Johnson et al. (2011), who reported a greater LPC effect for true autobiographical statements compared to general facts. As observed in the N400 time window, both personal semantics conditions were associated with more positive voltage amplitudes than general facts. Under a liberal threshold ($p < 0.05$, uncorrected), LPC amplitudes were also greater for unique events than for both types of personal semantics. These differences were observed over posterior parietal sites, where this component is usually maximal (Rugg & Curran, 2007; Wilding & Ranganath, 2012).

Interestingly, contrary to our hypothesis, no difference in the neural correlates of memory for autobiographical facts and repeated personal events was observed in any of the analyses. Even though no study to our knowledge had directly compared the neural correlates of these types of memory before, this finding is compatible with certain conceptualizations of them belonging to the same category of "semantic autobiographical memory" (e.g., Martinelli et al., 2012). By their very nature of being repeated, memories of repeated events are more extended in time than unique events. It is possible that when such events are repeated over a very long period of time, they may end up being similar to autobiographical facts, which are acontextual and usually more abstract, constituting a transition stage in one type of transformation of episodic memories to schemas (Ghosh & Gilboa, 2014) or to facts and semantic memory (Winocur & Moscovitch, 2011). It is thus important to note that the similarity between autobiographical facts and repeated events in our study was observed despite the fact that we limited the category of repeated events to the last year. If anything, this manipulation should have decreased the similarity between autobiographical facts and repeated events, and increased the similarity between repeated and unique events. Yet, it is possible that the use of everyday scenarios rather than statements taken from individual interviews may have made the retrieval of repeated events more similar to that of autobiographical facts. While this is a possibility, it is important to specify that these general statements still resulted in general semantics differing from the two aspects of personal semantics.

More generally, the sentence verification paradigm has sometimes been criticized because even when the sentences are based on personal events, the act of verification does not necessarily require subjective re-experiencing, and even if this occurs it is not assessed (e.g., M. A. Conway, et al., 2002; Graham, Lee, Brett, & Patterson, 2003). In a review of these studies, Maguire (2001) nevertheless argued that participants in her experiments typically reported that the sentences evoked the recall of the original unique events. While we did not obtain detailed ratings from our participants allowing us to make such statement, we found that the LPC, associated with episodic recollection (Wilding & Ranganath, 2012), was maximal over posterior parietal sites when participants verified statements based on unique events, as compared to when they verified general facts. The LPC was also greater when they verified statements based on autobiographical facts or repeated events as compared to general facts. Although autobiographical fact and repeated personal events were also distinguished from unique events, the comparison did not survive correction for multiple comparisons. Such findings indicate that retrieval of personal semantics likely engages episodic memory to some extent (Westmacott & Moscovitch, 2003), a process which is reflected in LPC amplitude. Consistent with this interpretation, we did not find any frontal effect similar to the FN400, often associated with familiarity (reviewed in Curran, Tepe, & Piatt, 2006). This constitutes indirect evidence that the events were recollected rather than simply familiar to the participants. Crucially, the major advantage of the sentence verification paradigm is that it allows us to optimally match conditions on task difficulty and retrieval demands. In the present study, no response time differences between conditions were observed when participants reported that the sentences were congruent with their personal experience (‘yes” responses).

While the use of paradigms involving rich and detailed episodic recollection is of crucial importance to better understand episodic memory, these paradigms may not necessarily constitute optimal contrasts with semantic memory. Moreover, the use of everyday autobiographical memories, as in the present study and in Foster et al. (2012), allows participants to enter different retrieval orientations (Rugg & Wilding, 2000), without the need to conduct pre-experimental interviews and to use different materials for each participant. Here, we chose to rely on the same sentence clauses across the four conditions and to add distinct cue words that preceded each condition and gave different degrees of temporal specificity: from specific time cues for unique events (e.g., “Last week-end, I watered a plant”), script-like cues for repeated events (e.g., “When on vacation, I have watered a plant”), general time cues for autobiographical facts (“Often, I water a plant”) and no time cues but the same number of 3rd person perspectives for general facts (“Most people water plants”). The tense of the sentences also changed from past for unique events, present perfect for repeated events, to present for facts (general and autobiographical). This was done as the type of awareness associated with semantic memory is thought to be centered in the present, whereas episodic recollection is oriented towards the past (Tulving, 2001, 2002). We considered the cues and tense used to be crucial to the adoption of different retrieval orientations as the clauses were otherwise identical.

Moscovitch and colleagues proposed a two-stage recollection process, with the first being fast and non-conscious, and the second one being slower and conscious (Hannula & Ranganath, 2009; Moscovitch, 2008; Sheldon & Moscovitch, 2010). In sentence verification paradigms like ours, it is unclear whether participants only rely on the first stage to come up with their decisions, that is, distinct types of ecphories (i.e., automatic interactions between the sentences and a corresponding memory trace; Tulving, 1983) or also on the second stage involving conscious and effortful re-experiencing. The first stage would involve the hippocampus, while the second would depend on interactions between the prefrontal and parietal cortex with the hippocampus. Neuroimaging studies of autobiographical memory are consistent with the importance of the hippocampus in the first stage, as hippocampal activity would typically peak during early recovery of the memory trace and then decline during the re-experiencing phase (Cabeza & St Jacques, 2007; Daselaar, et al., 2008; Sheldon & Levine, 2015; Vilberg & Rugg, 2012). The present ERP effects may be tapping into both types of recollections or only the former. Future studies, along the lines of Sheldon and Moscovitch (2010) and Hannula and Ranganath (2009) are needed to determine which is the case.

