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The ERP Correlate of Episodic Recollection Is a Neurocognitive Determinant of Subjective Memory Complaints: Implications on Their Predictive Validity

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Objective: Subjective memory complaints (SMCs) seem to be a promising marker of cognitive decline and progressing dementia in healthy older adults. However, SMCs have not been invariably related to memory performance, probably because objective tests do not always target the specific neurocognitive processes that underlie SMCs. This study disentangles the neurocognitive basis of memory-specific SMCs by investigating their dependence on episodic recollection which relies on the hippocampal relational memory system as well as their predictive value for memory tests that target such processes. ***Method:*** In 29 healthy participants, aged 52–70 years, we assessed SMCs, using the Memory Assessment Clinics Self-Rating Scale (MAC-S), episodic recollection and associated event-related potentials (ERPs), the Verbal Learning and Memory Test (VLMT), which assesses hippocampal functions, as well as depressive symptomology, using Beck Depression Inventory II (BDI). We used correlational and regression models to estimate the association of SMCs with recollection and VLMT performance, independent of age, depressive symptomology, and the P300, an ERP correlate of attentional processes. ***Results:*** The ERP correlate of source-recollection significantly accounted for 9% unique variance in SMCs. Moreover, SMCs explained unique proportions of variance in several VLMT measures (ΔR^2 ranging from .07 to .17). ***Conclusions:*** SMCs are partially determined by malfunctioning of the hippocampal relational memory system. In line with this, SMCs predict performance in objective memory tests if they also target hippocampally dependent processes. The study emphasizes the prognostic relevance of SMCs as episodic memory decline is an important preclinical marker for the development of Alzheimer's Disease (AD).

Key Points

Question: Which neurocognitive processes are affected when patients subjectively complain about their memory abilities? ***Finding:*** Problems with hippocampus-driven recollection of prior episodes seem to be one determinant of memory complaints in middle-to-old adult age (range 52–70 years). ***Importance:*** As problems with episodic recollection is one of the earliest signs of incipient Alzheimer's dementia, it is useful to asses subjective memory complaints and take them seriously. ***Next Steps:*** Populations in this age range shall be encouraged to report subjective memory complaints and further determinants of subjective memory complaints have to be investigated whereby the assessment should be tailored to target problems with episodic recollection.

Keywords: subjective memory complaints, episodic recollection, event-related potential, cognitive aging

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Open data and analysis script to reproduce the reported results are available at: https://osf.io/uks2a/

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Investigating the development of memory functions in aging seems highly important since global population aging is supposed to become one of the most significant social transformations of the twenty-first century (United Nations, 2015). Whereas semantic memory is less affected by age, episodic memory (i.e., memory for specific information a person acquired at a particular time and place) displays the largest degree of age-related decline (Nyberg et al., 2003; Rönnlund et al., 2005; see Nyberg et al., 2012, for a review). Critically, episodic memory decline is an important preclinical marker for the development of Alzheimer's Disease (AD) whose rates increase with age (Alzheimer's Association, 2018; Bastin & Salmon, 2014; Lane et al., 2018). Diagnosing AD in early stages of the disease results in medical and financial benefits (e.g., early medical treatment that temporarily improves/prolongs cognitive functions and reduction in individual and national health care costs). Thus, interest in the predictive value of early warning signs such as biomarkers, mild cognitive impairment (MCI), and subjective memory complaints (SMCs) has increased (Alzheimer's Association, 2018). SMCs are described as subjective reports of memory decline compared to an earlier period in life. They increase with age (Burmester et al., 2016; Jonker et al., 2000; Ponds et al., 2000; Reid & Maclullich, 2006) and have been identified as an at-risk factor for MCI (Donovan et al., 2014; Jessen et al., 2010; Luck et al., 2010) and subsequent AD (Jessen et al., 2014; Luck et al., 2015). SMCs therefore seem to be a promising marker of progressing memory problems especially as they are easily assessable and can be incorporated in clinical interviews without effort. However, using SMCs as a diagnosing tool for memory dysfunction presupposes that SMCs have a predictive value for decline in objective memory performance which is controversial to date (Burmester et al., 2016; see also Jonker et al., 2000; Reid & Maclullich, 2006, for reviews). Therefore, the main goal of the present study was to resolve this discrepancy by examining neurocognitive processes that underlie SMCs and by showing that a relationship between SMCs and objective memory performance can be established if they tap on the same neurocognitive processes.

Linking SMCs and Objective Memory Performance Through Hippocampally Dependent Memory Processes

Some studies report that SMCs are accompanied by deficits in objective memory performance (Amariglio et al., 2011; Bassett & Folstein, 1993; Christensen, 1991; Gallassi et al., 2010; Horn et al., 2018; Carrasco et al., 2017; Rijs et al. 2013; Schofield et al., 1997; Vaskivuo et al., 2018; see also Jonker et al., 2000; Brigola et al., 2015, for reviews) whereas other studies report no relationship (Balash et al., 2010; Caramelli & Beato, 2008; Minett et al., 2008; Pearman et al., 2014). Additionally, a literature review concludes that there is no association between SMCs and objective memory performance (Riedel-Heller et al., 2000) or only a small relationship as in the meta-analysis by Crumley et al. (2014).

Several factors such as demographical effects of age and education, as well as depressive symptomology and aspects of the study design (longitudinal vs. cross-sectional) were previously pointed out to explain diverging results (Crumley et al., 2014; Jonker et al., 2000; Reid & Maclullich, 2006). Another explanation might be that objective memory tests which are frequently used in such studies do not target the neurocognitive processes underlying subjective memory evaluations. However, it is important to consider these processes when exploring the predictive value of SMCs for objective memory performance. We assume that people probably derive SMCs from episodic memory problems as such problems are highly salient and have particular impact on everyday life and social interactions (e.g., problems with remembering details of a family event that occurred during the past year). Episodic memory technically relies on relational memory processes (i.e., constructing and representing relations among arbitrary individual events, as for example, remembering what a family member said or did during the specific family event) and episodic memory deteriorations appear as an early sign of AD (Bastin & Salmon, 2014). Importantly, the encoding and retrieval of relational, episodic memories depend on the integrity of the hippocampus and its ability of pattern separation, that is, to store similar representations in a nonoverlapping way (see Eichenbaum, 2004; Konkel & Cohen, 2009; Yassa & Stark, 2011, for reviews). Thus, we assume that SMCs are at least partially driven by the malfunctioning of hippocampally dependent episodic memory processes.

These assumptions are in line with studies reporting SMCs to be uniquely associated with episodic memory performance (Gifford et al., 2015; Hohman et al., 2011; Lenehan et al., 2012) and with the outcome of the meta-analysis by Crumley et al. (2014), who reported a relationship of SMCs only with those objective memory measures that assess episodic and prospective memory. Moreover, Lucas et al. (2016) showed that SMCs were most strongly related to performance in a spatial reconstruction task, which relies on hippocampally dependent relational memory processes (see Eichenbaum, 2004, for a review). Moreover, previous studies showed that healthy elderly participants with SMCs have smaller hippocampal volume than comparable control participants without SMCs (Cantero et al., 2016; Hafkemeijer et al., 2013; van der Flier et al., 2004; van Norden et al., 2008; but see Jessen et al., 2006). In addition, for participants who carry higher β-amyloid burden, Vannini et al. (2017) report a negative correlation between SMC-score and fluorodeoxyglucose-metabolism in the right hippocampus.

The described relationship between hippocampal malfunction and SMCs suggests that SMCs can predict performance in objective memory tests only if these tests capture hippocampally dependent episodic memory processes.

Objective Memory Measures

Previous studies suggest that two memory measures are particularly sensitive to hippocampal integrity and indicative of neurocognitive processes that potentially underlie SMCs. The first group of memory measures can be derived from dual-process models of recognition memory. These models assume that recognition memory is comprised of two distinguishable subprocesses: familiarity and recollection (see Yonelinas, 2002; Yonelinas et al., 2010, for reviews). Familiarity is described as a fast-acting process, assessing the strength of a memory representation without retrieving contextual information. Recollection in turn, reflects the retrieval of qualitative relational representations from a prior study episode. It can be appropriately measured in a source memory task wherein a participant studies items from different sources (e.g., two different tasks). During recognition, an item must not only be recognized as old but participants also indicate the source (e.g., the task) that was associated with the item at study (Yonelinas et al., 2010). The high relevance of hippocampal integrity for (source)-recollection (but not for familiarity) is illustrated in several patient- and imaging-studies (Bowles et al., 2010; Davachi et al., 2003; Liang & Preston, 2017; Staresina & Davachi, 2008, see Eichenbaum et al., 2007; Rugg &

Curran, 2007; Yonelinas et al., 2010, for reviews). In the scalp-recorded event-related potential (ERP), successful (source)-recollection has been associated with a positive-going, left-parietally distributed ERP modulation, between 500 and 800 ms poststimulus (Addante et al., 2012, see Rugg & Curran, 2007, for a review). This modulation is referred to as the late positive component (LPC) and is of particular interest in this study since it is attenuated in patients with selective hippocampal injury (Addante et al., 2012; Düzel et al., 2001) and depends on structural and functional integrity of the hippocampus in healthy elderly participants (Schiltz et al., 2006) and in children who had suffered from infant febrile seizures (Kipp et al., 2010). It seems therefore that source recollection, that is, accurate recollection of contextual details of prior episodes, and the LPC, its electrophysiological correlate, are promising measures of hippocampally dependent relational memory processes. The fact that the LPC word-repetition effect was identified as a preclinical marker for conversion from MCI to AD (Olichney et al., 2008) qualifies it even more for the validation of SMCs.

