Fluency Affects Source Memory for Familiar Names in Younger and Older Adults: Evidence from Event-related Brain Potentials

Jessica Komes, Stefan R. Schweinberger & Holger Wiese

DFG Research Unit Person Perception &

Department of General Psychology and Cognitive Neuroscience

Friedrich Schiller University of Jena, Germany

Author Note

Jessica Komes, Stefan R. Schweinberger and Holger Wiese, DFG Research Unit Person Perception and Department for General Psychology and Cognitive Neuroscience, Friedrich Schiller University of Jena, Germany.

This work was supported by a grant of the Deutsche Forschungsgemeinschaft (DFG) to H.W. (Wi 3219/4-2). We gratefully acknowledge help during data collection by Kathrin Rauscher, Kristin Oehler, and Franziska Krahmer. We thank the anonymous reviewers for helpful comments on an earlier version of the manuscript.

Correspondence concerning this article should be addressed to Jessica Komes, M.Sc., DFG Research Unit Person Perception and Department of General Psychology and Cognitive Neuroscience Friedrich Schiller University of Jena, Am Steiger 3/1 07743 Jena; Germany. E-Mail: jessica.komes@uni-jena.de, Phone: +49 3641 945934, Fax: +49 3641 945182

Abstract

A current debate in memory research is whether and how the access to source information depends not only on recollection, but on fluency-based processes as well. In three experiments, we used event-related brain potentials (ERPs) to examine influences of fluency on source memory for famous names. At test, names were presented visually throughout, whereas visual or auditory presentation was used at learning. In Experiment 1, source decisions following old/new judgments were more accurate for repeated relative to non-repeated visually and auditorily learned names. ERPs were more positive between 300 and 600 ms for visually learned as compared to both auditorily learned and new names, resembling an N400 priming effect. In Experiment 2, we omitted the old/new decision to more directly test fast-acting fluency effects on source memory. We observed more accurate source judgments for repeated versus non-repeated visually learned names, but no such effect for repeated versus non-repeated auditorily learned names. Again, an N400 effect (300-600 ms) differentiated between visually and auditorily learned names. Importantly, this effect occurred for correct source decisions only. We interpret it as indexing fluency arising from within-modality priming of visually learned names at test. This idea was further supported in Experiment 3, which revealed an analogous pattern of results in older adults, consistent with the assumption of spared fluency processes in older age. In sum, our findings suggest that fluency affects person-related source memory via within-modality repetition priming in both younger and older adults.

Keywords: source memory, fluency, familiar names, priming, ERPs, N400

Introduction

Memory for whether or not we have heard a certain name before is crucial for daily-life social interactions. Often, however, it is important not only to recognize that name, but also to remember in which context the name had occurred. Confusing such information can be embarrassing, and thus prejudicial to social interaction – an issue, which may be particularly disadvantageous for older adults, as social interactions form an important part of their everyday life (Leirer, Morrow, Sheikh, & Pariante, 1990). The present study examined neural correlates of remembering context information for familiar names in both young and older adults.

Our episodic memory system is not only constituted by storage and retrieval of a particular item, but may also yield related information, such as the spatial and temporal context or perceptual information. Such detail is often termed source information as it informs about the conditions under which an item originated (Johnson, Hashtroudi, & Lindsay, 1993; Mitchell & Johnson, 2009; Mollison & Curran, 2012). Typically, source memory has been examined by experimentally varying different aspects during encoding (e.g. such as an item was presented visually or auditorily during learningWilding, Doyle, & Rugg, 1995). Importantly for the present study, previous research suggests that source memory is substantially reduced in older adults (Anderson & Craik, 2000; Cansino et al., 2013; Spencer & Raz, 1995).

Source memory is commonly tested in addition to item memory, and in order to determine *how* a stimulus was remembered. Many current models of recognition memory assume two processes of retrieval: familiarity and recollection (Yonelinas, 2002). Familiarity is defined as a fast-acting context-free ‘feeling of knowing’, whereas recollection is assumed to enable the re-experience of an episode, and thus necessarily involves context or source information which is accessed more slowly (e.g.Mandler, 1980; Yonelinas, 2002). Until recently, there has been scant disagreement that source memory predominantly relies on recollection. Recent studies, however, suggest a prominent role of familiarity for source decisions as well (Diana, Yonelinas, & Ranganath, 2008).

Event-related potentials (ERPs) may contribute to specify the role of familiarity during the retrieval of source information. It is well-established that correctly recognized items (i.e., hits) elicit more positive ERP amplitudes than correct rejections (Rugg, 1995), a phenomenon known as the old/new effect. More specifically, a relatively early (approximately 300 – 500 ms) frontal old/new effect, sometimes referred to as FN400, has been related to familiarity (e.g. Curran, 2000). Alternatively, others related this effect to conceptual priming (Paller, Voss, & Boehm, 2007), and thus to implicit memory. A subsequent left parietal old/new effect (approximately 500 –800 ms) is commonly related to recollection (Rugg & Curran, 2007). In line with the idea of recollection contributing to source memory, this left parietal positivity is larger for hits with correct as opposed to incorrect or missing source information (Senkfor & Van Petten, 1998; Wilding & Rugg, 1996). Finally, a late frontal old/new effect (LFE), starting at approximately 500 – 800 ms and lasting for several hundred milliseconds, is assumed to index retrieval monitoring (Cruse & Wilding, 2009; Wilding & Rugg, 1996).

A number of previous studies examined ERP old/new effects in older adults. Whereas some researchers observed similar parietal effects in young and older adults (e.g. Mark & Rugg, 1998; Osorio, Ballesteros, Fay, & Pouthas, 2009; Trott, Friedman, Ritter, & Fabiani, 1997), others found this effect to be reduced or absent in older groups (Nessler, Friedman, Johnson, & Bersick, 2007; Swick & Knight, 1997; Wang, de Chastelaine, Minton, & Rugg, 2012). While these latter findings are generally in line with the suggestion of reduced recollection in older adults (e.g. Anderson & Craik, 2000), the discrepancy in ERP results may be partly related to task effects (Wolk et al., 2009). For instance, old/new effects of older and young adults become more similar with stronger environmental support (e.g., with longer word stems in a cued recall task; Angel et al., 2010). In addition, several studies found the earlier frontal old/new effect to be absent in older adults (in a deep but not in a shallow encoding condition, see Osorio et al., 2009; Wang et al., 2012; Wolk et al., 2009). As familiarity is typically assumed to be intact in this age group, this finding has been interpreted as reflecting qualitative differences in the neural signals reflecting familiarity in young versus older adults (Wang et al., 2012). Finally, with respect to late frontal effects, results are again mixed, with some studies showing similar LFEs in young and older adults (e.g. Mark & Rugg, 1998), while others reported age-related changes (Cansino, Hernandez-Ramos, & Trejo-Morales, 2012; Swick, Senkfor, & Van Petten, 2006).

A number of previous studies examined these ERP effects to clarify the specific processes related to source retrieval. Supporting the notion of beneficial familiarity effects on source memory in young adults, Diana and colleagues (Diana, Van den Boom, Yonelinas, & Ranganath, 2011) observed a mid-frontal ERP effect for correct versus incorrect source judgments. This effect was restricted to a condition emphasizing unitization of an item with its context (such as representing an object with the background color as one single unit). It should be noted, however, that the frontal effect in this study occurred substantially later (i. e. 700 – 1000 ms) than the typical frontal old/new effect described above.

Several ERP studies suggested contributions of familiarity on source judgments independent of unitization (e.g. Addante, Ranganath, & Yonelinas, 2012). For instance, Peters and Daum (2009) reported a more positive FN400 for correct relative to incorrect source retrieval and for incorrect trials relative to correct rejections. Mollison and Curran (2012) observed that correct source memory for spatial location (but not frame color) was accompanied by an increase in behavioral measures of familiarity. Similarly, an FN400 modulation, which differentiated between correct versus incorrect source responses was only apparent when source memory for spatial information was tested.

While familiarity reflects processes of explicit memory, implicit processes, such as perceptual priming, have also been reported to affect source memory (Kurilla, 2011). Interestingly, both familiarity and priming are assumed to be related to fluency. Fluency is typically defined as a feeling of ease associated with a cognitive operation, and has been shown to influence a variety of judgments based on, for instance, conceptual or perceptual similarity (for overview, see Oppenheimer, 2008). It has been proposed that enhanced fluency manifests in priming and can concomitantly be experienced as (or translated into) familiarity during recognition (Hayes & Verfaellie, 2012). Others have suggested that fluency signals are implicit in nature and therefore separate from familiarity, but may (accidentally) contaminate explicit forms of memory, i.e. familiarity-based recognition (for a similar line of argument, see Lucas, Taylor, Henson, & Paller, 2012; Voss, Lucas, & Paller, 2012).