In our review on personal semantics (Renoult, et al., 2012), we concluded that the extant literature supported the idea that the neural correlates of autobiographical facts would be similar to general facts, and those of repeated events would be similar to unique events, and that studies contrasting these four types of memory were needed. Even though our results show a significant overlap in the scalp distribution of general and autobiographical facts, particularly over centro-parietal sites, the neural correlates of these types of memory could clearly be differentiated both in the N400 and LPC time windows. In the N400 time window, general facts were associated with more negative amplitudes than autobiographical facts at sagittal and posterior parietal sites, while autobiographical facts produced more negative amplitudes than general facts at lateral sites, especially at fronto-temporal sites. In the LPC time window, autobiographical facts were associated with more positive amplitudes than general facts over posterior parietal sites. In agreement with Renoult et al. (2012) taxonomy, the neural correlates of repeated events did not consistently differ from those of unique events. Similarly to Addis et al. (2004), differences only emerged when using a liberal threshold ($p < 0.05$, uncorrected). In these conditions, repeated events were associated with more negative amplitudes than unique events over posterior parietal sites, both in the N400 and LPC time windows. In any case, repeated events could clearly be more easily distinguished from general facts than from unique events. The scalp distribution observed for memories of repeated events in the LPC time window was indeed similar to that usually observed for episodic retrieval (e.g., old-new effects) and here for unique events. In fMRI studies, activation of the hippocampus was sometimes reported to be greater for unique than repeated events (Ford, et al., 2011; Holland, et al., 2011), but not always (Addis, McIntosh, et al., 2004; Addis, Moscovitch, et al., 2004; Levine, et al., 2004). Further studies are thus needed to specify how the neural correlates of memories of repeated events differ from those of unique events. As we note below, one possible factor to explain a certain inconsistency in the difference between unique and repeated events is that it is possible that some memories of repeated events evoked recollective experiences, while others do not (Renoult, et al., 2015)

Three broad conceptualizations of personal semantics were proposed in our review (Renoult et al, 2012): 1) that personal semantics could be a sub-domain of semantic memory, 2) that declarative memory could be organized according to a continuum of abstraction from abstract/acontextual to personal/contextual and 3) that PS, semantic and episodic memory could involve a different weighting of different component processes (see Cabeza & Moscovitch, 2013 on process-specific alliances). While the present results cannot be used to definitively decide between these views, a number of observations can be made. First the apparent graded ERP modulations observed for the four types of memory appear, at first view, compatible with a continuum model. Both ERP components were sensitive to the continuum of abstraction from general/acontextual (general facts) to personal/acontextual or personal/contextually repeated information (autobiographical facts and repeated events), to personal and contextually unique information (unique events). Brain regions sensitive to such a continuum of temporal specificity have been described by a number of fMRI studies. They include regions such as the medial prefrontal cortex and retrosplenial cortex that show a graded decreasing pattern of activity from unique events to autobiographical facts to general facts (Maguire & Frith, 2003; Maguire & Mummery, 1999; Maguire, Vargha-Khadem, et al., 2001) and from unique events to repeated events to general facts (Levine, et al., 2004). However, our results are also compatible with a component process perspective (Cabeza & Moscovitch, 2013; Moscovitch, 1992). Memory for general facts and for unique events were essentially associated with modulations of different ERP components: The N400 was maximal for general facts and minimal for unique events, while the LPC was maximal for unique events and not really apparent for general facts. There would thus be a qualitative gap between these two poles as only episodic memory would rely on processes such as self-reflection, detailed sensory-perceptual imagery, or chronological re-experiencing. Besides, the fact that all the personal conditions (autobiographical facts, repeated events and unique events) produced greater amplitudes than general facts at anterior temporal sites during the time window of the N400 could indicate that these personal forms of memory involved greater weighting of a common component process, perhaps involved in self-reflection or in extracting the more idiosyncratic aspects of semantic information (Ross & Olson, 2011; Tranel, 2009).

The present findings indicate that the neural correlates of personal semantics can be differentiated from semantic and episodic memory. Crucially, we observed this using a design that could have minimized these differences: the sentences we used were very closely matched between conditions and no reaction time differences were associated with these neural differences. Personal semantics thus really appears as an intermediate form of memory: memories of autobiographical facts were associated with modulations of the N400 with amplitudes falling halfway between the two extremes constituted by general facts and unique events. Similar observations were made for memories for repeated events and in the LPC time window, using a liberal threshold ($p = 0.05$). Our results, therefore, show that personal semantics has shared neural bases with both semantic and episodic memory, while being distinguishable from each of these types of memory. It will be important in the future to integrate these intermediate forms of memory into more comprehensive models of declarative memory.

One possible challenge will be the potential heterogeneity of personal semantics, not only across its four operational definitions (i.e., autobiographical facts, self-knowledge, repeated personal events, and autobiographically-significant concepts), but also within each of these categories. For example, in a review of studies of amnesia following medial temporal lobe damage, Grilli and Verfaellie (2014) noted that roughly half of patients with isolated MTL lesions (14 out of 26) had impaired memory for autobiographical facts. A similar proportion was observed for patients with lesions restricted to the hippocampus (7 impaired out of 15). Certain autobiographical facts and memories of repeated events may be experience-near and bound to unique episodic memories (Renoult, et al., 2015; Westmacott, Black, Freedman, & Moscovitch, 2004; Westmacott & Moscovitch, 2003), while other may be more abstract and similar to general facts. One could thus argue that the observation that memories of autobiographical facts and repeated events were associated with intermediate modulations of N400 and LPC as compared to general facts and unique events, could be due to this heterogeneity. It will thus be important to measure phenomenological properties of individual memories such as their vividness (Sheldon & Levine, 2013) and associated subjective experience (Gardiner, 2001; Tulving, 1985) in future studies to control for this potential heterogeneity of personal semantics.

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Figures

Figure 1. A continuum of abstraction in memory content. In this figure, two types of personal semantics are represented alongside semantic and episodic memory with a continuous color code, illustrating that, conceptually, they form a type of continuum of abstraction from the personal/contextually unique (unique events) to the general/acontextual (general facts). As discussed in Renoult et al. (2012), it is yet unknown whether this continuum is materialized in differential (graded) involvement of a common network of brain regions or in different sets of brain regions for the different types.