A second group of memory measures can be derived from the Verbal Learning and Memory Test (VLMT), a German version of the Rey Auditory-Verbal Learning Test (RAVLT; Helmstaedter et al., 1997, 2001). The VLMT is a standard memory examination tool which is considered to be a reliable measure of episodic memory. In line with this, performance in the VLMT declines after hippocampal resection (Gleissner et al., 2002; Helmstaedter et al., 1997, 2011) and several scores of the RAVLT have been related to episodic memory processes and hippocampal integrity (see Saury & Emanuelson, 2017, for a review).

The Present Study

In the present study, we primarily set out to examine the determining role of hippocampally dependent relational memory processes on SMCs in healthy middle-aged and older adults. Thus, we investigated whether source memory performance and the associated LPC predict the number of SMCs in a middle-to-old-aged sample. For this purpose, we let participants study single words in either of two tasks ("Is this item pleasant? (yes/no)" or "Is this item alive? (yes/no)" and subsequently asked them to report in which of these tasks a word had been studied. Second, we assumed if SMCs indeed depend on impairments in relational memory processes, they can be used as an easy-to-apply first diagnosing tool which predicts performance in a standardized objective memory test. Therefore, we tested whether SMCs reliably predict performance in the VLMT since this test is thought to also capture hippocampally dependent memory processes. SMCs were acquired using the Memory Assessment Clinics Self-Rating Scale (MAC-S; Crook & Larrabee, 1990), a questionnaire commonly used for evaluating SMCs (Huang et al., 2014; Polczyk et al., 2004; Woods & Kneebone, 2016). The questionnaire measures self-ratings of memory abilities and frequency of memory problems. We combined those items that target subjective evaluation of episodic memory performance into an Episodic/Spatial-Scale (e.g., the subjective appraisal of memory for: "gifts you have received at holidays during the past several years" or "details of family events that occurred during the past year," see Appendix for the entire scale).

In order to determine whether any relationships between SMCs and the LPC are specific to memory retrieval processes and are not confounded by attentional processes that could also influence memory performance, we additionally recorded ERPs in a visual classification (oddball) task. During the oddball task, participants classify standard and rare target events (in our case numbers and letters). It has been shown repeatedly that participants display a large, parietally focused P300 component to rare targets (i.e., the P300 oddball effect). The P300 oddball effect is functionally distinct from the LPC as it is associated with attentional processes during stimulus encoding (see Polich, 2007, for a review), and is not dependent on hippocampal integrity (Fonken et al., 2020; Polich & Squire, 1993). Thus, any SMC variance that is explained through the LPC over and above the P300 can be more specifically related to differences in relational memory abilities (see Mecklinger et al., 1998, for a similar argument). To investigate whether the predictive validity of SMCs on the VLMT is specific for the memory-related items of the MAC-S (i.e., the Episodic/Spatial-Scale), we included the MAC-S Attention/Concentration-Scale as a covariate, which focuses on attentional and working memory abilities rather than episodic memory performance. Since depressive symptomology is related to SMCs (Balash et al., 2010, 2013; Buckley et al., 2013) and to memory performance (see Rock et al., 2014, for a review), we further assessed depression scores in order to control for the impact of depression on the relationship between SMCs and objective memory.

Considering the experimental memory measures, we predicted more positive going LPC amplitudes for correct source judgments (SC, i.e., items that are correctly classified as old and for which the source is indicated correctly) than incorrect source judgments (SI, i.e., items that are correctly classified as old but for which the source is not correctly indicated) whereas both should elicit more positive LPC amplitudes than correct rejections (CR, i.e., items that are correctly classified as new). In the oddball-task, we predicted more positive P300 amplitudes for deviants than for standards. In order to gain an overall impression concerning the associations between SMCs, objective memory performance and covariates, bivariate correlations were calculated. Subsequently, we used hierarchical regression models to specifically test the following predictions: First, regarding the neurocognitive determinants of SMCs, we expected that relative source memory performance and the LPC predict higher rates of SMCs that specifically target hippocampally dependent memory processes, independently of age, depression, and the P300 (in case of the LPC). Second, we expected that especially these SMCs that specifically target hippocampally dependent memory processes negatively predict VLMT performance, independently of age and depression and above and beyond SMCs that are not memory specific (i.e., the Attention/Concentration-Scale).

Method

Participants

A total of 31 participants were recruited via newspaper advertisement and the participant database of the Psychology Department at Saarland University. In the announcement, potential participants were informed that the study investigates memory functions and that they could receive individual feedback about their memory performance. Data from two participants had to be excluded due to left-handedness (1 participant) and excessive α-artefacts. The mean age of the remaining 29 participants (19 female) was 62.86 years (range 52–70). We chose this middle-to-old adult age range as we assumed that SMCs start to emerge in this period of life while episodic memory and its neural substrates show high variability during this period (Nyberg et al., 2012). All

participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) and were native German speakers. In advance, potential participants were screened for diseases and every medication they are currently taking (even if not prescribed by a doctor). Potential participants were precluded from participation if they suffered from psychiatric or neurological issues or took respective medication. Moreover, none of the potential participants suffered from untreated hypertension but were precluded if they were treated with β-blockers as β-blockers might reduce the ability to concentrate throughout the experiment. Written informed consent was required, payment was provided at a rate of €8/hr, and participants were debriefed after the experiment and received feedback about their performance in the VLMT. The experiment was approved by the ethics committee of the Faculty of Human and Business Sciences at Saarland University and adhered to the Declaration of Helsinki.

Material and Procedure

The whole session lasted approximately 3 hr including the MAC-S, the VLMT as well as the source memory task. The oddball task took place during the retention interval of the source memory task. The temporal structure of the testing session is shown in Table 1. The source memory task (adapted from Addante et al., 2011) as well as the oddball task (adapted from Luck et al., 2009) were designed using E-Prime 2.0 (Psychology Software Tools) and were conducted on a standard PC. Participants were seated in front of a monitor at a distance of approximately 80 cm, inside a sound-attenuated and electrically shielded chamber.

Measures

SMCs. SMCs were assessed using a German version of the MAC-S (Crook & Larrabee, 1990; Weber, 2008), a questionnaire that contains 21 ability items (measuring self-perception of everyday memory abilities) and 24 frequency items (measuring everyday frequency of memory deficits) as well as a global memory scale (4 items). Each item is rated on a 5-point Likert scale, with higher scores indicating a subjective evaluation of higher memory abilities or lower frequency of memory deficits in everyday life, respectively. All items together can be joined to a Total-Scale. However, the MAC-S subscales are empirically derived by factor analyses and not theoretically motivated. In order to investigate SMCs that specifically target hippocampal core functions such as episodic memory and spatial memory/navigation, we subsumed seven ability- and three frequency-items to an SMC Episodic/Spatial-Scale (see Appendix for the entire scale). This scale includes only items that target episodic memory performance ("How well do you remember details of family events that occurred during the past year?") or spatial memory performance ("How well do you remember verbal directions to a geographic location given minutes earlier?") as contemporary models of hippocampal contributions to episodic memory suggest that processing spatial information is crucial for episodic memory formation and retrieval (Maguire & Mullally, 2013; Moscovitch et al., 2016). The SMC Attention/Concentration-Scale (Crook & Larrabee, 1990) served as covariate, with higher scores indicating higher subjective evaluation of attentional and working memory abilities (see Appendix for the entire scale). Cronbach's α in our sample amounts to .80 for the SMC Episodic/Spatial-Scale and .71 for the SMC Attention/Concentration-Scale.

Table 1
Schedule of Measurements and Content in Temporal Order

Measure	Content
MAC-S	Subjective memory complaints (SMCs)
ERP cap application	
VLMT	Objective memory test
EHI	Handedness
DST	Processing speed (covariate)
SMT (study phase)	
Oddball	ERP cognitive task (P300)
SMT (test phase)	Source memory and ERP (LPC)
ERP cap removal	
MMSE	Dementia screening
BDI	Depression

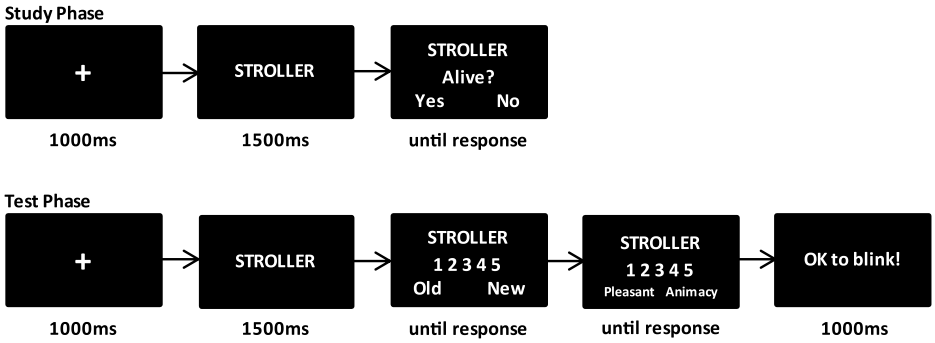
Note. MAC-S = memory assessment clinics self-rating scale; VLMT = verbal learning and memory test; EHI= Edinburgh handedness inventory; DST = digit symbol test; SMT = source memory task; ERP = event related potential; LPC = late positive component; MMSE = mini mental status examination; BDI = Beck depression inventory II.