Independent of the exact interrelation of familiarity and priming, fluency-related processes may not only contribute to the accessibility of source information in younger adults, but also affect source memory in older age. Bastin et al. (2013) reported beneficial effects of familiarity-based processes on source memory in older adults when applying the unitization procedure previously introduced by Diana and colleauges (2008, 2011). Moreover, in an fMRI study, (Dulas & Duarte, 2012) observed activity in the perirhinal cortex, a structure associated with familiarity-based processes, to increase with enhanced source memory performance in older adults. This finding was interpreted as reflecting greater reliance on familiarity with higher age. Corresponding evidence from ERP studies is lacking.

Taken together, growing evidence suggests a prominent role of fluency for source memory, but the precise circumstances under which fluency may or may not enhance source decisions are not clear at present. We reasoned that using familiar names as stimulus material would be particularly promising in this context. In contrast to (abstract or concrete) nouns or objects, personal names are relatively pure referents, with little or no inherent meaning (Wittgenstein, 1922), pointing to unique mental representations for individual persons (Burton, Bruce, & Johnston, 1990; Valentine, Bredart, Lawson, & Ward, 1991). Fluency-based processes, such as modality-specific long-term repetition priming, easily activate these representations (e.g. Bruce & Valentine, 1985). Whereas priming has been investigated in a number of previous studies, source memory for person-related information has been examined relatively scarcely (Dywan, Segalowitz, & Arsenault, 2002; Yovel & Paller, 2004).

Previous studies on name priming yield valuable information for the present purposes. Participants are faster to indicate that a name is familiar if it has been presented previously (Bruce & Valentine, 1985; Pickering & Schweinberger, 2003). Importantly, effects of long-term repetition priming of names (and faces) do not cross input modality (see e.g. Burton et al., 1990), which means that, e.g., the prior presentation of a written name results in a faster decision if that same written name is presented again, whereas a spoken name should not prime a familiarity decision on a written name. This is generally in line with reduced or even absent cross-modality priming with auditory versus visual word presentation (e.g. Roediger & Blaxton, 1987), but in contrast to cross-modality priming in both younger and older adults for ecologically valid stimuli presented in the visual and auditory, as well as in the visual and tactual modality (Ballesteros, Gonzáles, Mayas, García-Rodríguez & Reales, 2009, Reales & Ballesteros, 1999). In an ERP study, repeated relative to non-repeated names elicited more positive amplitudes between 500 - 600 ms (Schweinberger, Pickering, Burton, & Kaufmann, 2002), resembling an N400 effect (Kutas & Federmeier, 2011), which was interpreted as reflecting the facilitated access to person-specific representations. Accordingly, an influence of repetition priming on source memory judgments for person-related information may manifest in N400-like ERP effects.

In the present study, we examined source memory for famous names. The use of these ecologically more valid stimuli appeared particularly important for examining older adults who often complain about difficulties remembering names (see e.g. Cohen & Burke, 1993; Cohen & Faulkner, 1986; Old & Naveh-Benjamin, 2012). Moreover, on the one hand age-related source memory deficits are typically observed in laboratory experiments, while on the other hand a considerable discrepancy between lab and daily-life situations has been noted (see e.g. Verhaeghen, Martin, & Sedek, 2012). In the present experiments, names were either presented visually or auditorily during learning. To test for potential effects of repetition priming on source judgments, all names were presented visually at test, and accordingly half of the names were repeated within the same modality between learning and test, whereas the other half was presented in a different modality. Thus, in context of the present study, fluency was conceptualized as the potentially facilitated processing for visually relative to auditorily learned names resulting from an overlap between study and test modality. Moreover, we presented half of the names repeatedly during learning, a manipulation that has been described to particularly enhance the recollection of the items (Dewhurst & Anderson, 1999). In all experiments reported below, we assessed neural correlates of the accompanying processes using ERPs. We reasoned that if fluency affected source memory in terms of within-modality repetition priming, more positive amplitudes for visually learned names as compared to both auditorily learned and new names should occur in an early time window (reflecting an N400/FN400). Moreover, if repetition during learning enhanced recollection for both visually and auditorily learned names (see Dewhurst & Anderson, 1999), larger old/new effects in the 600 – 900 ms time range for items repeated during learning, independent of study-test modality overlap, should be observed.

Experiment 1

Method

Participants. The studied population consisted of 20 young undergraduate students (*M* = 23.2 years, *SD* = 2.7, 18 female) at the Friedrich Schiller University, who either received course credit or monetary compensation. All participants were right-handed according to a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971)and none reported neurological or psychiatric disorders or receiving central-acting medication. All participants gave written informed consent. Before the experiment, visual acuity and contrast vision (Bach, 1996), as well as cognitive covariates were assessed (see Table 1 and Participant Section of Experiment 3).

Stimuli and Design. Stimuli were 400 famous names (e.g., “Brad Pitt”, “Angela Merkel”, “Steffi Graf”, “Robbie Williams”), taken from a previous rating study (see Wiese & Schweinberger, 2008). Care was taken that names were familiar to young and older adults (see Experiment 3), which was confirmed in additional familiarity ratings carried out after the main experiment. The names were either presented visually (Courier New, font size 28) or auditorily during learning. The auditory stimuli were created via audio recordings from a male speaker vocalizing each of the names. Recordings were made by means of a Beyerdynamic™ MC-930 condenser 146 microphone with pop protection and a Zoom H4n audio interface (44.1 kHz, 16 bit). By means of Adobe Audition™ software, stimuli were normalized to 70 db RMS. Auditory stimuli had an average length of 1486 ms (SD = 220).

During learning, of 100 spoken names, 50 were presented once and 50 were presented twice. Similarly, 50 written names were presented once and 50 were presented twice. The remaining 200 names were used as new names during test. Assignment of stimuli to each of these five conditions was counterbalanced across participants. During learning, written and spoken names were presented in a pseudo-randomized sequence, such that a minimum of 22 and a maximum of 292 (M = 151) intervening items occurred between any repetitions.

Procedure. Participants were seated in a dimly lit, electrically shielded, and sound-attenuated chamber (400-A-CT-Special, Industrial Acoustics, Niederkrüchten, Germany) with their heads in a chin rest approximately 90 cm from a computer monitor. The experimental session began with a series of practice trials, which were excluded from data analysis. After practice our participants were asked to indicate whether sound level was sufficient or needed to be adjusted.

During the learning phase visual and auditory names were presented in an alternating sequence, in which modality changed after every stimulus. Visually presented names (forename and surname) were displayed horizontally in white font in the center of a black screen. All items were presented at a stimulus onset asynchrony (SOA) of 3000 ms, including an initial fixation cross (500 ms) and a final blank screen (500 ms). Auditory names were presented in mono via Sennheiser headphones. During learning participants were asked to categorize each name via key press as male or female and to memorize the names with their respective source (visual vs. auditory presentation).

In the subsequent test phase, names were presented in white font in the center of a black screen. Each test trial started with a fixation cross (500 ms), followed by a name (2000 ms). Participants were informed that the test list would include names that they had either read or heard earlier (previously learned names) intermixed with an equal number of new names, and that the sets of read and heard names were non-overlapping. They were instructed to indicate via key presses as fast and correctly as possible whether the name was certainly old, probably old, probably new, certainly new, or whether they did not know. Key assignment was counterbalanced across participants. If a name was judged to be old, it remained on the screen (3000 ms) with the instruction to indicate as fast and correctly as possible whether the respective name was certainly heard, probably heard, probably read, certainly read, or whether they could not remember the source of the name[1]. If a stimulus was judged new, the next test trial was initiated.

EEG recording and analysis. 32-channel EEG was recorded during test using a BioSemi Active II system (BioSemi, Amsterdam, Netherlands). The active sintered Ag/Ag-Cl-electrodes were mounted in an elastic cap. EEG was recorded continuously from Fz, Cz, Pz, Iz, FP1, FP2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, F9, F10, FT9, FT10, TP9, TP10, P9, P10, PO9, PO10, I1, I2, with a 512-Hz sample rate from DC to 155 Hz. Please note that BioSemi systems work with a “zero-Ref” set-up with ground and reference electrodes replaced by a CMS/DRL circuit (for further information, see www.biosemi.com/faq/cms&drl.htm).

Contributions of blink artifacts were corrected using the algorithm implemented in BESA 5.1 (MEGIS Software GmbH, Graefelfing, Germany). EEG was segmented from -200 until 2000 ms

[1] Please note that we collapsed across confidence ratings as too few subjects made use of the option to indicate that a previously studied item was *probably* old or new or heard or seen for an appropriate number of trials (mean number of key presses was 8 for *probably* old/new and 7 for *probably* heard/seen responses) regarding the analysis of ERPs.

relative to stimulus onset, with the first 200 ms as baseline. Since insufficient numbers of trials (< 16) were available for conditions with incorrect responses in the majority of participants, only trials with correct responses, i.e. correct rejections or hits plus correct source judgments, entered the analysis. Trials contaminated by non-ocular artifacts and saccades were excluded. Artifact rejection was carried out using the BESA 5.1 tool, with an amplitude threshold of 100 μV and a gradient criterion of 75 μV. Remaining trials were recalculated to average reference, digitally low-pass filtered at 40 Hz (12 db/oct, zero phase shift), and averaged according to experimental conditions (correct rejections, non-repeated visually learned hits plus source correct, repeated visually learned hits plus source correct, non-repeated auditorily learned hits plus source correct, repeated auditorily learned hits plus source correct). The mean number of trials contributing to an individual averaged ERP for these conditions was 148, 21, 31, 22, and 28, respectively.