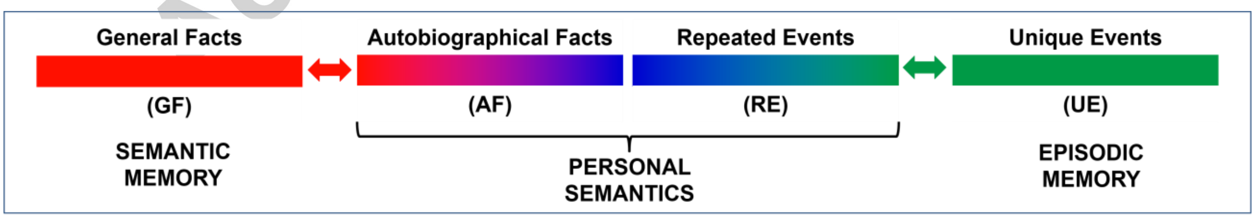


Figure 2. Scalp location of the regions of interest (ROIs). Electrode sites were grouped into 5 subsets: Prefrontal: Light red; Sagittal: Yellow; Posterior-parietal: Grey; Para-sagittal: Brown; Lateral: Blue.

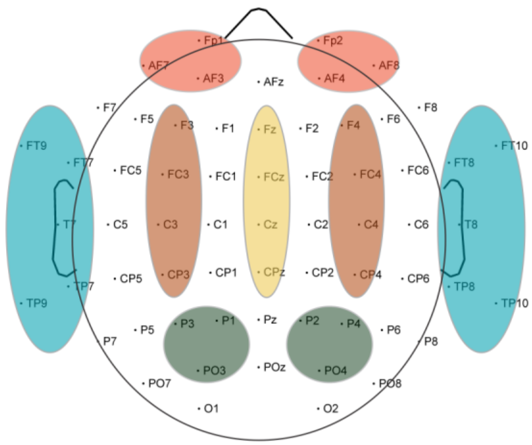


Figure 3 Mean reaction times (RTs) and standard-error bars in the 4 experimental conditions (in ms). GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events; UE: Unique Events.

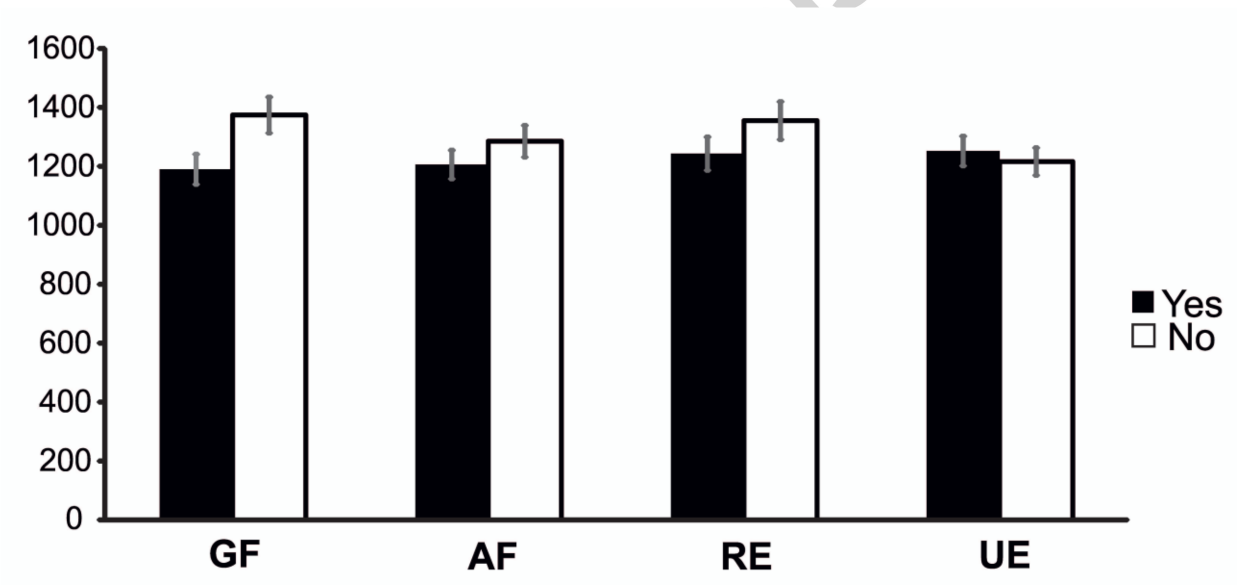


Figure 4. Grand average ERPs (N=27) to the final words of the sentences (for "yes" responses). ERPs were averaged across the electrodes of the prefrontal (A), sagittal (B), posterior parietal (C), para-sagittal (D) and lateral (E) subsets. GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events; UE: Unique Events. Negative voltage is plotted upwards.