VLMT. In the VLMT (Helmstaedter et al., 2001), participants are presented verbally with a list of 15 words (list A) five times in succession (learning trial 1–5). After each presentation, they are required to recall as many words as possible. After presentation and recall of an interference list (list B), participants free-recall list A (short delay), and after a period of 30–40 min (duration of electroencephalogram, EEG, preparation), free-recall it again (long delay). Finally, recognition memory is tested using a visually presented list of 50 words containing 15 words from study list A as well as phonologically and semantically related lures. The five dependent variables are: *total learning* (sum of recalled words from trial one through five); *proactive interference* (difference of recalled words from list B and trial one, relative to correct recalled words from trial one); *short delay recall* (number of correctly recalled items after short temporal delay); *long delay recall* (number of correctly recalled items after short temporal delay); and finally *recognition* quantified as [p (hits) − p (false alarms)].

Source Memory Task. The procedure of the source memory task corresponds to the one used in Eschmann et al. (2020, see also Addante et al., 2011) and is presented in Figure 1. In an incidental study phase, 200 German nouns were presented in four 50-item blocks and participants were asked to perform one of two tasks in each block. They either had to rate the animacy (task A, "alive" yes or no) or the pleasantness (task B, "pleasant" yes or no) of the word. Order of task blocks was implemented in an ABBA design.[1] Importantly, all items were randomly assigned to one of both tasks in advance and did not differ with respect to word length and word frequency (Heister et al., 2011). Each study trial began with a fixation cross for 1,000 ms, which was followed by the study item for 1,500 ms and the respective question "lebendig?" (German for "alive?") or "angenehm?" (German for "pleasant?"). The question remained until participants indicated their yes/no response with their left or right index finger on the keys "C" and "M" on a conventional keyboard. Assignment of stimuli to conditions, order of study tasks and stimulus presentation was not counterbalanced between participants as this is a source of error variance when interindividual differences are analyzed (Wentura & Degner, 2010). During the 15 min retention interval, the visual oddball-task (see

[1] The ABBA design is a standard procedure to avoid temporally dependent confounding effects between both tasks (e.g., task-familiarity, tiredness) and to equate the average study-test delay between tasks.

Figure 1
Source Memory Task Procedure



Note. In the study phase, participants incidentally encoded words making "animacy" or "pleasantness" judgments. During retention, an oddball task was performed. In the test phase, participants first made an old/new judgment (item memory test) for old and new items and a source memory judgment concerning the encoding task for items judged as old. Note that if participants did not respond within 1,500 ms, they received the information "Please respond faster!" on the screen.

below) was performed. In the ensuing test phase, a fixation cross appeared for 1,000 ms. Afterward, studied items were presented for 1,500 ms, randomly intermixed with 100 new words. Participants first indicated their item memory on a 5-point confidence scale (1 = *sure old*; 2 = *probably old*; 3 = *don't know*; 4 = *probably new*; 5 = *sure new*). If an item was judged as old, participants subsequently had to indicate their source memory on a 5-point confidence scale (1 = *sure pleasantness*; 2 = *probably pleasantness*; 3 = *don't know*; 4 = *probably animacy*; 5 = *sure animacy*). Importantly, as the items were randomly assigned to one of the two tasks, it was not possible to infer the respective study task from the test item per se. Left and right index and middle fingers were positioned on the number keys "1," "2," "4," and "5." The "don't know" response was given with the right index finger. Participants could take as long as they needed for item and source memory judgments. Note that since participants rarely used the categories "2" and "4," their judgments were binned for analyses so that "1" and "2" counted as "old" or "pleasantness" while "4" and "5" counted as "new" or "animacy." "Don't know" responses were not taken into account.

Oddball Task. In the visual oddball task, participants classified black letters and digits presented in the middle of a gray screen. Each stimulus was presented for 200 ms, followed by a blank intertrial interval of 1,100–1,500 ms (jittered). The session was divided into two halves and each half was divided into two blocks (each block consisting of 320 trials). During the first half, participants responded to letters with the index finger of their left or right hand and to digits with the other. In the second half, the assignment of hands to letters/digits was reversed. In one of the blocks in each half, letters appeared in 80% of the trials (standards) while digits appeared in 20% of the trials (deviants). The assignment of letters and digits to standards and deviants was reversed for the other block. A rest break was provided every 80 trials. Directly preceding each half, participants performed a brief training block.

Digit Symbol Test. The Digit Symbol Test (DST) is a subtest of the German version of the Wechsler Adult Intelligence Scale IV (Petermann, 2012) and was used to measure processing speed as a covariate. Note that the DST score was not considered in the analyses and is not reported as it was erroneously not administered in the standard way.

Mini Mental State Examination. To preclude dementia or cognitive impairment in our sample, we used the German version of the MMSE (Folstein et al., 1975). None of our participants scored below 27 points and all of our participants recalled more than zero out of three items in the recall test.

BDI-II. The Beck Depression Inventory II (BDI; Hautzinger et al., 2009) contains 21 items which focus on different symptoms of depression with each item score ranging from 0 to 3 (higher scores represent higher depression). The maximum score therefore accounts for 63 points and was used as a covariate.

Education. Years of education concern years of formal education in school, vocational education, and university or college.

EEG Recording and Analysis

EEG in the test phase of the source memory task as well as in the visual oddball task was continuously recorded from 28 Ag/AgCl scalp electrodes mounted in an elastic cap and labeled according to the extended 10–20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC3, FCz, FC4, FC6, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, O2, and A2; Sharbrough et al., 1991). All electrodes were recorded with reference to the left mastoid electrode (A1). Data were rereferenced offline to the average of the left and right mastoid. Electrooculogram was recorded from electrodes that were located above and beyond the right eye and at the canthi of each eye. EEG was amplified with a BrainAmp DC amplifier (Brain products) from 0.016 to 100 Hz and digitized at a sampling rate of 500 Hz. Electrode impedances were kept below 5 kΩ. Data were recorded using the Brain Vision Recorder 1 (Brain Products).

Offline processing was performed with Brain Vision Analyzer 2.1 (Brain Products). A bandpass filter ranging from 0.05 to 30 Hz (order: 4) and a 50 Hz notch filter were applied. Independent Component Analysis was used to correct for ocular artefacts. For ERP analyses, trial-wise segments were formed: 1,300 ms in the source memory task (including a 300 ms prestimulus baseline) and

1,200 ms in the oddball task (including 200 ms prestimulus baseline). After baseline-correction, segments containing artefacts were rejected using the following criteria: Maximal allowed voltage step of 30 μV/ms, a maximal difference of values of 200 μV within 200 ms (100 μV within 200 ms in the oddball task), and minimal and maximal allowed total amplitude of ±70 μV.

In the source memory task ERP, averages were formed for SC-, SI- and CR-trials. Mean trial numbers (range) were: 80.17 (10–147) for SC trials, 47.55 (16–66) for SI trials, and 73.10 (26–97) for CR trials. As LPCs are usually largest at left parietal electrode sites but temporally delayed in elderly populations (Duarte et al., 2006; Rugg & Curran, 2007; Wang et al., 2012) analyses were restricted to mean amplitudes of left parietal electrode sites (P3, P7) in the time window of 600–900 ms after stimulus onset (as in Addante et al., 2012). In the oddball-task, only correct trials were considered for analyses. ERP averages were formed for standards and deviants. Mean trial numbers (range) were: 333.41 (156–380) for standards and 78.17 (40–96) for deviants. Analyses were restricted to mean amplitudes at parietal electrodes (P3, Pz, P7) in the time window of 400–700 ms after stimulus onset (Luck et al., 2009). For illustration purposes, a 12 Hz low pass filter was applied to all waveforms.

Statistical Analyses

All analyses were conducted using the RStudio 3.5.0 software (R Core Team, 2019), especially the packages Tidyverse (Wickham et al., 2019), Psych (Revelle, 2018), ez (Lawrence, 2016), nlme (Pinheiro et al., 2019), and MBESS (Kelley, 2020). Significance level was set to $\alpha = .05$. Figures were compiled using the Brain Vision Analyzer 2 software (Brain Products) as well as the RStudio 3.5.0 software, especially the ggplot2 package (Wickham, 2016).

Source Memory Task and Oddball Task

Behavioral parameters of the source memory task were *Item-PR* [*p* (hits) − *p* (false alarms)] for the item recognition test, as well as *Absolute Source Memory* [correct source judgements/total number of old items] and *Relative Source Memory* [correct source judgements/number of hits] for source recollection.

ERP mean amplitudes of the source memory task and the oddball task were analyzed using repeated measures analysis of variances (ANOVAs) and two-sided paired samples *t* tests for decomposing significant ANOVA results. Greenhouse–Geisser corrected degrees of freedom and *p* values are reported whenever the assumption of sphericity was violated. Only main effects or interactions involving the factors of interest will be reported. As measures of effect sizes, generalized eta-squared (η_G^2; Bakeman, 2005; Olejnik & Algina, 2003) is reported for ANOVA results. Effect sizes (*d_av*) for paired *t* tests and 95% confidence intervals (CI) were computed according to Lakens (2013) and Lakens (2019).

Correlations

Descriptive statistics of the variables considered in the correlation analyses are depicted in Table 2. Outliers were identified at the recommendation of Tukey (1977), for example, values below first quartile − (1.5 × interquartile range) and above third quartile + (1.5 × interquartile range).[2] In order to keep sample sizes comparable between analyses, outliers were winsorized and therefore set to the respective boundary value according to the criterion of Tukey (1977). For correlational analyses, Pearson's *r* was used and correlations were tested two-sided.