We analyzed two time ranges from 300 to 600 and from 600 to 900 ms, which have been related to familiarity/conceptual priming and recollection, respectively (see introduction). Visual inspection of the data suggested a further analysis in a more restricted time range (400-500 ms). Moreover, after inspection of the scalp distribution of old/new effects we decided to analyze the two earlier time windows at midline sites (Fz, Cz, Pz). As the later old/new effect is typically left-lateralized for verbal material, we tested the 600 – 900 ms time window in a larger grid of electrodes, additionally including lateral sites (F3/F4, C3/C4, P3/P4). Statistical analyses were performed by calculating repeated-measures analyses of variance (ANOVA), with degrees of freedom corrected according to the Greenhouse-Geisser procedure where appropriate.

Results and Discussion

Old/new recognition accuracy. A repeated measures analysis on the hit rate[2] with factor condition (visually learned non-repeated, visually learned repeated, auditorily learned non-repeated, auditorily learned repeated and new) resulted in a significant effect of condition, $F(1.32, 24.98) = 11.20$; $p = .001$; $\eta^2_p = .25$. Follow-up t-tests indicated higher accuracies for correct rejections as compared to both non-repeated visually, $t(19) = 2.50$; $p = .021$; $d = 0.91$, and non-repeated auditorily learned names, $t(19) = 3.21$; $p = .005$; $d = 1.02$. Furthermore, repeatedly relative to non-repeatedly learned names resulted in higher accuracies in both the visually, $t(19) = 7.32$; $p < .001$; $d = 1.29$ and auditorily learned condition, $t(19) = 7.52$; $p <= .001$; $d = 1.20$; see Table 2. No further differences were detected, t ranging from 0.45 – 1.54; p ranging from .964 - .140.

Reaction times. A corresponding analysis on mean reaction times for correct old/new responses resulted in a trend for the factor condition, $F(2.43,46.17) = 2.62$; $p = .073$; $\eta^2_p = .12$, pointing towards slower responses for auditorily learned as compared to visually learned or new names; see Table 3.

Source memory accuracy[3]. Source memory was analyzed by comparing correct source decisions between the different experimental conditions, since the major question of the present study addressed the role of learning phase modality for source accuracy (see also Jacoby, 1999). This cannot be examined by using corrected source memory measures, such as Pr or d'' (as correcting visually learned items for incorrect "seen" decisions for auditorily learned items would result in identical scores as correcting auditorily learned items for incorrect "heard" decisions).

A repeated measures analysis on correct source judgments (see Table 3) with the factors modality during learning (visual versus auditory) and repetition during learning (non-repeated versus repeated) resulted in a significant effect of repetition, $F(1,19) = 14.52$; $p = .001$; $\eta^2_p = .43$, with higher source accuracies for repeated relative to non-repeatedly learned names. Although repetition

[2] Please note that old/new recognition is measured in % correct. With the current design it is not possible to report corrected hit rates as incorrect responses to new items during test (false alarms) cannot be assigned to a specific experimental condition.

[3] We decided not to analyze mean RTs for the source decision since the respective stimulus was already on the screen during the preceding old/new task. Hence, it is not possible to clearly determine the timing of the source decision.

during learning appeared to be more pronounced for visually learned names, the interaction of modality during learning by repetition during learning was not significant, $F(1,19) = 1.63$; $p = .217$; $\eta^2_p = .08$; see Table 4.

Event-related potentials (ERPs). Grand Mean ERPs for each of the experimental condition of Experiment 1 are depicted in Figure 1.

300-600 ms. An ANOVA with factors site (Fz, Cz, Pz) and condition (non-repeated visually learned, repeated visually learned, non-repeated auditorily learned, repeated auditorily learned and correct rejections) revealed an effect of condition, $F(4,76) = 4.57$; $p = .002$; $\eta^2_p = .19$. Relative to correct rejections, non-repeated visually learned names, $F(1,19) = 4.98$; $p = .038$; $\eta^2_p = .21$, repeated visually learned names, $F(1,19) = 18.89$; $p < .001$; $\eta^2_p = .21$, and repeated auditorily learned names, $F(1,19) = 7.91$; $p = .011$, $\eta^2_p = .29$, elicited more positive amplitudes. No differences were detected between correct rejections and non-repeated auditorily learned names, $F < 1$.

Furthermore, among hits plus correct source judgments, an ANOVA with the factors site (Fz, Cz, Pz), modality during learning (visual, auditory), and repetition during learning (non-repeated, repeated) yielded effects of learning modality, $F(1,19) = 12.47$; $p = .002$; $\eta^2_p = .40$, with more positive amplitudes for visually relative to auditorily learned names, and of repetition during learning, $F(1,19) = 8.54$; $p = .009$; $\eta^2_p = .31$, with more positive amplitudes for repeated relative to non-repeatedly learned names; see Figure 1.

Analyses in 100 ms steps. As visual inspection of the waveforms indicated differential effects within the 300 – 600 ms time window, more fine-grained analyses with intervals from 300 – 400 ms, 400 – 500 ms, and 500 – 600 ms were conducted. Statistical indices for these analyses are reported in Table 5. In short, analysis of the 300 – 400 ms time window yielded a significant main effect of condition, reflecting more positive amplitudes for both repeated visually learned and repeated auditorily learned names relative to correct rejections. The analysis on hits plus correct source decisions revealed significant effects of modality, with more positive amplitudes for visually relative to auditorily learned names, and repetition, with more positive amplitudes for repeatedly learned names.

The analysis of the 400 – 500 ms time window resulted in a significant effect of condition. Notably, relative to correct rejections, non-repeated visually learned and repeated visually learned names elicited more positive amplitudes, but no differences were detected between correct rejections and non-repeated auditorily learned or repeated auditorily learned names, see upper part of Figure 2. The analysis on hits plus correct source decisions resulted in a main effect of learning modality, with more positive amplitudes for visually relative to auditorily learned names, see Figure 3. The effect of repetition during learning did not reach significance.

Finally, analysis of the 500 – 600 ms time range yielded a significant main effect of condition. All conditions except for the non-repeated auditorily learned names elicited more positive amplitudes than correct rejections. As in the 300 – 400 ms time window, the analysis on hits plus correct source decisions revealed significant effects of modality, with more positive amplitudes for visually relative to auditorily learned names, and repetition, with more positive amplitudes for repeatedly learned names.

600-900 ms. An ANOVA with the factors laterality (left, midline, right), site (anterior, central, posterior position), and condition yielded an effect of condition, $F(4,76) = 13.56$; $p < .001$; $\eta^2_p = .42$. Relative to correct rejections, more positive ERP were elicited by all other conditions (non-repeated visual: $F(1,19) = 17.78$; $p < .001$; $\eta^2_p = .48$, repeated visual: $F(1,19) = 43.36$; $p < .001$; $\eta^2_p = .70$, non-repeated auditory: $F(1,19) = 5.78$; $p = .027$; $\eta^2_p = .23$, repeated auditory: $F(1,19) = 46.04$; $p < .001$; $\eta^2_p = .71$; see Figure 1.

Again, we also conducted an analysis on hits plus correct source decisions via an ANOVA with factors laterality, site, modality during learning and repetition during learning and revealed a main effect of learning modality, $F(1,19) = 5.51$; $p = .030$; $\eta^2_p = .23$, with more positive ERPs for visually relative to auditorily learned names and a main effect of repetition during learning, $F(1,19)$

= 8.30; p = .010; η^2_p = .30, with more positive ERPs for repeated relative to non-repeatedly learned names; see lower part of Figure 2.

Discussion. Experiment 1 tested item recognition and source memory for familiar names. Unsurprisingly, we found more accurate item memory for those items repeated during learning. Similarly, repetition during learning enhanced correct source decisions (see Table 4).