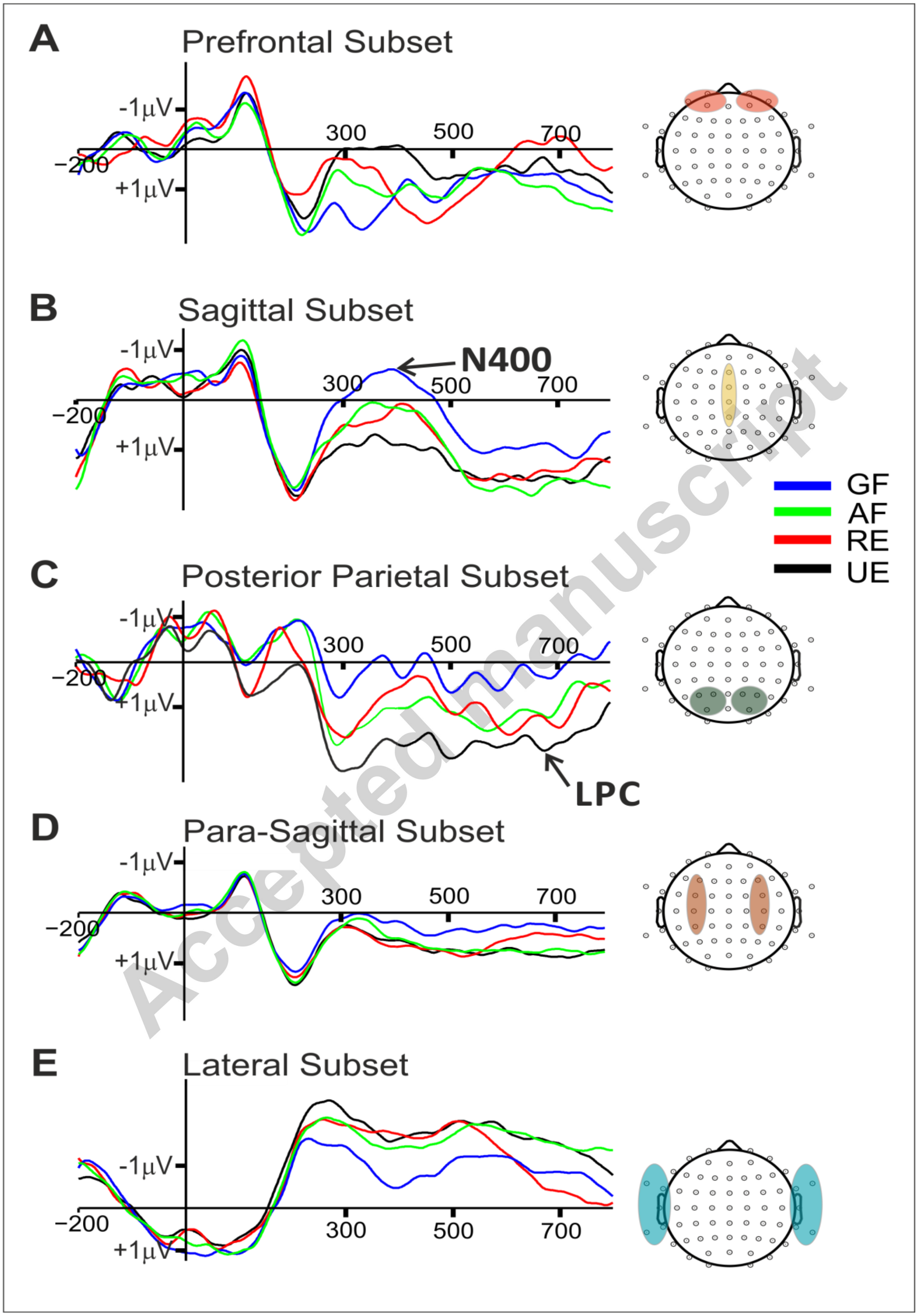

A
Prefrontal Subset
-1μV
+1μV
−200
300
500
700
B
Sagittal Subset
N400
C
Posterior Parietal Subset
LPC
D
Para-Sagittal Subset
E
Lateral Subset
GF
AF
RE
UE

Figure 5. Spline interpolated isovoltage maps for the condition “general facts” in the N400 time window (300-500). This map was obtained by subtracting the mean voltage of the grand mean ERPs evoked across the AF, RE and UE conditions from the mean voltage evoked in the GF condition. GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events, UE: Unique Events.

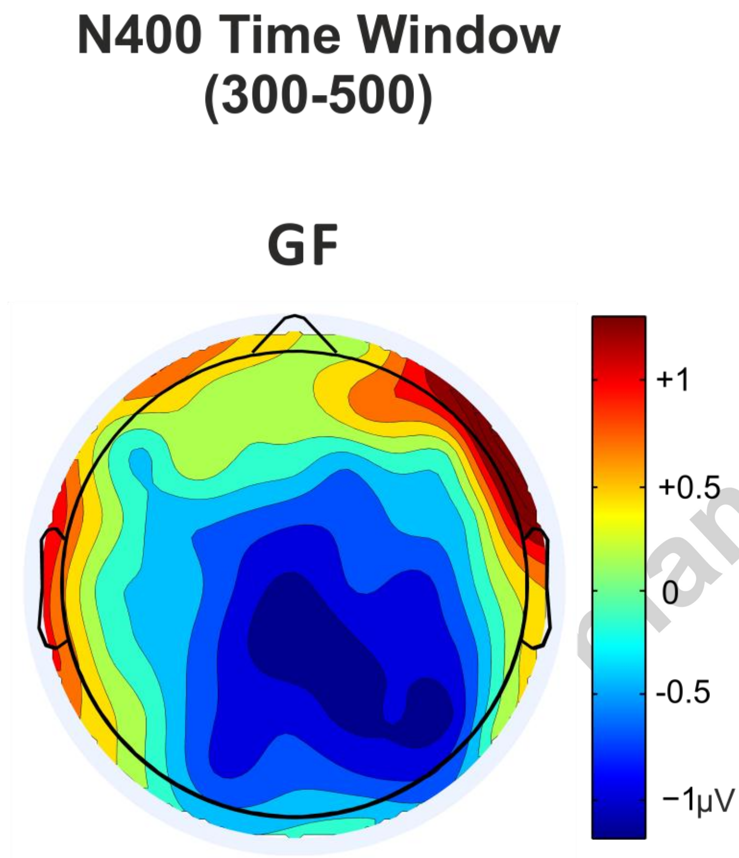


Figure 6. Spline interpolated isovoltage maps for the conditions “autobiographical facts” and “repeated events” in the N400 time window (300-500). Each map was obtained by subtracting the mean voltage of the grand mean ERPs evoked by the GF condition from those evoked in each condition (AF and RE). GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events.