Table 2
Descriptive Statistics of Variables used in Correlational and Regression Analyses

Variable	*M* (*SD*)	Range
MACs tot	181.38 (22.89)	127–221
MACs ep/sp	36.83 (5.48)	26–47
MACs att	19.69 (2.84)	14–25
VLMT tot	53.95 (9.38)	29.5–67
VLMT pi	−0.13 (0.30)	−.67 to .50
VLMT sr	10.98 (2.50)	5.5–15
VLMT lr	11.14 (2.23)	7–15
VLMT rec	.90 (.09)	.70–1
Item-PR	.54 (.18)	.11–.86
ASM	.43 (.13)	.08–.74
RSM	.61 (.10)	.40–.80
LPC	0.04 (0.21)	−0.43 to 0.41
P300	0.45 (0.34)	−0.42 to 1.13
BDI	4.76 (3.94)	0–16
MMSE	29.00 (0.93)	27–30
Age	62.86 (5.56)	52–70
Education	15.91 (3.05)	9–22

Note. MACs tot = MAC-S total scale; MACs ep/sp = MAC-S episodic/spatial-scale; MACs att = MAC-S attention/concentration-scale; VLMT tot = total learning; VLMT pi = proactive interference; VLMT sr = short delay recall; VLMT lr = long delay recall; VLMT rec = recognition; ASM = absolute source memory; RSM = relative source memory; LPC = standardized LPC effect (SC vs. SI); P300 = standardized oddball effect (deviants vs. standards); BDI = Beck depression inventory II; MMSE = mini mental status examination.

ERP effects were standardized for two reasons: First, effects need to be relativized to participant-specific mean amplitudes in order to control for (irrelevant) interindividual differences in overall amplitude size. Second, participant-specific variance in amplitudes must be taken into account to more accurately depict reliable participant-specific effect sizes. The individually standardized LPC effect[3] was calculated participant-wise in three steps: For the difference between source correct and source incorrect judgments, SC and SI amplitudes were first averaged condition-wise across left-parietal electrode sites (P3, P7) in the given time window. Second, these condition averages for SC and SI were standardized regarding the participant-specific distribution of all SC and SI amplitudes [SC_stand = (mean_SC − mean_SC.SI)/sd_SC.SI; SI_stand = (mean_SI − mean_SC.SI)/sd_SC.SI].[4] Note that the whole SC and SI distribution was used as reference because it reliably captures

[2] Outliers occurred in the VLMT Total Learning (1), the VLMT Proactive Interference (2), the VLMT Short Delay Recall (1), the VLMT Long Delay Recall (2), Item-PR (1), Relative Source Memory (2), Absolute Source Memory (1), and the BDI (1).

[3] Even if the overall LPC effect was nonsignificant, this does not imply that it was absent in every single participant (see Table 2 for descriptive statistics). As correlational and regression analyses are based on individual data points and require some variance, it is not problematic that the overall LPC effect is not significantly different from zero.

[4] Mean_SC and mean_SI signify the subject-specific mean amplitude for all SC or SI trials, respectively. Mean_SC.SI and sd_SC.SI signify the subject-specific mean amplitude and standard deviation of the whole distribution of SC and SI trials, respectively.

information about the participant-specific overall amplitude size. Third, differences were calculated between standardized amplitudes of SC and SI (LPC_effect_stand = SC_stand − SI_stand). The same procedure was applied for the oddball effect (difference of standardized mean amplitudes of standards and deviants averaged across parietal electrode sites (P3, Pz, P4) in the given time window).

Hierarchical Multiple Regression

As in correlational analyses, in each regression model outliers were winsorized and standardized ERP effects were used. As we had directed hypotheses on the predictors of interest (i.e., relative source memory, the LPC effect, SMC Episodic/Spatial-Scale), p values for β-weights and ΔR^2 are always reported one-sided.

Results

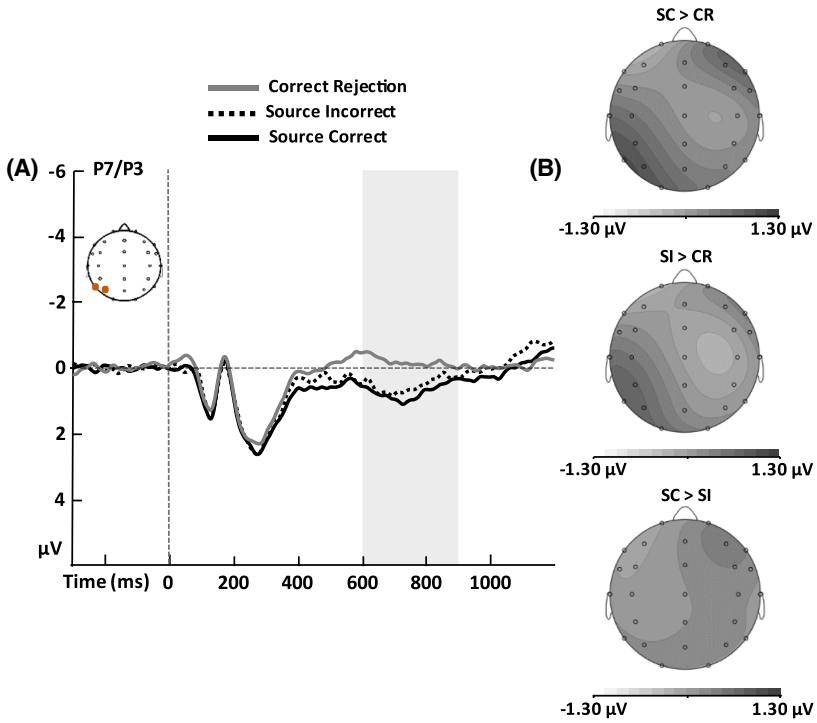
The results section is structured as follows: First, we report ERP results from the source memory and the oddball task. Second, to test for associations between SMCs, objective memory performance and covariates, we report correlational data and emphasize particular relations in scatterplots. Third, we report hierarchical regression models that examine the determining role of relative source memory and the LPC for SMCs as well as the predictive validity of SMCs on VLMT performance (each controlled for respective covariates).

Source Memory Task—ERP Results

As depicted in Figure 2A, hits (irrespective of source judgment) elicited more positive waveforms than CRs whereas SC trials elicited on average only minimally more positive-going waveforms than SI trials in the time window between 600–900 ms, collapsed across left parietal electrodes (P3, P7). As can be seen in Figure 2B, differences of SC and CR as well as SI and CR show the typical LPC distribution with a maximum at left parietal electrode sites.

A two-way ANOVA with the within-subjects factors electrode (P7, P3) and condition (SC, SI, CR) revealed a main effect of condition, $F(2, 56) = 8.10$, $p < .001$, $\eta_G^2 = .021$. The two-way interaction was not significant, $F(2, 56) = 0.07$, $p = .931$. Follow-up paired t tests were conducted for the factor condition averaged across electrodes revealing that SC trials elicited significantly more positive-going waveforms than CR trials, $t(28) = 3.38$, $p = .002$, $d\_av = 0.37$, 95% CI [0.13–0.60] and ERPs to SI trials were more positive than those to CRs, $t(28) = 2.81$, $p = .009$, $d\_av = 0.28$, 95% CI [0.07–0.49]. Waveforms elicited by SC and SI trials did not differ, $t(28) = 1.10$, $p = .279$. In sum, the analyses revealed LPC effects for correct old responses irrespective of source accuracy relative to correctly rejected new items at left parietal electrode sites while there was no difference in the LPC between correct and incorrect source judgment trials.

Figure 2
ERP Results of the Source Memory Recognition Task



Note. (A) ERP waveforms for correct rejections, correct source judgments, and incorrect source judgments at pooled electrodes P7 and P3. Shaded bars indicate the 600–900 ms time window used for analysis. (B) Topographic distributions of mean ERP differences between response conditions across the scalp during the 600–900 ms time window. SC = source correct, SI = source incorrect, CR = correct rejection. See the online article for the color version of this figure.

Oddball Task—ERP Results

As evident from Figure 3A, deviants were associated with more positive amplitudes than standards in the time window from 400–700 ms. Topographic distributions depicted in Figure 3B show that differences between deviants and standards show a typical P300 distribution with a maximum over parietal electrode sites in the given time window.

A two-way ANOVA consisting of the within-subjects factors electrode (P3, Pz, P4) and condition (deviants, standards) revealed a main effect of condition, $F(1, 28) = 39.70$, $p < .001$, $\eta_G^2 = .109$. The interaction was not significant, $F(2, 56) = .91$, $p = .408$.