We detected more positive ERPs from 300 – 600 ms for visually learned hits (plus correct source decisions) relative to correct rejections, while old/new effects for auditorily learned items were substantially smaller (when repeated during learning) or absent (when non-repeated). In a more restricted time range from 400 – 500 ms, while no old/new effects were detected for auditorily learned names, visually learned names elicited a substantially larger positivity, independent of repetition during learning. These results are in resemblance with previous findings from a lexical decision task reported by (Joyce, Paller, Schwartz, & Kutas, 1999), who observed larger amplitudes for old relative to new items from 200 – 500 ms, whereas more positive amplitudes for within-modality relative to across-modality repetitions were detected in a more restricted time window (300 – 400 ms). It is well established that within-modality repetitions leads to enhanced fluency relative to between-modality repetitions (see e.g. Kurilla, 2011; Roediger & Blaxton, 1987), and our ERP modality effect may therefore reflect an N400 priming effect for those items presented in the same modality during learning and test (see also Joyce et al., 1999). In addition, items repeated during learning elicited more positive amplitudes in the 300 – 600 ms time window, as well as from 300 – 400 and from 500 – 600 ms. Although repetition during learning has been specifically associated with recollection (Dewhurst & Anderson, 1999, see also below), it appears unlikely that such effects should have no effect on familiarity (see Jacoby, 1999; Jacoby & Rhodes, 2006). Our finding may thus reflect an FN400 old/new effect in terms of enhanced familiarity resulting from repeated presentation during learning.

Alternatively, the effect of modality during learning in the present study may be interpreted as reflecting retrieval orientation. Hornberger, Morcom, and Rugg (2004) reported increased ERP amplitudes (300 – 1200 ms) in case of a study-test format match relative to a mismatch, and interpreted this finding as differential processing needs to maximize an overlap between the retrieval cues and memory representations. Of note, Hornberger et al. (2004) concede that overall similarity between items during study and test also increases a feeling of familiarity (or fluency). Because the experimental manipulations that are used to examine fluency effects and retrieval orientation are highly similar, it is difficult to disentangle the respective contributions of these processes. Importantly, however, as discussed above highly similar effects as those reported in the present study have been observed in a lexical decision task (Joyce et al., 1999), in which retrieval orientation effects are unlikely to occur.

In a subsequent time window from 600 – 900 ms, we detected larger old/new effects for repeatedly relative non-repeatedly learned names. This finding is well in line with previous studies demonstrating larger old/new effects in this time range with increasing amounts of retrieved information (Vilberg, Moosavi, & Rugg, 2006). Hence, repetition during learning in the present study may have fostered the retrieval of more detailed study phase information (see also Dewhurst & Anderson, 1999). In addition, larger old/new effects for visually than auditorily learned items were observed. This finding may not be independent of the earlier effect, which was more pronounced for visually learned items, but may instead reflect a similarly pronounced later old/new effect, which builds upon a difference between hits and correct rejections in the visual but not in the auditory modality.

In sum, ERP results suggest that both fluency- and recollection-related processes modulate source memory for familiar names. As a qualification, it is not clear from Experiment 1 to what degree fluency-related processes indeed were related to source memory decisions. Assuming that fluency emerges within a few hundred milliseconds, any influence of this fast-acting process on a source decision could well be diminished when that source decision is delayed by a preceding old/new judgment task, as was the case in Experiment 1. Thus, in Experiment 2 we omitted the old/new decision to capture fast-acting neural processes more directly related to source memory. In addition, Experiment 1 did not allow the analysis of incorrect source decisions. In Experiment 2 we modified our design to test whether ERP effects of learning modality were contingent on the accuracy of source decisions. Our reasoning here was that if this were the case, the early effect of learning modality should be absent for trials in which the correct source information is not available.

Experiment 2

Method

Participants. The studied population consisted of 20 young adults (12 female; *M* = 23.5, *SD* = 3.2). Participant selection criteria were identical to Experiment 1. All participants gave written informed consent and before the experiment, visual acuity and contrast vision (Bach, 1996), as well as cognitive covariates were assessed (see Table 1 in Participant Section of Experiment 3).

Stimuli and Design. Stimuli were equivalent to those used in Experiment 1. In contrast to Experiment 1, all 400 names were presented during learning. Of 200 auditorily learned names, 100 were presented once and 100 were presented twice. Similarly, 100 visually learned names were presented once and 100 were presented twice. Visually and auditorily learned items were presented in a pseudo-randomized sequence, with a minimum of 156 and a maximum of 440 (*M* = 300) intervening items between repetitions.

Procedure. The procedure was identical to Experiment 1, except that old/new decisions were omitted. Each test trial started with a fixation cross for 500 ms, followed by a 3000 ms presentation of the name stimuli. Participants were instructed to indicate as fast and correctly as possible via key presses whether the respective name was certainly heard, probably heard, probably read, certainly read, or whether they could not remember the source of the name[4]. Participants were informed that the test list would only include names that they had either read or heard earlier and that the sets of read and heard names were non-overlapping.

EEG recording and analysis. EEG recording and analysis was analogous to Experiment 1, except for the following changes. Trials were averaged according to the two experimental factors modality during learning and repetition during learning (non-repeated visually learned, repeated visually learned, non-repeated auditorily learned, repeated auditorily learned) for both correct source decisions and trials in which no correct source information was available (including false source decisions and 'could not remember' responses; "no source" condition). The mean number of trials contributing to an individual averaged ERP for these conditions was 43, 57, 52, and 60 for correct trials, and 56, 41, 44, and 38 for "no source" trials, respectively.

We analyzed mean amplitudes during test at frontal, central and parietal electrode sites (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) in a 300 - 600 ms and 600 – 900 ms time window. Visual inspection of the data further suggested analyses from 900-1200 ms at the same electrode sites.

Results and Discussion

Performance. A repeated-measures ANOVA on accuracy (see Table 6) with the within-subject factors modality during learning (visual vs. auditory) and repetition during learning (non-repeated vs. repeated) resulted in a significant interaction, $F(1,19) = 8.34$; $p = .009$; $\eta^2_p = .19$. Paired t-tests revealed a significant effect of repetition in the visually learned condition, $t(19) = 7.12$; $p < .001$; $d = 0.98$, but a trend only in the auditorily learned condition, $t(19) = 1.98$; $p = .063$; $d = 0.39$. Moreover, source memory for non-repeated auditorily learned names was significantly more accurate relative to the non-repeated visually learned condition, $t(19) = 3.08$; $p = .006$; $d = 1.23$, while

[4] Please note that we collapsed across confidence ratings as too few subjects made use of the option to indicate that an item was *probably* heard or seen for an appropriate number of trials (mean number of key presses for *probably* heard/seen responses was 14) regarding the analysis of ERPs.

repeated visually and auditorily learned items did not differ significantly, $t(19) = 1.20$; $p = .245$; $d = 0.35$.

A corresponding ANOVA on mean reaction times for accurate source memory decisions (see Table 7) resulted in a trend for the interaction of Modality during learning x Repetition during learning, $F(1,19) = 3.34$; $p = .083$; $\eta^2_p = .15$. Table 7suggests a degree of repetition benefits for visually but not for auditorily learned names.

Event- related Potentials. Grand mean ERPs for correct and "no source" source memory for Experiment 2 are depicted in the upper and lower part of Figure 4, respectively.

300-600 ms. A repeated measures ANOVA with the factors laterality, electrode site, modality during learning (visual, auditory), repetition during learning (non-repeated, repeated) and response (correct source memory, "no source" memory) resulted in a main effect of modality during learning, $F(1,19) = 4.46$; $p = .048$; $\eta^2_p = .19$, which was further qualified by an interaction with site, $F(1.38,26.17) = 11.53$; $p < .001$; $\eta^2_p = .38$. Separate post-hoc ANOVAs at frontal, central and parietal sites revealed a main effect of learning modality, with more positive amplitudes for visual as compared to auditory names, at frontal, $F(1,19) = 7.75$; $p = .012$; $\eta^2_p = .29$, and central, $F(1,19) = 9.53$; $p = .006$; $\eta^2_p = .33$, but not parietal sites, $F < 1$.

In addition, there was an interaction of Modality during learning x Response, $F(1,19) = 4.66$; $p = .004$; $\eta^2_p = .20$; see upper part of Figure 5. Post-hoc ANOVAs indicated an effect of learning modality for correct trials, $F(1,19) = 8.08$; $p = .010$; $\eta^2_p = .30$, with more positive amplitudes for visual than auditory names. Importantly, no corresponding effect was detected for "no source" trials, $F < 1$. Moreover, relative to "no source" trials correct source trials elicited more positive amplitudes for visually, $F(1,19) = 4.75$; $p = .042$; $\eta^2_p = .20$, but not auditorily learned names, $F(1,19) = 1.01$; $p = .329$; $\eta^2_p = .05$.

As in the analysis described above 'could not remember' responses were included in the "no source" condition, one might argue that the absent modality effect in this condition might result from missing item memory. To rule out this potential restriction, we additionally calculated an ANOVA on false source decisions, which revealed no significant effects involving the learning modality factor; all F < =1.73; all p > = .19, all η^2_p < = .08.