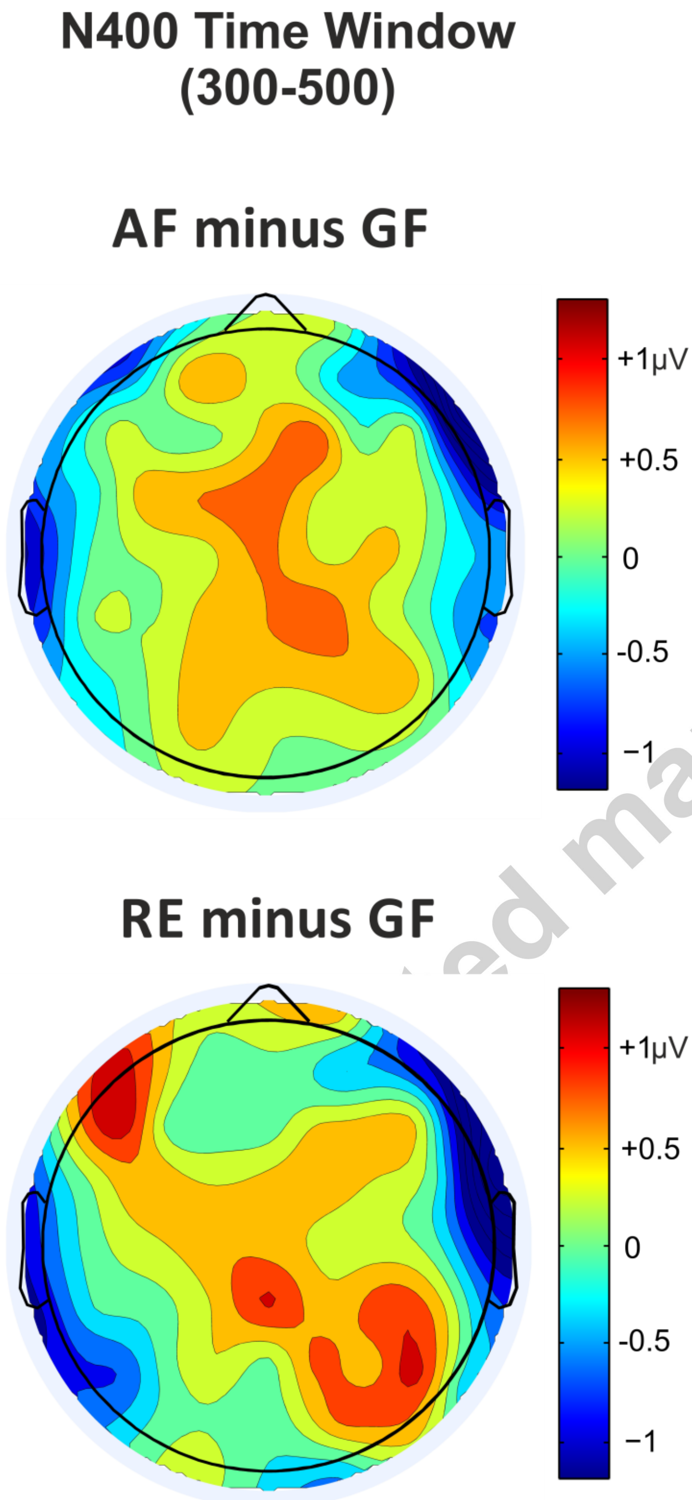

N400 Time Window
(300-500)
AF minus GF
+1μV
+0.5
0
-0.5
−1
RE minus GF
+1μV
+0.5
0
-0.5
−1

Figure 7 Grand average ERPs (N=27) to the final words of the sentences (for "yes" responses) showing some of the individual electrodes composing the sagittal (A), posterior parietal (B), and para-sagittal (C) subsets. GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events; UE: Unique Events. Negative voltage is plotted upwards.

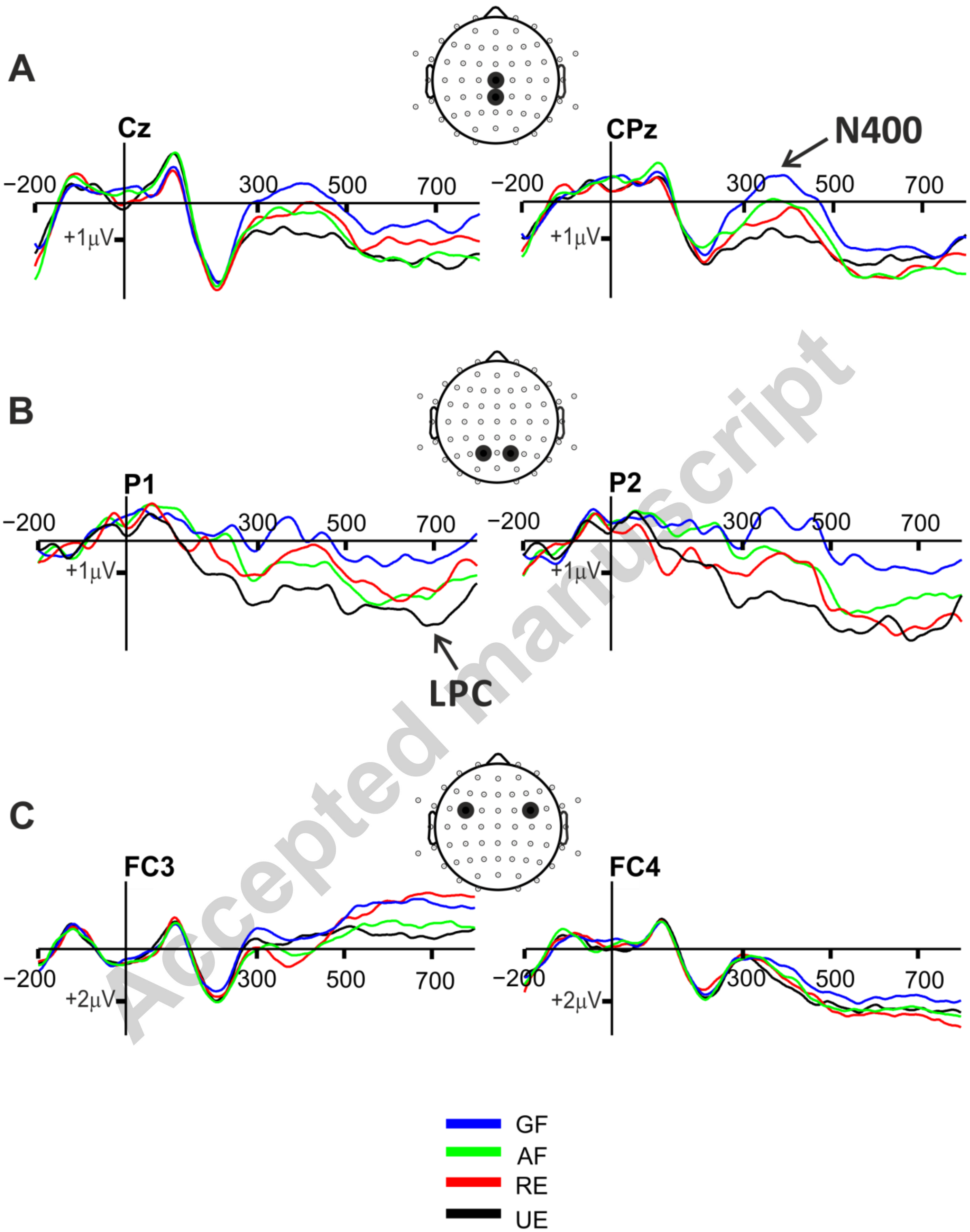


Figure 8. Grand average ERPs (N=27) to the final words of the sentences (for "yes" responses) showing some of the individual electrodes composing the lateral subset of electrodes. GF:

General Facts, AF: Autobiographical Facts, RE: Repeated Events; UE: Unique Events. Negative voltage is plotted upwards.