Correlational Analyses

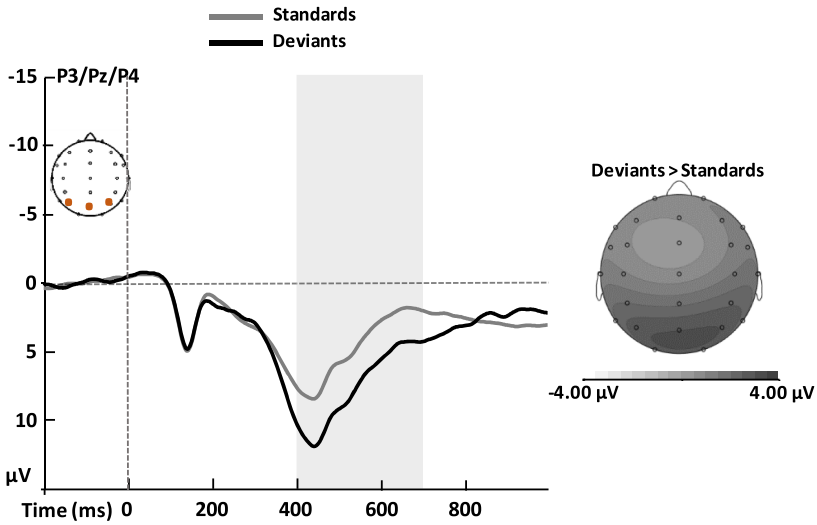
Table 3 depicts a correlation matrix for all conducted measurements. In the following, we report the most relevant correlations in more detail. The correlations between the SMC Episodic/Spatial-Scale and the objective memory measures that are relevant for our hypotheses are illustrated in Figure 4.

The correlation between relative source memory performance and the SMC Episodic/Spatial-scale was not significant, $r(27) = .13$, $p = .499$. The LPC effect (the standardized ERP difference between correct and incorrect source judgments) was significantly positively correlated with the SMC Episodic/Spatial-Scale (higher scores imply less SMCs), $r(27) = .41$, $p = .029$. This indicates that individuals with less source recollection complain more about everyday memory abilities. Note that the SMC Episodic/Spatial Scale did not correlate with the standardized P300, $r(27) = .12$, $p = .551$, in line with the memory specificity of this scale. We additionally found a trend toward a positive correlation between the SMC Episodic/Spatial-Scale and Item-PR of the source memory task, $r(27) = .33$, $p = .082$.

Moreover, the SMC Episodic/Spatial-Scale was positively correlated with all the objective memory measures from the VLMT: Total Learning, $r(27) = .59$, $p = .001$; Proactive Interference, $r(27) = -.38$, $p = .041$; Short Delay Recall, $r(27) = .39$, $p = .034$; Long Delay Recall, $r(27) = .52$, $p = .004$; and the Recognition score, $r(27) = .44$, $p = .017$. Overall, these results indicate that individuals who express higher behavioral scores in objective memory tests that are sensitive to hippocampal integrity also have a self-appraisal of higher memory abilities and lower frequencies of memory problems in everyday life.

Further, the SMC Attention/Concentration Scale and the SMC Episodic/Spatial-Scale were highly correlated, $r(27) = .73$, $p < .001$. Interestingly, however, the SMC Attention/Concentration Scale was only marginally correlated with the VLMT Total Learning score, $r(27) = .35$, $p = .061$ and positively correlated with the VLMT Long Delay Recall, $r(27) = .46$, $p = .011$ but unlike the SMC Episodic/Spatial-Scale, not with any other VLMT measure. This indicates that although the two SMC scales share common variance, the SMC Episodic/Spatial-Scale seems to more specifically reflect objective memory abilities. Regarding the behavioral memory measures (VLMT and source memory task) only the VLMT Recognition score correlated positively with Item-PR, $r(27) = .54$, $p = .002$, and marginally positively with Absolute Source Memory, $r(27) = .31$, $p = .098$, and Relative Source Memory, $r(27) = .34$, $p = .076$. Regarding the ERPs, the LPC effect was marginally correlated with the VLMT Total Learning, $r(27) = .33$, $p = .083$, but with no other behavioral memory measure (all $p > .35$). The P300 effect was positively correlated with the VLMT Total Learning, $r(27) = .44$, $p = .017$, but with no other behavioral memory measure (all $p > .30$). The BDI score was significantly negatively correlated with the SMC Total Scale, $r(27) = -.61$, $p < .001$,the SMC Episodic/Spatial-Scale, $r(27) = -.46$, $p = .011$, and the Attention/Concentration-Scale $r(27) = -.50$, $p = .006$, indicating that people who show higher

Figure 3
ERP Results of the Visual Oddball Task



Note. (A) ERP waveforms for standards and deviants at pooled electrodes P3, Pz, and P4. Shaded bars indicate the 400–700 ms time window used for analysis. (B) Topographic distribution of mean difference between standards and deviants during the 400–700 ms time window. See the online article for the color version of this figure.

Table 3
Correlation Matrix

Variable	MACs ep/sp	MACs att	VLMT tot	VLMT pi	VLMT sr	VLMT lr	VLMT rec	Item-PR	ASM	RSM	LPC	P3	BDI	MMSE	Age	Education
MACs tot	.87***	.83***	.59**	−.37*	.30	.48**	.34†	.20	.11	.20	.37*	.13	−.61***	.11	−.17	−.24
MACs ep/sp		.73***	.59**	−.38*	.39*	.52**	.44*	.33†	.09	.13	.41*	.12	−.46*	.16	−.21	.03
MACs att			.35†	−.22	.22	.46*	.26	.17	.12	.15	.19	.03	−.50**	−.12	−.11	.12
VLMT tot				−.47*	.65***	.65***	.65***	.30	.28	.30	.33†	.44*	−.36†	.44*	−.35†	−.22
VLMT pi					−.18	−.23	−.04	.11	.23	.29	−.13	−.18	.36†	−.27	.00	.20
VLMT sr						.82***	.64***	.28	.12	.18	.18	.19	.03	.44*	−.33†	−.23
VLMT lr							.64***	.30	.06	.04	.17	.20	−.03	.38*	−.32†	−.20
VLMT rec								.54**	.31†	.34†	.12	.12	−.15	.41*	−.36†	−.13
Item-PR									.75***	.56**	−.04	−.08	−.03	.17	−.08	.04
ASM										.85***	−.17	.06	−.08	.02	.13	.12
RSM											−.06	.03	−.21	−.09	.02	.14
LPC												.22	−.15	.00	−.31	−.21
P3													.04	.23	−.04	−.08
BDI														.00	.25	−.22
MMSE															−.16	−.03
Age																−.24

Note. MACs tot = MAC-S total-scale; MACs ep/sp = MAC-S episodic/spatial-scale; MACs att = MAC-S attention/concentration-scale; VLMT tot = total learning; VLMT pi = proactive interference; VLMT sr = short delay recall; VLMT lr = long delay recall; VLMT rec = recognition; ASM = absolute source memory; RSM = relative source memory; LPC = standardized LPC effect (SC vs. SI); P3 = standardized oddball effect (deviants vs. standards); BDI = Beck depression inventory II; MMSE = mini mental status examination.
† $p = .05$–$.1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

depression scores also have higher SMCs. The BDI score was also marginally correlated with VLMT Total Learning, $r(27) = -.36$, $p = .057$, and VLMT Proactive Interference, $r(27) = .36$, $p = .053$, indicating that memory performance tends to be decreased in people with higher depression scores.

Hierarchical Linear Regression Models

Hierarchical linear regression was used to test our specific predictions regarding the relationship between SMCs and objective memory measures.

Source Memory Performance and LPC Predicting SMCs

The following two models are illustrated in Table 4, whereby the SMC Episodic/Spatial-Scale served as dependent variable. First, when relative source memory performance was entered as predictor in a second step in order to evaluate its predictive validity above and beyond age and depression (Table 4A), it did not account for additional variance, $\beta = .04$, $t(25) = 0.24$, $p = .812$. In the second model (Table 4B), the LPC effect was entered in the second step. Besides age and depression, the P300 was included as a first step predictor. The LPC significantly predicted the SMC Episodic/Spatial-Scale above and beyond age, depression and the P300, $\beta = .33$, $t(24) = 1.83$, $p = .040$ and accounted for 9% of the residual variance. This result suggests that a particular amount of variance (independent of age and depression) in SMCs is neurocognitively based on relational memory processes as reflected in the electrophysiological correlate of episodic recollection (i.e., the LPC).