600-900 ms. An ANOVA yielded a main effect of response, $F(1,19) = 9.59$; $p = .02$; η^2_p = .21, which was further qualified by an interaction of Laterality x Repetition during learning x Response, $F(1,38) = 5.01$; p = 006; η^2_p = .21. Subsidiary ANOVAs at left, midline and right electrodes sites and for correct and "no source" trials separately indicated an effect of repetition during learning over midline, $F(1,19) = 4.95$; $p = .038$; η^2_p = .21 and right electrode sites, $F(1,19)$ = 5.21; $p = .034$; η^2_p = .22, for correct responses, with more positive amplitudes for repeatedly learned names. No such effect was detected over left hemispheric sites, $F < 1$. For "no source" trials, there was no corresponding effect (left: $F[1,19] = 1.92$; $p = .182$; η^2_p = .00, midline and right: both $F < 1$; see lower part of Figure 5).

900-1200 ms. An ANOVA yielded a main effect of response, $F(1,19) = 12.14$; $p = .002$; η^2_p = .39, which was qualified by an interaction with modality during learning, $F(1,19) = 5.57$; $p = .029$; η^2_p = .23; see upper part of Figure 5. For correct trials, post-hoc ANOVAs revealed a trend towards more positive waveforms for visually as compared to auditorily learned names, $F(1,19) = 4.19$; p = .055; η^2_p = .18. Importantly, no corresponding effect was apparent for "no source" trials, $F < 1$. Moreover, more positive amplitudes for correct relative to "no source" trials were detected in the visually, $F(1,19) = 29.80$; $p < .001$; η^2_p = .61, but not in the auditorily learned condition, $F(1,19)$ = 2.00; $p = .174$; η^2_p = .09.

In addition, an interaction of Site x Modality during learning, $F(1.4, 26.61) = 5.97$; $p = .006$; η^2_p = .24, was observed, suggesting a fronto-central distribution of the learning modality effect.

Discussion. In Experiment 2 we found larger benefits of repetition during learning on source memory for visually as compared to auditorily learned names. Accordingly, repetition during learning was particularly helpful when modality did not change between learning and test (note that a similar pattern, although not significant, was observed in Experiment 1). Moreover, auditorily learned names were remembered more accurately (which was significant for the non-repeated learning conditions). Thus, one might argue that the lack of a repetition effect for auditorily learned items may be related to generally increased memory, and a similar repetition effect might have occurred if memory was matched for the non-repeated learning conditions. While we cannot completely rule out this possibility on the basis of the present data, we note that an additional repetition effect for auditorily learned names would have been well possible, given that performance in these conditions was still substantially below ceiling. Moreover, overall increased source memory accuracies for auditorily as compared to visually learned items might be related to the idea that the default mode of language perception is auditory rather than visual, and that human voices are richer in perceptual detail relative to written words. Previous research has suggested that word and voice information are stored together in case of auditory presentation (Palmeri, Goldinger, & Pisoni, 1993), which may increase memory. Additionally, greater saliency of the auditory relative to the visual modality has been previously observed in intermixed (as in the present study) relative to blocked presentation conditions (Mulligan & Osborn, 2009). Finally, the auditory signal presumably contains more distinct information and does not require grapheme-to-phoneme conversion (see Joyce et al., 1999, for a similar interpretation), which may have led to increased source memory. If this were the case, effects of repetition during learning on source memory accuracy may be related to recollection (see Dewhurst & Anderson, 1999), or more precisely to relatively reduced recollection in visually non-repated condition: While the more distinct auditorily learned names are recollected independent of repetition during learning, study phase detail for non-repeated visually learned items may be particularly poor and repetition may therefore result in enhanced recollection.

Importantly, our ERP findings support a prominent role of long-term repetition priming for source memory for familiar names. As in Experiment 1, more positive fronto-central ERPs were seen between 300 – 600 ms for visually as compared to auditorily learned names. This ERP effect might represent an N400 priming effect or an FN400 (for an FN400 effect in source memory studies, see also Groh-Bordin, Zimmer, & Ecker, 2006), and thus reflect fluency-based processes. Crucially, our finding of an early learning modality effect for correct source decisions but not when source information is missing, which strongly suggests that this fluency-based ERP effect reflects a process that is intimately related to source memory. It should be noted that in our initial analysis we included could not remember responses to the "no source" condition, which principally leaves the possibility that ERP modality effects were contaminated by forgotten names. In other words, an absent modality effect in the "no source" trials might have resulted from the presence of completely forgotten names (likely categorized as "could not remember"), and may thus reflect absent item instead of source memory. Our additional analysis, which was restricted to false source decisions, largely ruled out this potential objection, as again no modality effect was detected. However, the possibility remains that false decisions may include both successful and unsuccessful spontaneous familiarity and mix of successful and unsuccessful familiarity may contribute to the lack of an effect of modality.

A substantially later effect of learning modality (900-1200 ms) was also seen for correct source decisions only. This late effect may index control processes related to source retrieval (see e.g., Cruse & Wilding, 2009). As participants‟ source memory decisions were less accurate in the visually learned conditions, the learning modality effect in this time range may reflect an enhanced need for post-retrieval monitoring in these conditions, as this process may be more pronounced for items closer to the decision criterion (see Henson, Rugg, Shallice, Josephs, & Dolan, 1999).

It is also important to note that, in the intermediate time window from 600 – 900 ms, prominent ERP effects of repetition during learning were observed. As in Experiment 1, more positive ERPs were elicited for repeatedly than non-repeatedly learned names. As noted previously, repetition during learning increases the amount of subsequently recollected information, which in turn results in more positive ERPs (Vilberg et al., 2006). In line with this idea, effects of repetition during learning were only observed for correct source decisions. Please note that repetition during learning led to increased ERPs for both visually and auditorily learned names, while source memory performance was only increased for repeated visually but not for repeated auditorily learned items. As discussed above, recollection for auditorily learned names may be generally higher as a result of a richer, more distinct signal. One could speculate that recollection strongly affected the behavioral response for auditory names even in the non-repeated learning condition. Repetition during learning may have still led to the enhanced retrieval of study phase detail and thus increased recollection (as indexed by the ERP repetition effect), which may have not resulted in more correct source decisions as the amount of recollected information was above the decision criterion even in the non-repeated condition. In contrast, as for visually learned names the signal contained less distinct perceptual information, repetition during learning may have led to both increased behavioral source memory and larger ERP amplitudes in the 600 – 900 ms time window.

As described in the introduction, source memory is typically impaired in older participants (Balota, Dolan, & Duchek, 2000), which has been related to diminished recollection (Anderson & Craik, 2000; Jacoby & Rhodes, 2006). By contrast, fluency-related processes are assumed to be relatively spared (Balota et al., 2000). Experiments 1 and 2 led us to conclude that fluency played a prominent role for source memory for familiar names. In Experiment 3, we addressed the question whether or not older participants would show a similar pattern of effects. If fluency was preserved in older adults (and if older adults' source memory indeed relied more strongly on fluency, see Dulas & Duarte, 2012), similar (or even more pronounced) ERP correlates of within-modality repetitions should be observed. By contrast if recollection was reduced, weaker evidence for repetition-related ERP effects should occur.

Experiment 3

Method

Participants. The studied population consisted of 24 older participants (15 female; M = 67.2; SD = 4.2) who were recruited in senior citizen groups and via a press release in a local newspaper. All participants reported to reside in independent living conditions and received a monetary compensation for participation. Participants were right-handed according to a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971). None reported neurological or psychiatric disorders or received central-acting medication. All participants gave written informed consent. Participants were selected on the basis of reporting normal hearing and none of them needed hearing aid. Measures of educational level (years of education), visual acuity and contrast sensitivity (Bach, 1996) and cognitive covariates were assessed before the experiment. These latter variables included a marker of perceptual speed (digit symbol substitution test; Wechsler, 1981) and a marker of verbal knowledge (Spot-A-Word; Lehrl, 1977). For the sake of completeness Table 1 displays the results from Experiment 1, 2 and 3. Notably, however, since Experiment 3 was highly similar to Experiment 2, age group comparisons on cognitive covariates and on educational level were conducted only between younger participants from Experiment 2 and older participants from Experiment 3. These analyses revealed significant age-related decline for older adults in perceptual speed, $F(1,42) = 68.99$, $p < .001$, $\eta^2_p = .62$. No age difference was observed for verbal knowledge, $F(1,42) = 1.83$, $p = .184$, $\eta^2_p = .04$, but incidentally, older adults obtained numerically slightly higher raw scores (see Table 1). These results are in line with both two-component theories of life span intelligence (Baltes, 1987; Horn, 1968) and empirical evidence (Li et al., 2004; Schaie, Maitland, Willis, & Intrieri, 1998) contrasting fluid mechanics and crystallized pragmatics of cognition. This confirms the age typicality of the samples. Visual acuity and contrast sensitivity was diminished in older compared to younger adults, $F(1,42) = 22.39$, $p < .001$, $\eta^2_p = .35$ and $F(1,42) = 14.96$, $p < .001$, $\eta^2_p = .26$, respectively. Younger and older adults did not differ with respect to years of education, $F < 1$.

Stimuli and Design. The stimuli and design were equivalent to Experiment 2.