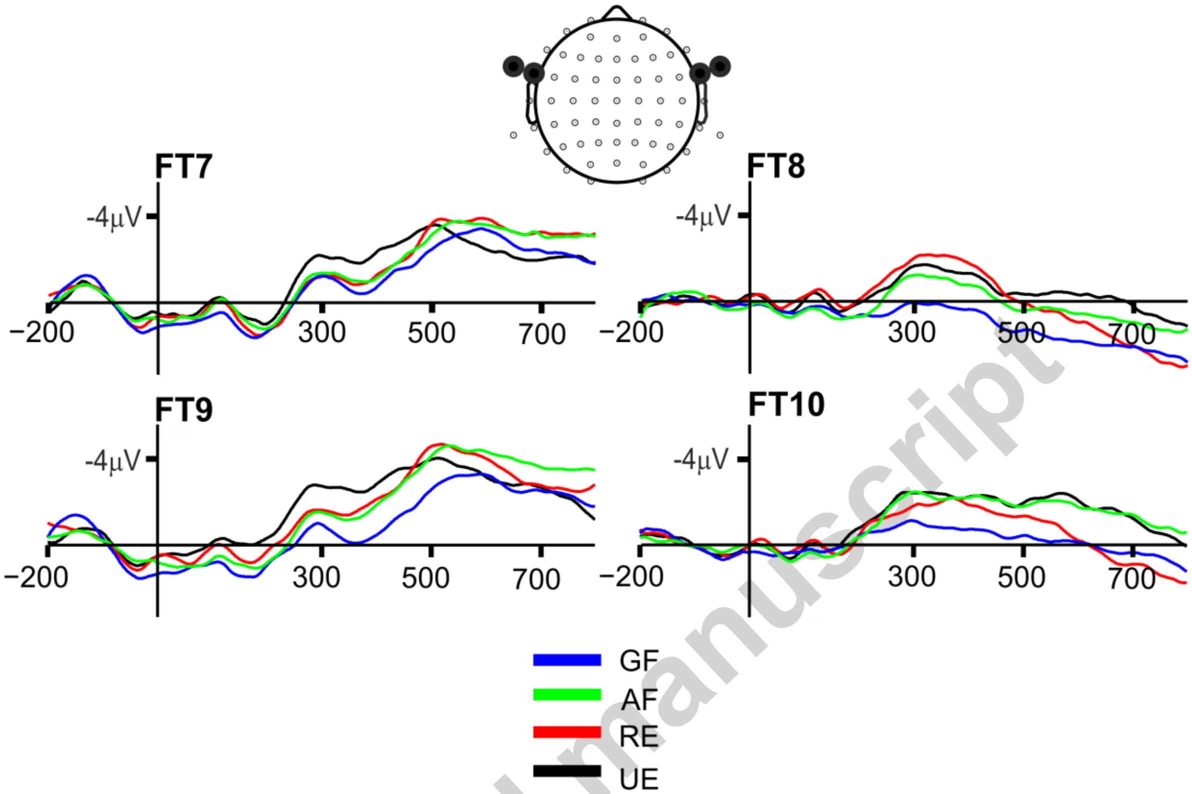


Figure 9. Spline interpolated isovoltage maps for the condition “unique events” in the LPC time window (500-700). This map was obtained by subtracting the mean voltage of the grand mean ERPs evoked across the GF, AF, and RE conditions from the mean voltage evoked in the UE condition. GF: General Facts, AF: Autobiographical Facts, RE: Repeated Events, UE: Unique Events.