SMCs Predicting VLMT

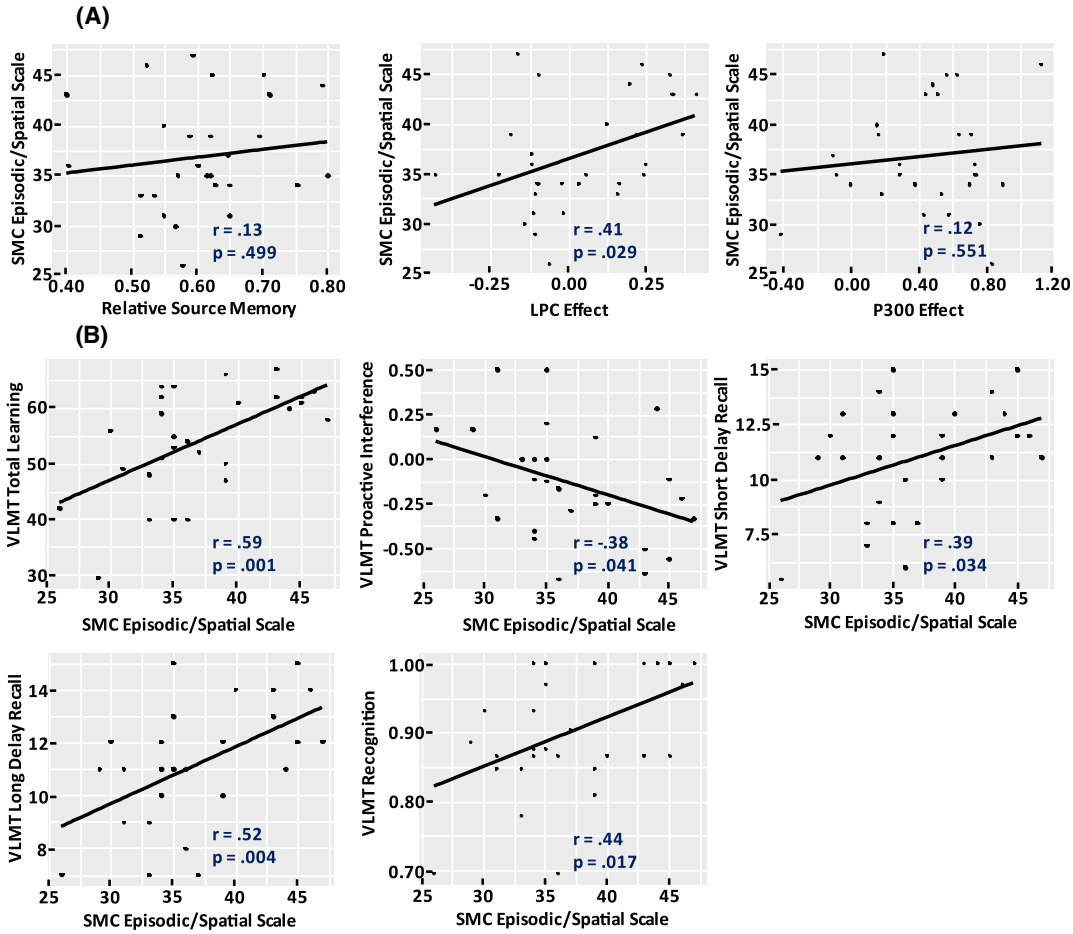
Five hierarchical regression models (each with one VLMT measure as dependent variable) are presented in Table 5. In order to elucidate the unique predictive value of the SMC Episodic/Spatial-Scale for VLMT measures, in addition to age and depression, we also controlled for the influence of the SMC Attention/Concentration Scale. This allows us to assess whether SMCs that target hippocampal processing (SMC Episodic/Spatial-Scale) predict objective memory performance above and beyond subjective estimations of nonmnemonic cognitive capabilities such as attention and working memory.

In the first model (Table 5A), VLMT Total Learning served as dependent variable. In the first step, the SMC Attention/Concentration-Scale was no significant predictor of the VLMT Total Learning score, independent of age and depression, $\beta = .24$, $t(25) = 1.19$, $p = .123$. In the second step, the SMC Episodic/Spatial-Scale was entered and significantly accounted for 17% of the residual variance above and beyond the other predictors, $\beta = .63$, $t(24) = 2.68$, $p = .016$. When the order of entrance was reversed and the SMC Episodic/Spatial-Scale was entered in the second step (before the SMC Attention/Concentration-Scale), it significantly accounted for 20% of the residual variance above and beyond age and depression, $\beta = .51$, $t(25) = 2.91$, $p = .004$.

In the second model (Table 5B), VLMT Proactive Interference served as dependent variable. In the first step, SMC Attention/Concentration-Scale was not a significant predictor, $\beta = -.06$, $t(25) = -0.27$, $p = .397$. In the second step, the Episodic/Spatial-Scale was entered and marginally significantly accounted for additional variance (9%) above and beyond the other predictors, $\beta = -.44$, $t(24) = -1.63$, $p = .058$, whereas the SMC Attention/Concentration-Scale still did not, $\beta = .24$, $t(24) = 0.87$, $p = .197$. When SMCs were entered in reversed order, the SMC Episodic/Spatial-Scale marginally accounted for variance above and beyond age and depression, $\beta = -.29$, $t(25) = -1.41$, $p = .085$.

In the third model (Table 5C), VLMT Short Delay recall served as dependent variable. In the first step, SMC Attention/Concentration-Scale marginally predicted the VLMT Short Delay Recall, independent of age and depression, $\beta = .32$, $t(25) = 1.54$, $p = .069$.

Figure 4
Scatterplots



Note. (A) SMC Episodic/Spatial Scale is predicted by measures of episodic recollection (relative source memory and LPC effect) and the oddball P300 effect. (B) SMC Episodic/Spatial Scale predicts several VLMT measures. Higher values in the SMC Episodic/Spatial-Scale represent lower SMCs. See the online article for the color version of this figure.

In the second step, the SMC Episodic/Spatial-Scale was entered and significantly accounted for 11% of additional variance, $\beta = .49$, $t(24) = 1.91$, $p = .034$. However, the SMC Attention/Concentration-Scale was not a significant predictor, $\beta = -.01$, $t(24) = -0.05$, $p = .482$. When the SMC Episodic/Spatial-Scale was entered in the second step (before the SMC Attention/Concentration-Scale), it significantly accounted for 18% of the residual variance above and beyond age and depression, $\beta = .48$, $t(25) = 2.56$, $p = .009$.

In the fourth model (Table 5D), the VLMT Long Delay Recall served as dependent variable. In the first step, the SMC Attention/Concentration-Scale significantly predicted the VLMT Long Delay Recall, independent of age and depression, $\beta = .60$, $t(25) = 3.33$, $p = .001$. In the second step, when the SMC Episodic/Spatial-Scale was entered, it significantly accounted for 7% of the residual variance above and beyond the other predictors, $\beta = .39$, $t(24) = 1.71$, $p = .04995$. However, the SMC Attention/Concentration-Scale was only a marginal predictor, $\beta = .34$, $t(24) = 0.34$, $p = .077$. When the SMC Episodic/Spatial-Scale was entered in the second step (before the SMC Attention/Concentration-Scale), it significantly accounted for 29% of the residual variance above and beyond age and depression, $\beta = .61$, $t(25) = 3.49$, $p = .001$.

In the fifth model (Table 5E), the VLMT Recognition score served as dependent variable. In the first step, the SMC Attention/Concentration-Scale was not a significant predictor, $\beta = .25$, $t(25) = 1.20$, $p = .120$. In the second step, when the Episodic/Spatial-Scale was entered, it significantly accounted for 10% of variance in the VLMT Recognition above and beyond the other predictors, $\beta = .49$, $t(24) = 1.87$, $p = .037$, whereas the SMC Attention/Concentration-Scale was still not a significant predictor, $\beta = -.07$, $t(24) = -0.28$, $p = .390$. When the SMC Episodic/Spatial-Scale was entered in the second step (before the SMC Attention/Concentration-Scale), it significantly accounted for 15% of the residual variance above and beyond age and depression, $\beta = .44$, $t(25) = 2.28$, $p = .016$.

In sum, these results indicate that SMCs indeed explain variability in the performance on several scales of the VLMT, which is not accounted for by age or depressive symptomology. Importantly, the regression analyses additionally revealed that SMCs which focus on

Table 4
Predictors of SMC Episodic/Spatial-Scale

Variable	*B* (*SE*)	β (*SE*)	R^2-Change	R^2-Total
(A) Predictor of interest: Relative source memory				
Step 1			.22	.22
Age	−0.10 (0.18)	−.10 (.18)		
BDI	−0.61 (0.25)*	−.44 (.18)*		
Step 2			.001	.23
Age	−0.10 (0.18)	−.11 (.18)		
BDI	−0.59 (0.26)*	−.43 (.19)*		
Relative source memory	2.49 (10.39)	.04 (.18)		
(B) Predictor of interest: LPC effect				
Step 1			.24	.24
Age	−0.09 (0.18)	−.09 (.18)		
BDI	−0.62 (0.25)*	−.44 (.18)*		
P300 effect	2.05 (2.79)	.13 (.17)		
Step 2			.09*	.33*
Age	0.00 (0.18)	.00 (.18)		
BDI	−0.58 (0.24)*	−.41 (.17)*		
P300 effect	0.97 (2.73)	.06 (.17)		
LPC effect	8.68 (4.76)*	.33 (.18)*		

Note. SMC = subjective memory complaint; LPC = late positive component; Two independent hierarchical regression models with different predictors of interest. *SE* = standard error; BDI = Beck Depression Inventory II. The effect of (A) relative source memory and (B) LPC effect is tested one-sided.
† $p = .05$–$.1$. * $p < .05$.

hippocampally dependent memory processes (SMC Episodic/Spatial-Scale) capture unique variance of objective memory performance which is not reflected by SMCs that target attentional and working memory abilities (SMC Attention/Concentration-Scale).

Discussion

Although SMCs count as an at-risk factor for MCI (Donovan et al., 2014; Jessen et al., 2010; Luck et al., 2010) and subsequent AD (Jessen et al., 2014; Luck et al., 2015), previous studies did not unequivocally relate more memory complaints to worse memory performance in objective tests (Balash et al., 2010; Buckley et al., 2013; Caramelli & Beato, 2008; Jungwirth et al., 2004; Lenehan et al., 2012; Pearman et al., 2014; see Burmester et al., 2016; Crumley et al., 2014; Reid & Maclullich, 2006; Riedel-Heller et al., 2000, for reviews). Thus, this study examined if SMCs are associated with specific mnemonic functions that are not always assessed in objective memory tests. We suggested that the decline in hippocampally dependent episodic relational memory processes (as measured in a source memory task and the associated LPC effect, the ERP correlate of episodic recollection) determines SMCs because malfunctioning of such processes is highly salient in daily life and the deteriorating integrity of the hippocampus is a driving factor of age-related memory problems (Bettio et al., 2017; Driscoll et al., 2003; Kramer et al., 2007; see Lucas et al., 2016, for a similar argument). Additionally, we assumed that SMCs predict performance in the VLMT as it is a standard memory test that captures such processes. Supporting our assumptions, this study is to our knowledge the first to show that a substantial amount of variance in hippocampally related SMCs is particularly accounted for by the LPC effect, a commonly agreed ERP measure of episodic recollection. This relationship is independent of the impact of attentional processes as reflected in the P300 ERP component as well as age and depression. Furthermore, our data imply that such SMCs—as long as they target hippocampally dependent memory functions—can indeed predict VLMT performance, over and above age and depressive symptomology.