Procedure. The same procedure was used as in Experiment 2 except for the following changes during test: Participants were instructed to indicate as fast and correctly as possible via key presses whether the names were heard, seen, or whether the source was not remembered. We withdrew from applying the confidence rating used in Experiment 2 to create a more appropriate task for our older participants. We were further encouraged to undertake this change as our young participants in Experiment 2 had barely used the intermediate steps of the confidence scale (see above).

EEG recording and analysis. EEG recording was analogous to Experiment 2. Trials were averaged according to modality during learning and repetition during learning (non-repeated visual, repeated visual, non-repeated auditory, and repeated auditory) for both correct source decisions and "no source" trails, respectively. The mean number of trials contributing to an individual averaged ERP for these conditions was 44, 55, 62, and 63 for correct trials and 54, 45, 37, and 35 for "no source" trials, respectively.

Results and Discussion

Performance. An ANOVA on accuracy of source memory decisions (see Table 8) resulted in main effects of learning modality, $F(1,23) = 18.00$; $p < .001$; $\eta^2_p = .44$, and repetition during learning, $F(1,23) = 38.95$; $p < .001$; $\eta^2_p = .63$, and in an interaction, $F(1,23) = 6.02$; $p = .022$; $\eta^2_p = .21$. Paired t-tests revealed that source memory accuracy increased with repetition in the visually, $t(23) = 4.99$; $p < .001$; $d = 0.68$, but not in the auditorily learned condition, $t(23) = .773$; $p = .447$; $d = 0.11$. Moreover, source memory for non-repeated auditorily learned names was more accurate relative to the non-repeated visually learned condition, $t(19) = 4.39$; $p < .001$; $d = 1.34$, and source memory for repeated auditorily learned items was more accurate relative to the repeated visually learned condition, $t(19) = 3.19$; $p = .004$; $d = 0.83$.

To compare older adults' performance with young adults, we ran an additional mixed-model ANOVA with a between-subjects factor age group combining data from Experiments 2 and 3. This analysis revealed significant main effects of modality during learning $F(1,42) = 20.61$; $p < .001$; $\eta^2_p = .33$, repetition during learning $F(1,42) = 71.05$; $p < .001$; $\eta^2_p = .63$, as well as a significant interaction of these factors, $F(1,42) = 13.34$; $p = .001$; $\eta^2_p = .24$. Moreover, a significant main effect of age group was observed, $F(1,42) = 10.31$; $p = .003$; $\eta^2_p = .20$. Notably, none of the experimental factors interacted with age group, $F < 1$, indicating a similar pattern of results in both younger and older adults.[5]

A corresponding ANOVA on mean reaction times for correct source memory decisions (see Table 9) resulted in a main effect of repetition during learning, $F(1,23) = 28.58$; $p < .001$; $\eta^2_p = .55$, indicating faster responses for repeatedly learned as compared to non-repeatedly learned names independent of learning modality.

Again, we ran an additional mixed-model ANOVA including the factor age group combining data from Experiments 2 and 3. This analysis revealed a trend for the main effect of learning modality, $F(1,42) = 3.84$; $p = .057$; $\eta^2_p = .08$, a significant main effect of repetition during learning $F(1,42) = 18.30$; $p < .001$; $\eta^2_p = .30$, as well as a significant interaction of these factors, $F(1,42) = 4.32$; $p = .044$; $\eta^2_p = .09$. Moreover, a significant main effect of age group was observed, $F(1,42) = 5.52$; $p = .024$; $\eta^2_p = .12$. Again, none of the experimental factors interacted with age group, $F < 1$, indicating a similar pattern of results in both younger and older adults.

Event-related potentials. Grand mean ERPs for correct source memory and "no source" trials for Experiment 3 are depicted in the upper and lower part of Figure 6, respectively.

300-600 ms. An interaction of Modality during learning x Response, $F(2,46) = 5.90$; $p = .023$; $\eta^2_p = .20$; see Figure 7, was detected. A follow-up ANOVA on correct responses resulted in a significant effect of modality during learning, $F(1,23) = 5.90$; $p = .023$; $\eta^2_p = .20$, with less positive

[5] We also ran an analysis on the number of 'could not remember' responses and found no significant group effect, $F(1,42) = 2.10$; $p = .154$; $\eta^2_p = .05$, or interaction with the group factor, all $F <= 2.04$; all $p >= .16$; $\eta^2_p <= .05$.

amplitudes for visually learned relative to auditorily learned items. No corresponding effect was detected for "no source" trials, $F(1,23) = 2.02$; $p = .169$; $\eta^2_p = .08$. Moreover, correct relative to "no source" trials elicited less positive amplitudes in the visually learned, $F(1,23) = 7.25$; $p = .013$; $\eta^2_p = .24$, but not in the auditorily learned condition, $F < 1$.

To rule out potential contaminations of the "no source" condition by forgotten items which might have elicited "could not remember" responses, we additionally calculated an ANOVA on false source decisions only, which again revealed no significant effects involving the learning modality factor, all $F <= 1.32$; all $p >= .27$, all $\eta^2_p <= .05$.

600-900 ms. An interaction of Modality during learning x Response, $F(1,23) = 15.76$; $p = .001$; $\eta^2_p = .41$, was further qualified by a three-way interaction of Laterality x Modality during learning x Response, $F(1.45,33.39) = 3.98$; $p = .040$; $\eta^2_p = .15$; see Figure 7. Post-hoc ANOVAs carried out separately for correct source memory decisions and "no source" trials at left, midline and right electrodes revealed significantly less positive amplitudes for correctly remembered visually learned versus auditorily learned names at midline, $F(1,23) = 9.34$; $p = .006$; $\eta^2_p = .29$, and right electrodes, $F(1,23) = 4.66$; $p = .042$; $\eta^2_p = .17$, but only a trend at left sites, $F(1,23) = 4.26$; $p = .050$; $\eta^2_p = .16$. Conversely, for "no source" trials, visually learned items elicited more positive amplitudes as compared to auditorily learned items at midline, $F(1,23) = 14.18$; $p = .001$; $\eta^2_p = .38$, and right electrodes, $F(1,23) = 11.16$; $p = .003$; $\eta^2_p = .33$. No such effect was detected at left electrode sites, $F < 1$. Moreover, in the visually learned condition, amplitudes for correct source relative to "no source" trials were less positive at left, $F(1,23) = 9.76$; $p = .005$; $\eta^2_p = .30$, midline, $F(1,23) = 11.62$; $p = .002$; $\eta^2_p = .34$, and right sites, with the latter effect emerging as a trend only, $F(1,23) = 3.29$; $p = .083$; $\eta^2_p = .13$. In the auditorily learned condition, amplitudes for correct source relative to "no source" trials were more positive at midline, $F(1,23) = 6.16$; $p = .021$; $\eta^2_p = .21$, and right, $F(1,23) = 9.65$; $p = .005$; $\eta^2_p = .30$, but not at left electrode positions, $F < 1$.

900-1200 ms. An ANOVA resulted in an interaction of Modality during Learning x Response, $F(1,23) = 9.41$; $p = .005$; $\eta^2_p = .29$; see Figure 7. Separate ANOVAs for correct source relative to "no source" trials revealed less positive amplitudes for correct source memory decisions for visually learned as compared to auditorily learned names, $F(1,23) = 6.62$; $p = .017$; $\eta^2_p = .22$. Conversely, for "no source" trials, there was a trend towards more positive amplitudes for visually learned as compared to auditorily learned names, $F(1,23) = 3.90$; $p = .061$; $\eta^2_p = .15$. Finally, amplitudes for correct relative to "no source" trials were more positive in the auditorily learned, $F(1,23) = 12.07$; $p = .002$; $\eta^2_p = .34$, but not in the visually learned condition, $F(1,23) = 1.20$; $p = .285$; $\eta^2_p = .05$.

ERP comparisons between young and older adults. Although combined analyses with data from Experiments 2 and 3 were not initially planned (due to the slight differences between paradigms and in the different number of participants), we conducted additional analyses to directly examine age-related differences.

300 - 600 ms. A mixed-model ANOVA including the between-subjects factor age group resulted in significant interactions of Site x Age Group, $F(2, 84) = 24.32$; $p < .001$; $\eta^2_p = .37$, with more positive amplitudes at parietal sites in young adults and at frontal sites in older adults, and of Learning Modality x Response x Age Group, $F(1,42) = 6.62$; $p = .017$; $\eta^2_p = .22$. This finding pointed towards more positive amplitudes for correctly assigned visually learned names in younger adults, and more positive amplitudes for correctly assigned auditorily learned names in older adults (see separate analyses for the two groups above).