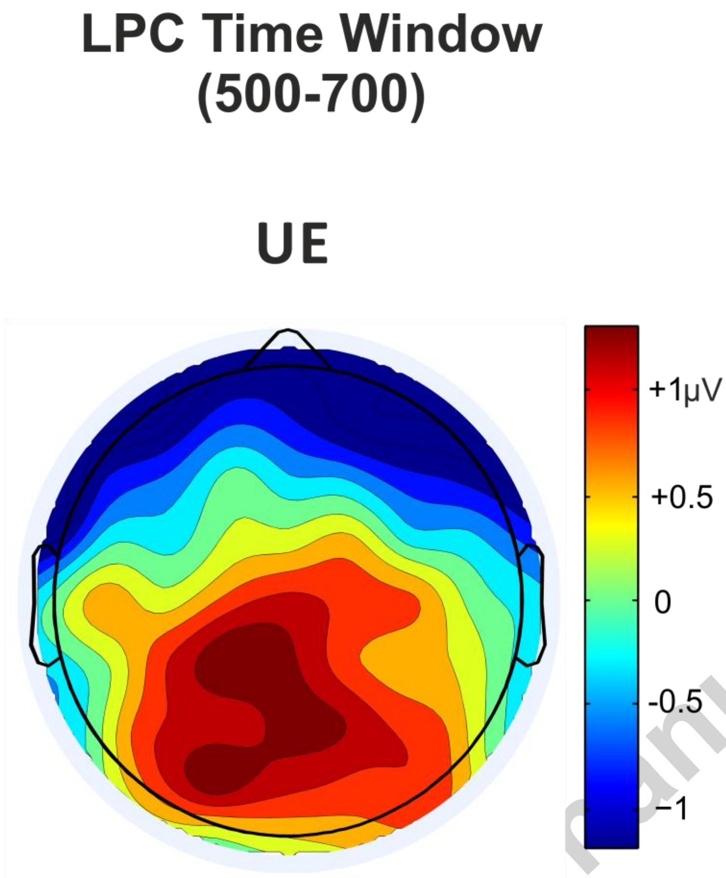
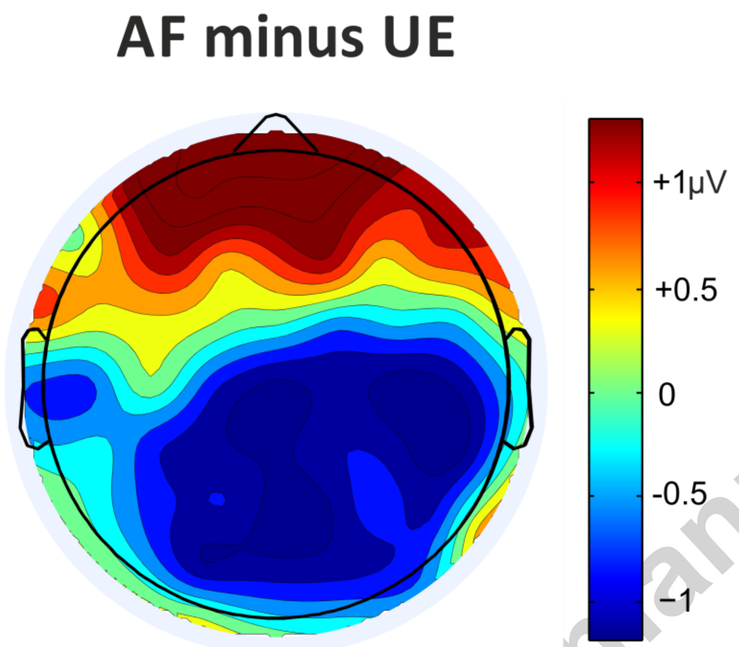
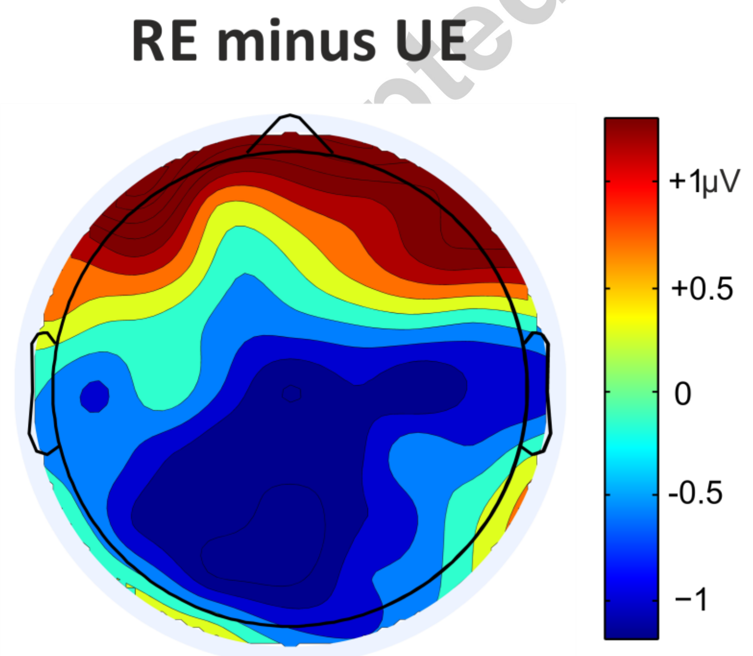


Figure 10. Spline interpolated isovoltage maps for the conditions "autobiographical facts" and "repeated events" in the LPC time window (500-700). Each map was obtained by subtracting the mean voltage of the grand mean ERPs evoked by the UE condition from those evoked in each condition (AF and RE). AF: Autobiographical Facts, RE: Repeated Events, UE: Unique Events.

LPC Time Window (500-700)





Highlights

- Autobiographical facts and repeated events are two types of personal semantics (PS)
- Their neural correlates were compared to general facts and unique events using ERPs
- N400 and LPC were used as ERP indexes of semantic and episodic retrieval, respectively
- N400 and LPC distinguished both types of PS from general facts
- N400 also differentiated autobiographical facts from unique events

Appendix: List of sentences used in the four experimental conditions. The cue words are in italic. See "experimental tasks" in Methods for more details.

ID	General Facts	Autobiographical Facts	Repeated Events	Unique Events
1	Everyone wears white socks?	Usually I wear white socks?	When shopping I have worn white socks?	Yesterday I wore white socks?
2	Most people take showers?	Often I take showers?	When at school I have taken a shower?	Last night I took a shower?
3	Few people use a computer?	Very often I use a computer?	When on the bus I have used a computer?	Last night I used a computer?
4	Some people skip breakfast?	Usually I eat breakfast?	When at school I have eaten breakfast?	Today I ate breakfast?
5	Few people make their bed?	Every day I make my bed?	When with friends I have made my bed?	This morning I made my bed?
6	Most people drive on the highway?	Rarely I drive on a highway?	When going to school I have driven on a highway?	Last week-end I was on a highway?
7	Most people eat fruits?	Rarely I eat fruits?	When shopping I have eaten a fruit?	Today I ate a fruit?
8	Few people read books?	Rarely I read books?	When on the bus I have read books?	This week I read a book?
9	No one eats at restaurants?	Often I eat at restaurants?	When at school I have eaten at a restaurant?	This week I ate at a restaurant?
10	Everyone watches TV?	Very often I watch TV?	When at work I have watched TV?	Last night I watched tv?
11	Few people go shopping?	Very often I go shopping?	When on vacation I have gone shopping?	This week I went shopping?