Neurocognitive Determinants of SMCs: Electrophysiological and Behavioral Measures

As predicted, this study revealed that problems with episodic recollection are one of the neurocognitive determinants of increasing SMCs in aging. This fits with the assumption that SMCs arise from deficits in hippocampally dependent episodic memory performance in daily life. In line with a general age-related decline in recollection (Bastin et al., 2013, Bridger et al., 2017; Koen & Yonelinas, 2014) the source-memory-specific LPC effect could not be observed for the whole sample of middle-to-old-aged participants with an age range between 52 and 70 years. However, even older participants can exhibit (reduced) ERP correlates of source memory (Dulas & Duarte, 2013; Dulas et al., 2011), for example, if their episodic memory abilities are less impaired (Duarte et al., 2006). In line with this, in the present study, some participants showed an intact LPC effect and others did not. Accordingly, participants with larger (intact) LPC effects expressed less complaints about their daily life episodic memory functions.

In contrast to the ERP LPC effect, behavioral source memory performance was not significantly associated with SMCs. Generally, null effects should not be overestimated in the present study due to the small sample size. Moreover, in the present study absolute and relative source memory performance was relatively low as compared to young adults in Eschmann et al. (2020) where the same task was used. This suggests that the task was highly difficult for our participants, implicating lower between-subjects variance which potentially constrained the correlational analyses. Importantly, high task difficulty might have also encouraged guess responses diluting behavioral source memory performance. As item memory performance is generally less affected by aging than source memory (McIntyre & Craik, 1987; see Spencer & Raz, 1995, for a review) it

Table 5
SMCs as Predictors of the VLMT

Variable	*B* (*SE*)	β (*SE*)	R^2-Change	R^2-Total
(A) Dependent variable = VLMT total learning				
Step 1			.24†	.24†
Age	−0.47 (0.30)†	−.28 (.18)†		
BDI	−0.40 (0.49)	−.17 (.21)		
Attention/concentration scale	0.79 (0.66)	.24 (.20)		
Step 2			.17**	.42**
Age	−0.36 (0.28)	−.21 (.16)		
BDI	−0.25 (0.44)	−.10 (.19)		
Attention/concentration-scale	−0.60 (0.79)	−.18 (.24)		
Episodic/spatial-scale	1.08 (0.40)**	.63 (.24)**		
(B) Dependent variable = VLMT proactive interference				
Step 1			.14	.14
Age	−0.01 (0.01)	.09 (.19)		
BDI	0.03 (0.02)†	.36 (.22)†		
Attention/concentration-scale	−0.01 (0.02)	−.06 (.21)		
Step 2			.09†	.23
Age	−0.01 (0.01)	−.14 (.19)		
BDI	0.03 (0.02)†	.31 (.21)†		
Attention/concentration-scale	0.03 (0.03)	.24 (.27)		
Episodic/spatial-scale	−0.02 (0.01)†	−.44 (.27)†		
(C) Dependent variable = VLMT short delay recall				
Step 1			.20	.20
Age	−0.17 (0.08)*	−.37 (.18)*		
BDI	0.18 (0.13)†	.28 (.21)†		
Attention/concentration-scale	0.28 (0.18)†	.32 (.21)†		
Step 2			.11*	.31†
Age	−0.14 (0.08)*	−.31 (.18)*		
BDI	0.21 (0.13)†	.33 (.21)†		
Attention/concentration-scale	−0.01 (0.23)	−.01 (.26)		
Episodic/spatial-scale	0.22 (0.12)*	.49 (.26)*		
(D) Dependent variable = VLMT long delay recall				
Step 1			.38**	.38**
Age	−0.14 (0.07)*	−.35 (.16)*		
BDI	0.20 (0.11)*	.36 (.19)*		
Attention/concentration-scale	0.47 (0.14)**	.60 (.18)**		
Step 2			.07*	.45**
Age	−0.12 (0.06)*	−.30 (.16)*		
BDI	0.23 (0.10)*	.40 (.18)*		
Attention/concentration-scale	0.27 (0.18)†	.34 (.23)†		
Episodic/spatial-scale	0.16 (0.09)*	.39 (.23)*		
(E) Dependent variable = VLMT recognition				
Step 1			.18	.18
Age	−0.01 (0.00)*	−.34 (.19)*		
BDI	−0.00 (0.00)	.06 (.21)		
Attention/concentration-scale	0.01 (0.01)	.25 (.21)		
Step 2			.10*	.28†
Age	−0.00 (0.00)†	−.29 (.18)†		
BDI	0.00 (0.00)	.11 (.21)		
Attention/concentration-scale	−0.00 (0.01)	−.07 (.27)		
Episodic/spatial-scale	0.01 (0.00)*	.49 (.26)*		

Note. SMCs = subjective memory complaints; VLMT = Verbal Learning and Memory Test; Five independent hierarchical regression models with different dependent variables. *SE* = standard error; BDI = Beck Depression Inventory II. If the SMC Attention/Concentration Scale has an bivariate correlation with the dependent variable, it is included in Step 1 (A) and (D). The effect of the SMC scales is tested one-sided.
† $p = .05$–$.1$. * $p < .05$. ** $p < .01$.

might constitute a more valid experimental measure of interindividual differences in memory performance in the present middle-to-old aged sample. Consistently, participants with higher Item-PR scores tended to report less SMCs in the present study. Importantly, this does not speak against the assumption that SMCs are determined by episodic memory problems as item memory can be accompanied by (noncriterial) recollection of episodic details (Parks, 2007; Yonelinas et al., 2010).

Discrepancies between the predictive value of the LPC and behavioral source memory measures on SMCs can further be explained by the greater sensitivity of the LPC to hippocampally dependent relational memory processes. Neural measures are more sensitive measures of cognitive processes than purely behavioral measures (Luck, 2005). Moreover, ERPs are less prone to be diluted by guessing responses. Consistent with this view, other studies have reported stronger relationships between SMCs and neural compared

to behavioral memory measures. For example, Erk et al. (2011) report a brain imaging study, wherein participants performed an associative memory task. Critically, participants with and without SMCs did not differ in task performance. However, participants with SMCs showed reduced right hippocampal activity during recall and increased activation of the right dorsolateral prefrontal cortex, compared to controls. The authors argue that hippocampally dependent memory deficits in participants with SMCs were not observable within their behavioral measures since they might have been compensated through additional recruitment of the prefrontal cortex. This conclusion is further supported by a study of Hafkemeijer et al. (2013), who report increased functional connectivity within the default mode network as well as the medial visual network in elderly adults with SMCs, indicating a compensatory mechanism. As a rare exception, Horn et al. (2018) report that SMCs in elderly participants were related to behavioral performance in an associative memory task (face-name-recognition) which might be explained by the high ecological validity of this task as problems in face-name-recognition do occur frequently in the daily life of elderly people (Naveh-Benjamin et al., 2004).

Together, these results emphasize the prognostic importance of SMCs that target hippocampal processes, as they might have a greater potential to reveal problems with episodic memory than standard source or associative memory tasks. These tasks are often already too difficult for memory-impaired individuals which might encourage guessing and therefore are less reliable indicators of the underlying mnemonic abilities. SMCs, in contrast, are not affected by factors such as guessing because even if people successfully guess in daily life, they are probably aware of and can account for this when reporting their SMCs. We conclude that problems with episodic recollection are one determinant of SMCs. This properly complements behavioral results that relate SMCs to hippocampally dependent relational memory processes (Horn et al., 2018; Lucas et al., 2016). However, as this study and others show, SMCs are multiply determined as they further rely on negative affective variables, such as depression, anxiety and neuroticism (Balash et al., 2010, 2013; Buckley et al., 2013; Pearman et al., 2014; Rowell et al., 2016; Yates et al., 2017), and memory self-efficacy (Lucas et al., 2016). Therefore, the multiple bases of SMCs should be carefully considered, when using SMCs for clinical demands.