600-900 ms. The corresponding ANOVA revealed interactions of Site x Age Group, $F(2, 84) = 21.30$; $p < .001$; $\eta^2_p = .34$ (see previous time window), and Age Group x Response, $F(1,42) = 11.66$; $p = .001$; $\eta^2_p = .22$. Whereas correct trials were less positive in the older participants, this pattern was reversed and more pronounced in the younger adults (see also separate analysis above). Furthermore, group interacted with learning modality and site, $F(2,84) = 5.03$; $p = .009$; $\eta^2_p = .11$, with more positive amplitudes over central and frontal sites for visually learned names in the young, and for auditorily learned names in older participants (please see analyses above). The factor group also interacted with site and response, $F(2,84) = 3.98$; $p = .002$; $\eta^2_p = .09$, indicating more positive amplitudes for correct versus "no source" trials in younger adults and the reversed pattern in older adults, particularly pronounced over central and posterior sites. There was also an interaction of Laterality x Learning Modality x Response x Age Group, $F(1,84) = 4.38$; $p = .016$; $\eta^2_p = .09$, presumably resulting from an interaction of Laterality x Learning Modality x Response in the older but not in the young adults (see previous analyses above).

900-1200. A respective ANOVA resulted in an interaction of Site x Age Group, $F(2, 84) = 13.17$; $p < .001$; $\eta^2_p = .24$ (see previous time windows), and in a three-way interaction of Site x Learning Modality x Age Group, $F(2, 84) = 4.22$; $p = .081$; $\eta^2_p = .09$, indicating that in younger adults visually learned names elicited more positive amplitudes than auditorily learned names at frontal and central sites, while the reversed pattern was apparent in older adults, which was particularly pronounced over the central and parietal scalp. Furthermore, the interaction of Laterality x Learning Modality x Response x Age Group, $F(2,84) = 3.21$; $p = .045$; $\eta^2_p = .07$, pointed towards more positive amplitudes for visually learned names among correct source decisions in young adults, whereas in older adults auditorily learned names elicited more positive going waveforms in the "no source" condition (see also separate group analyses above) – a pattern particularly pronounced over the midline and right hemispheric sites.

Discussion. In Experiment 3 we examined older participants with a slightly modified version of Experiment 2. Older people are known to show reduced source memory performance (Balota et al., 2000), which is often attributed to decreases in recollection (Anderson & Craik, 2000). As we suggested that fluency-based processes influenced the results in our first two experiments, we expected a similar pattern of respective results as in Experiment 2 for older adults.

Although an overall decrease in source memory was observed, the pattern of behavioral results from older participants in Experiment 3 were remarkably similar to those in young adults. While repetition during learning led to more accurate source memory decisions for visually learned names, no significant benefit was observed for auditorily learned names. Similar to Experiment 2, source memory in older adults was generally increased for auditorily relative to visually learned names, but again, a lack of a repetition effect due to this overall increase appears unlikely, as performance for auditorily learned names was still substantially below ceiling (see related discussion above). The similar pattern in older and younger adults, however, may point to an influence of fluency on source memory, given that implicit relative to explicit memory processes are relatively spared in older participants (Balota et al., 2000; Jacoby & Rhodes, 2006).

ERPs in older participants revealed an early effect of learning modality between 300 and 600 ms for correct source but not “no source” trials. While this pattern is similar to the findings from young adults, one notable difference concerns the polarity of ERP modulations: While visually learned items elicited more positive amplitudes than auditorily learned items in young adults, they elicited less positive amplitudes in older adults. Polarity reversed ERP effects have been observed in older participants before, and have been linked to strategic processes aiming at compensation of age-related impairments, which may be accompanied by age-related changes in brain function (Duarte, Ranganath, Trujillo, & Knight, 2006; Swick et al., 2006; Wiese, Komes, & Schweinberger, 2012). It should be noted that previous studies observed polarity-reversed effects in later, presumably recollection-related time windows, which may be under strategic control to a larger extent. By contrast, the present study is to our knowledge the first to describe polarity-reversed effects in an earlier time window, which presumably reflects fast-acting and automatic processes. Generally in line with a compensation-based explanation, a previous study on priming has shown more widespread ERP effects in older adults in an overlapping time window, which was interpreted to reflect compensation of neuro-cognitive aging (Osorio, Fay, Pouthas, & Ballesteros, 2010).

Alternatively, the near-chance performance in older adults for visually learned names might prompt the idea that larger amplitudes for auditorily learned names reflect a stronger familiarity signal in this latter condition. This interpretation in turn would suggest that the processes reflected in the 300 – 600 ms time window in older adults are different from those observed in young adults, who demonstrated larger amplitudes for visually learned names. Potentially related to this idea it has been proposed that qualitatively different signals accompany fluency-based processes in older and younger adults (Wang et al., 2012). Independent of the exact interpretation of this finding, a relatively early ERP effect again clearly distinguished between correctly assigned auditorily and visually learned items. Thus, this finding corroborates the suggestion that source memory for familiar names can be attended by fluency-based processes, both in young and older adults.

In the two following time windows (600-900 ms and 900-1200 ms) more positive amplitudes for correctly judged auditorily learned (versus visually learned) items and at the same time more positive amplitudes for "no source" trials for visually learned (versus auditorily learned) names were observed. In other words, ERPs in these time ranges were more positive whenever the participants decided that the names had been auditorily learned, independent of whether this was correct or not. In Experiment 2, we interpreted effects of modality during learning in the 900-1200 ms time window in young participants as reflecting an increased need for monitoring processes, as visually learned names were presumably closer to the criterion. In older participants, such monitoring processes do not appear to be effective. Inefficient monitoring may contribute to the overall reduction in source memory performance in older adults (see also Cansino et al., 2012; Swick et al., 2006).

Finally, and at some variance with the results from Experiment 2, no significant effects of repetition during learning were observed in the ERPs of Experiment 3. As such effects in young participants presumably reflected recollection-based retrieval processes, their absence in older adults is in line with suggestions of age-related impairments of recollection (Friedman, de Chastelaine, Nessler, & Malcolm, 2010; for recent review, see also Friedman, 2013).

General Discussion

In a series of experiments, examining both young and older adults, we investigated source memory for familiar names. The behavioral results of Experiment 1 suggested that source memory increased with repetition of names during learning. Experiment 2 revealed that this effect occurred only when modality was kept constant between learning and test. In Experiment 3, while source memory was generally reduced in older adults, a modality-specific effect of repetition during learning was replicated. Intriguingly, in all three experiments we found converging evidence for an early (300 – 600 ms) ERP effect of learning modality, which we interpret as reflecting fluency-based processes.

Increased fluency at test was reflected in an early (300 – 600 ms) ERP effect of modality during learning in all three experiments, which clearly differentiated between visually and auditorily learned names. As discussed above, this effect was polarity-reversed in older participants, which may reflect effects of aging. Importantly, however, this effect of learning modality consistently occurred for correct source decisions only, suggesting decision-relevance of the underlying signal. Although the present experiments do not use a classical N400 paradigm, our early effect may be related to an N400-like priming effect, given its timing and its scalp-distribution. Similar effects, with relatively more positive amplitudes for repeated relative to non-repeated items, have been observed in long-term repetition priming experiments using famous names and faces (Schweinberger et al., 2002). The effect in Experiments 1 and 2 may resemble within-modality long-term repetition priming, as names repeated in the same stimulus modality between learning and test elicited more positive amplitudes than non-repeated new names and names presented in a different modality at test. At first sight this interpretation appears to be at variance with previous studies on immediate repetition priming of famous names and faces (Pickering & Schweinberger, 2003) , in which N400 priming effects were reported to not depend on a change between prime and target domain. However, unlike long-term repetition, as examined in the present study, immediate repetition effects are usually assumed to be based on a pre-activation of a target representation by the prime, which has not completely decayed by the time the target is processed. By contrast, as noted above, behavioral long-term repetition priming is domain-specific and explained by the strengthened link between a modality-specific name representation and a modality-independent representation of person identity (see Burton et al., 1990). Accordingly, in our study, the early ERP effect of modality during learning in the 300-600 ms time window may represent a neural correlate of within-modality long-term repetition priming.

An alternative but related interpretation would be that ERPs in the 300-600 ms time window reflect an FN400-like effect. More positive amplitudes for correct relative to incorrect source memory decisions at frontal sites and in similar time ranges have been interpreted as reflecting an FN400 (e.g. Groh-Bordin et al., 2006; Mollison & Curran, 2012), a component which has been interpreted to indicate familiarity (Curran, 2000). For the present study, an interpretation of the early ERP effect in terms of familiarity-based processes appears unlikely. If this effect indeed reflected familiarity, one would have assumed more pronounced familiarity for auditorily learned relative to new items at test. A difference between these two conditions, however, was not consistently found in the 300 – 600 ms time window, and was completely absent in the 400 – 500 ms time window of Experiment 1. Moreover, the interpretation of the FN400 in terms of conceptual priming (Paller et al., 2007) appears inconsistent with our finding of amplitude differences for correct versus incorrect trials in the visually learned (within-modality) condition only.