12	Many people drink coffee?	Every day I drink coffee?	When shopping I have drunk coffee?	This morning I drank coffee?
13	Everyone talks on the phone?	Very often I talk on the phone?	When on the bus I have talked on the phone?	Today I talked on the phone?
14	Most people eat pizza?	Every day I eat pizza?	When shopping I have eaten pizza?	Last night I ate pizza?
15	Many people go to the movies?	Sometimes I go to the movies?	When alone I have gone to the movies?	This week I went to the movies?
16	Everyone reads newspaper?	Rarely I read the newspaper?	When with friends I have read a newspaper?	Today I read a newspaper?
17	No one spends money?	Every day I spend money?	When at work I have spent money?	Today I spent money?
18	Some people rent movies?	Rarely I rent movies?	When alone I have rented a movie?	Last week-end I rented a movie?
19	Most people read magazines?	Often I read magazines?	When with friends I have read a magazine?	Yesterday I read a magazine?
20	Most people listen to music?	Often I listen to music?	When at work I have listened to music?	Today I listened to music?
21	No one washes the dishes?	Every day I wash the dishes?	When at work I have washed dishes?	Yesterday I washed dishes?
22	Most people talk to family members?	Often I talk to a family member?	When going to school I have talked to a family member?	This morning I talked to a family member?
23	Most people wear jeans?	Sometimes I wear jeans?	When at work I have worn jeans?	Yesterday I wore jeans?
24	No one sleeps well?	Usually I sleep well?	When alone I have slept well?	Last night I slept well?
25	No one wakes up early?	Usually I wake up early?	When on vacation I have waken up early?	This morning I woke up early?
26	Everyone eats chicken?	Sometimes I eat chicken?	When at work I have eaten chicken?	Yesterday I had chicken?
27	Few people listen to the radio?	Every day I listen to the radio?	When going to school I have listened to the radio?	Today I listened to the radio?
28	Some people go to bed early?	Usually I go to bed early?	When with friends I have gone to bed early?	Last night I went to bed early?
29	No one takes naps?	Often I take naps?	When on the bus I have taken naps?	Yesterday I took a nap?

30	Many people cook dinner?	Rarely I cook dinner?	When at school I have cooked dinner?	Last night I cooked dinner?
31	Few people dance?	Often I go dancing?	When alone I have gone dancing?	Last week-end I went dancing?
32	Everyone watches sports games?	Often I watch sports games?	When alone I have watched sports games?	This week I watched a sports game?
33	Everyone checks their email?	Often I check my email?	When on the bus I have checked my email?	This morning I checked my email?
34	Some people play with dogs?	Rarely I play with dogs?	When alone I have played with a dog?	This week I played with a dog?
35	No one buys CDs?	Rarely I buy CDs?	When on vacation I have bought CDs?	This week I bought a CD?
36	Many people eat fries?	Rarely I eat fries?	When on the bus I have eaten fries?	This week I ate fries?
37	No one goes to the mall?	Often I go to the mall?	When on vacation I have gone to the mall?	Last week-end I went to the mall?
38	Many people drink juice?	Very often I drink juice?	When at school I have drunk juice?	This morning I drank juice?
39	Some people go on walks?	Sometimes I go on walks?	When alone I have gone on a walk?	Today I went on a walk?
40	Some people eat candy?	Rarely I eat candy?	When at work I have eaten candy?	Yesterday I ate candy?
41	Few people go to the bank?	Sometimes I go to the bank?	When with friends I have gone to the bank?	Yesterday I went to the bank?
42	Most people play video games?	Very often I play video games?	When at school I have played a video game?	Last week-end I played a video game?
43	Some people work out?	Very often I work out?	When on vacation I have worked out?	This week I worked out?
44	Everyone does the laundry?	Very often I do my laundry?	When with friends I have done my laundry?	Last week-end I did my laundry?
45	Some people eat pancakes?	Sometimes I eat pancakes?	When with friends I have eaten pancakes?	Last week-end I ate pancakes?
46	Everyone logs on Facebook?	Very often I log on Facebook?	When at work I have logged on Facebook?	Today I logged on Facebook?
47	Some people send text messages?	Every day I send text messages?	When on the bus I have sent a text message?	Yesterday I sent a text message?
48	Some people eat	Rarely I eat	When at work I have	This week I ate a sandwich?

	sandwiches?	sandwiches?	eaten a sandwich?	
49	Many people hug friends?	Sometimes I hug a friend?	When on vacation I have hugged a friend?	Last week-end I hugged a friend?
50	Many people water plants?	Often I water a plant?	When on vacation I have watered a plant?	Last week-end I watered a plant?
51	No one sings tunes?	Sometimes I sing a tune?	When shopping I have sung a tune?	Last night I sang a tune?
52	Most people kiss each others?	Every day I kiss somebody?	When on vacation I have kissed somebody?	This morning I kissed somebody?
53	Everyone buys gifts?	Rarely I buy gifts?	When with friends I have bought a gift?	Last week-end I bought a gift?
54	Few people go to the gym?	Sometimes I go to the gym?	When at school I have been to the gym?	Yesterday I went to the gym?
55	No one misses meetings?	Often I miss a meeting?	When at work I have missed a meeting?	Today I missed a meeting?
56	Many people have a drink?	Very often I have a drink?	When alone I have had a drink?	Last night I had a drink?
57	Few people take pictures?	Very often I take pictures?	When shopping I have taken a picture?	Yesterday I took a picture?
58	Everyone goes to the pharmacy?	Rarely I go to the pharmacy?	When on vacation I have been to the pharmacy?	Last week-end I went to a pharmacy?
59	Few people pray?	Sometimes I pray?	When with friends I have prayed?	This morning I prayed?
60	Everyone hears jokes?	Every day I hear jokes?	When shopping I have heard jokes?	Last night I heard a joke?
61	Few people give to charity?	Usually I give to charity?	When shopping I have given to charity?	This week I gave to a charity?
62	Many people visit museums?	Rarely I visit a museum?	When with friends I have visited a museum?	Last week-end I visited a museum?
63	Many people take a course?	Every day I take a course?	When on vacation I have taken a course?	Yesterday I took a course?
64	Many people have a cold?	Rarely I have a cold?	When on vacation I have had a cold?	Last week-end I had a cold?
65	No one goes swimming?	Sometimes I go swimming?	When at work I have gone swimming?	This week I went swimming?
66	Few people check the news online?	Every day I check the news online?	When at school I have checked the news online?	Today I checked the news online?

67	Most people drive their car?	Very often I drive my car?	When going to school I have driven my car?	Last night I drove a car?