VLMT and the Predictive Validity of SMCs on Objective Memory Measures

Confirming our prediction, several measures of the VLMT were successfully predicted by SMCs. However, this stands in contrast to many studies that report no association between SMCs and objective memory performance (Balash et al., 2010; Buckley et al., 2013; Burmester et al., 2017; Caramelli & Beato, 2008; Jungwirth et al., 2004; Pearman et al., 2014). As our first set of analyses suggests, SMCs—especially those that target hippocampal contributions to episodic memory—at least partially rely on episodic recollection which relies on the hippocampal relational memory system. The VLMT and especially the recall and recognition measures can be related to such processes. In the short and long delay recall, information must be protected against retroactive interference as an irrelevant item list is studied and recalled between acquisition and retrieval of the relevant learning list. Importantly, retroactive interference seems to be one driving factor of anterograde amnesia (Dewar et al., 2010) which is associated with hippocampal malfunctioning (Cipolotti & Bird, 2006, see Pohlack et al., 2014, for a similar argument). In the recognition task, targets must be discriminated from semantically and phonologically related lures, a task that is dependent on hippocampal pattern separation processes, that is, generating highly distinct representations to encode the details of specific events (Kirwan & Stark, 2007; Yassa & Stark, 2011). Accordingly, previous studies showed that patients with hippocampal lesions are impaired in several measures covered by the VLMT such as the total learning score, short and long delay recall, and recognition performance (Bartsch et al., 2010; Manns et al., 2003). Moreover, van Norden et al. (2012) report an association between the microstructural integrity of the HC and performance in total learning, delayed recall, and recognition in nondemented elderly participants. Deterioration in delayed recall was also associated with age-related degradation of the perforant path, a structure which is crucial for hippocampal functioning (Yassa et al., 2010). Additionally, studies have shown that larger hippocampal volume goes along with higher performance in total learning, short and long delay recall and the recognition task in elderlies with SMCs (Mueller et al., 2011) and young healthy adults (Pohlack et al., 2014). In our view, this makes an association between the VLMT and SMCs more likely compared to objective memory measures that rely less on hippocampal episodic memory functions.

Another methodological aspect that differs between this study and some others which do not report an association (i.e., Balash et al., 2010; Caramelli & Beato, 2008; Jungwirth et al., 2004) is that these studies treated SMCs as a grouping variable (participants with vs. without SMCs) as compared to the gradual measure we used in this study. It might be advantageous to exploit the whole range of variance in SMCs, in order to use them as a reliable predictor of objective memory performance. This suggests that the severity of SMCs rather than their presence is crucial when exploring memory deficits in clinical contexts.

A further important aspect is related to the particular cognitive processes captured by SMCs. Studies vary extensively considering the definitions of SMCs and the cognitive domains for which self-reported complaints are assessed (Abdulrab & Heun, 2008; Rabin et al., 2015). This is one possible reason for the controversial findings regarding the relation of SMCs with objective memory performance. In line with our prediction, the SMC Episodic/Spatial-Scale predicted VLMT Total Learning, VLMT Short Delay Recall, VLMT Long Delay Recall and VLMT Recognition when controlled for age, depression, and the SMC Attention/Concentration-Scale whereas the predictive value of the SMC Attention/Concentration-Scale on the VLMT was less robust. This highlights that in order to use SMCs as an indicator of objectively measurable memory performance, both need to target the same underlying processes (e.g., episodic memory). Moreover, Abdulrab and Heun (2008) suggested that meaningful SMCs should target valid examples of memory problems and their frequency in daily life. This is fulfilled in the Episodic/Spatial-Scale which presumably has strengthened the association between SMCs and objective memory measures. Thus, the present study suggests that if SMCs are used clinically as a diagnosing tool, they need to reflect everyday memory functions that are prone to decline in MCI and AD, such as those with high dependence on the hippocampal relational memory system.

Further, it seems to be important in which temporal order SMCs, objective memory performance, and depressive symptomology are

assessed. In the present study, SMCs were measured first, followed by objective memory measures and finally the depression score. This sequence increases the validity of SMCs as they are not biased by objective memory performance and depressive symptomology. It is not unlikely that especially elderly participants perceive their memory performance in an unfamiliar and difficult laboratory task worse than it actually is. This could lead to an overestimation of their memory problems in daily life. However, depression scores were potentially influenced by SMCs and memory performance in the present study, which might artificially increase the amount of shared variance between BDI and these measures. Since we were primarily interested in the relationship between SMCs and objective memory while depressive symptomology served as a covariate, this seems to be a minor concern.

The Relationship Between the Source Memory Task and the VLMT

Recognition performance was the only VLMT measure that correlated with behavioral measures of the source memory task (positively with Item-PR and marginally positively with absolute and relative source memory performance). An explanation for this relationship could be that all four measures test recognition memory in a similar format and are therefore highly comparable. However, the absence of any other correlation between behavioral source memory measures and the VLMT scores could be accounted for by the fact that Item-PR is not a selective measure of hippocampal memory functions and source memory performance is a less valid reflection of interindividual memory performance in the present sample (see discussion above). Moreover, it is also conceivable that our middle-to-old aged participants are less familiar with computer-based tasks and therefore produced more error variance in behavioral measures of the computer-based source memory task than in the VLMT which is conducted verbally in a face-to-face setting. Thus, we consider the VLMT as the most meaningful behavioral memory measure in the present study.

However, as both the LPC and the VLMT are considered valid measures of hippocampally dependent episodic memory processes it is somehow surprising that LPC magnitude was only marginally correlated with the total learning score but not with any other VLMT measure. Total learning is generally considered a measure of short term or working memory (Helmstaedter et al., 1997), which is supported by the correlation between VLMT total learning and the P300 effect in the present study. This convergence between LPC and P300 emphasizes the importance of controlling P300 related variance in the regression analyses. Further, one account that potentially explains why the LPC magnitude is associated with the Episodic/Spatial-scale but not with any other behavioral measure in the source memory task or VLMT (except VLMT total learning) can be derived from the view that LPC magnitude covaries with the subjectively experienced quality or richness of recollection (MacLeod & Donaldson, 2017) and does not indicate the mere presence or absence of recollection. Accordingly, there is some evidence that the LPC amplitude is sensitive to the amount or precision of recollected information when recollection occurs (Murray et al., 2015; Vilberg et al., 2006). This subjective experience of the quality of a memory is not reflected in behavioral measures of source memory or the VLMT subscales which assess memory more in an all-or-none fashion. Thus, it seems plausible that the independent proportions of variance explained by the LPC amplitude and the VLMT measures in the Episodic/Spatial-Scale reflect that SMCs are determined by deterioration of both, quantitative episodic memory performance (VLMT) and subjective experience of the quality of episodic memory (LPC). Therefore, SMCs cover problems with episodic memory functions in a comprehensive way.

Limitations and Further Directions

The present study clearly indicates that SMCs are determined by relational episodic memory processes and therefore have predictive validity for objective memory performance. However, our studies also bear some limitation that need to be addressed in further research.

First, bivariate correlations (Table 3) convey an impression of the overall data in the present study. However, as they were not corrected for multiple testing and our sample size was relatively small (reduced power), bivariate correlations (e.g., reasoning on the absence of a relationship between the LPC effect and behavioral memory measures) must be carefully interpreted and need to be replicated in further research. Most importantly, our main conclusions remain valid as they are derived from significant effects in multiple regression models for which we had directed, a priori specified hypotheses.

Second, the present study was not designed to investigate sex-related differences regarding the association between SMCs and hippocampally dependent memory functions. However, previous studies found that the predictive utility of self-reported SMCs for objective memory performance in patients with amnestic MCI is limited to women (Sundermann et al., 2018, but see Tomita et al., 2014) and that the presence of subjective cognitive decline predicts subsequent dementia only in women (Heser et al., 2019). Such moderating effects must be further investigated and must be carefully considered when SMCs are assessed in a clinical context.

Third, another factor that potentially impacts the association between SMCs and objective memory performance concerns the simulation of memory impairment. A study by Armistead-Jehle et al. (2012) suggests that participants who exaggerate their cognitive complaints are prone to inflate their cognitive difficulties by underachieving in cognitive tests. Thus, further studies are required that address this issue for example by including symptom and performance validity tests. However, one strength of the present study is that SMCs are validated by their relationship with the LPC which is less likely intentionally modified by participants.

Conclusion

Our study showed that deficits in memory processes with high dependence on the hippocampal relational memory system (as reflected in the ERP correlate of episodic recollection) are one determinant of SMCs in the middle-to-old adult age range, supporting their importance for diagnosing MCI (Petersen, 2016). Moreover, the present study shows that if the assessment of SMCs targets problems with hippocampally dependent memory functions, they can be used to reliably predict objective memory performance. Therefore, SMCs provide an economical and easy way to assess progressing mnemonic deficits at an early stage (as we investigated a relatively broad age-range), which is highly important as AD

patients' benefit from treatment is maximal if it is initiated early in the course of the disease (Cummings et al., 2007). The use of SMCs seems to be especially advantageous as some behavioral measures seem to less reliably reflect the underlying neurocognitive processes. Thus, it seems promising to sensitize populations in the middle-to-old adult age range for the occurrence of SMCs, encouraging them to consult medical advice early.

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Appendix

Episodic/Spatial-Scale

How well do you remember the following things: 1 (*very poor*) to 5 (*very good*)

1. "Gifts you have received at holidays during the past several years"
2. "Details of holidays or special occasions of your childhood"
3. "Verbal directions to a geographic location given minutes earlier"
4. "Details of family events that occurred during the past year"
5. "Which door you entered when shopping in a large department store or mall"
6. "How to reach a geographic location you have visited once or twice"
7. "Who was with you at events attended weeks or months ago"

How often do the following things happen to you: 1 (*very often*) to 5 (*very seldom*)

8. "Forget which waiter took your order in a restaurant"
9. "Fail to recognize people who recognize you"
10. "Meet people who seem familiar but can't remember where you met them"

(*Appendix continues*)

Attention/Concentration-Scale

How often do the following things happen to you: 1 (*very often*) to 5 (*very seldom*)

1. "Miss the point someone else is making during a conversation"
2. "Have difficulty following a conversation when there are distractions in the environment such as noise from a TV or a radio"
3. "Have to reread earlier paragraphs from a newspaper or magazine story to understand the point"
4. "Have trouble finding your place again when interrupted in reading"
5. "Confuse one word with another when they sound the same"

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