Interestingly, ERP effects of modality during learning were largely independent of repetition during learning, and thus did not parallel the pattern observed in performance. It is important to note that ERPs represent neural correlates of cognitive sub-routines and may not necessarily mirror behavioral measures, which reflect the end product of a series of processing stages. Moreover, the processes reflected in the ERP signal may underlie a later decision about an item. In line with this suggestion, the early ERP effect of learning modality was observed for correct trials only. This suggests that the availability of modality-specific information in this early time window was a basis of a correct source decision, both in the repeated and non-repeated learning condition. At the same time, if source decisions in the visual learning conditions were (at least partly) based on fluency, this did not result in increased source memory performance relative to the auditory learning conditions. Consequently, it appears that fluency can contribute to source memory, but that its contribution may not necessarily be beneficial.

We also observed an additional later effect in young participants, which was presumably related to recollection. Starting at approximately 600 ms, names repeated during learning elicited more positive amplitudes as compared to non-repeated names. It is known from previous studies that repetition during learning increases recollection, probably because multiple episodic traces are created for the same item (Dewhurst & Anderson, 1999). Moreover, a number of ERP studies suggest that memory effects in this time window reflect processes of recollection. Of particular relevance, Vilberg et al. (2006) reported that the ERP amplitude increased with the amount of recollected information. In the present study, repetition during learning may have led to the recollection of more information from the study phase at test, and in turn to more positive ERP amplitudes. In that context, it is of interest to note that a corresponding ERP repetition effect was not observed in older participants, in line with the suggestion of impaired recollection in this age group.

In conclusion, the present findings consistently establish a role of fluency for source memory in both younger and older adults by using the ecologically valid stimulus class of famous names. Our ERP findings suggest that within-modality repetition priming underlies the fluency effect associated with correct source memory decisions. Importantly, while this specific mechanism has not been demonstrated before, the mutual interpretation of our behavioral and ERP findings does not suggest a beneficial effect of fluency on source memory as implied by previous ERP studies (Diana et al., 2011; Mollison & Curran, 2012). Therefore, these findings represent an important and novel contribution to the current debate on the interplay of fluency-based processes and source memory.

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Table 1. Demographic information, sensory and cognitive covariates from Experiment 1, 2 and 3; *M* (*SD*).

	Experiment 1	Experiment 2	Experiment 3
Age	23.20 (2.74)	23.20 (3.90)	67.21 (4.20)
Years of education	14.55 (1.10)	14.55 (1.19)	13.04 (3.74)
Visual Acuity *	.07 (.07)	.06 (.03)	.30 (.19)
Contrast Vision **	1.40 (.37)	1.29 (.36)	5.34 (11.59)
Digit Symbol	66.9 (12.21)	66.40(8.21)	41.62 (11.02)
Spot a Word	31.50 (1.92)	30.65 (3.08)	32.08 (3.82)

* logMAR; ** Michelson Contrast

Table 2. Overall proportions of old/new decisions, time-outs and could not remember responses, as well as the proportions of correct and false old/new decisions from Experiment 1.

	Old/New decisions	Time-Outs	Could not remember	Correct old/new	False old/new
New Items	.91 (.16)	.09 (.16)	.00 (.00)	.82 (.20)	.18 (.20)
Non-rep Auditory	.92 (.09)	.08 (.09)	.00 (.00)	.65 (.12)	.35 (.12)
Repeated Auditory	.93 (.07)	.07 (.07)	.00 (.00)	.80 (.13)	.20 (.13)
Non-rep Visual	.92 (.10)	.08 (.10)	.00 (.00)	.66 (.16)	.34 (.16)
Repeated Visual	.95 (.06)	.05 (.06)	.00 (.00)	.82 (.09)	.18 (.09)

Table 3. Mean Reaction times of correct and false old/new decisions from Experiment 1.

	Correct Old/New	False Old/New
New Items	1292.75 (187.47)	1471.92 (156.86)
Non-rep Auditory	1348.37 (185.35)	1371.52 (158.26)
Repeated Auditory	1363.75 (182.22)	1291.82 (200.63)
Non-rep Visual	1256.12 (204.79)	1371.88 (185.91)
Repeated Visual	1249. 52 (153.70)	1245.66 (247.57)

Table 4. Overall proportions of source decisions, time-outs and could not remember responses, as well as the proportions of correct and false source decisions from Experiment 1.

	Source decisions	Time-Outs	Could not remember	Correct Source	False Source
Non-rep Auditory	.60 (.13)	.40 (.13)	.01 (.02)	.80 (.13)	.20 (.13)
Repeated Auditory	.74 (.13)	.26 (.13)	.00 (.00)	.74 (.12)	.16 (.12)
Non-rep Visual	.60 (.00)	.40 (.00)	.00 (.00)	.76 (17)	.24 (.17)
Repeated Visual	.79 (.10)	.20 (.12)	.00 (.00)	.85 (.11)	.15 (.11)

Table 5. Statistical indices for the ERP analyses in 100 ms time windows from Experiment 1.

	300-400 ms	400-500 ms	500-600 ms
ANOVA: old and new names (exp. factor: condition)			
Main effect	$F(4,76) = 3.49$; $p = .011$; $\eta^2_p = .16$	$F(4,76) = 4.75$; $p = .002$. $\eta^2_p = .20$	$F(4,76) = 8.01$; $p < .001$; $\eta^2_p = .30$
Vis-Non > CR	$F(1, 19) = 1.53$; $p = .231$; $\eta^2_p = .07$	$F(1, 19) = 5.50$; $p = .030$; $\eta^2_p = .23$	$F(1, 19) = 5.89$; $p < .001$; $\eta^2_p = .30$
Vis-Rep > CR	$F(1, 19) = 10.49$; $p = .004$; $\eta^2_p = .36$	$F(1, 19) = 17.49$; $p = .001$; $\eta^2_p = .47$	$F(1, 19) = 20.34$; $p < .001$; $\eta^2_p = .52$
Aud-Non = CR	$F < 1$	$F < 1$	$F < 1$
Aud-Rep > CR	$F(1, 19) = 4.71$; $p = .043$; $\eta^2_p = .20$	$F(1, 19) = 2.60$; $p = .123$; $\eta^2_p = .12$	$F(1, 19) = 14.70$; $p < .001$; $\eta^2_p = .43$
ANOVA: hits plus source (exp. factors: modality, repetition)			
Modality Vis > Aud	$F(1, 19) = 5.25$; $p = .033$; $\eta^2_p = .22$	$F(1, 19) = 12.60$; $p = .002$; $\eta^2_p = .40$	$F(1, 19) = 10.78$; $p = .004$; $\eta^2_p = .36$
Repetition Rep > Non-Rep	$F(1, 19) = 6.79$; $p = .017$; $\eta^2_p = .26$	$F(1, 19) = 3.06$; $p = .096$; $\eta^2_p = .14$	$F(1, 19) = 9.91$ $p = .005$; $\eta^2_p = .34$

Table 6. Overall proportions of source decisions, time-outs and could not remember responses, as well as the proportions of correct and false source decisions from Experiment 2.

	Source decisions	Time-Outs	Could not remember	Correct Source	False Source
Non-rep Auditory	.72 (.12)	.17 (.12)	.11 (.16)	.74 (.15)	.26 (.18)
Repeated Auditory	.77 (.12)	.14 (.10)	.10 (.15)	.79 (.13)	.21 (.13)
Non-rep Visual	.71 (.14)	.16 (.11)	.13 (.18)	.61 (.14)	.39 (.14)
Repeated Visual	.78 (.13)	.14 (.08)	.08 (.15)	.74 (.13)	.26 (.13)

Table 7. Mean reaction times (SD) for correct and false source decisions, as well as for could not remember responses from Experiment 2.

	Correct Source	False Source	Could not remember
Non-rep Auditory	1559.66 (141.84)	1588.75 (149.87)	1576.68 (253.38)
Repeated Auditory	1546.42 (126.86)	1596.76 (185.12)	1518.42 (229.42)
Non-rep Visual	1562.79 (152.45)	1569.43 (204.88)	1581.02 (290.21)
Repeated Visual	1486.13 (69.13)	1551.42 (234.76)	1581.43 (391.20)

Table 8. Overall proportions of source decisions, time-outs and could not remember responses, as well as the proportions of correct and false source decisions from Experiment 3.

	Source decisions	Time-Outs	Could not remember	Correct Source	False Source
Non-rep Auditory	.89 (.12)	.04 (.05)	.06 (.11)	.70 (.13)	.30 (.13)
Repeated Auditory	.92 (10)	.03 (.05)	.05 (.09)	.70 (.13)	.30 (.13)
Non-rep Visual	.89 (12)	.05 (.07)	.06 (.11)	.50 (.15)	.50 (.15)
Repeated Visual	.91 (.11)	.04 (.06)	.05 (.10)	.60 (.14)	.40 (.14)

Table 9. Mean reaction times (SD) for correct and false source decisions, as well as for could not remember responses from Experiment 3.

	Correct Source	False Source	Could not remember
Non-rep Auditory	1695.62 (229.57)	1744.98 (217.59)	1955.36 (330.37)
Repeated Auditory	1656.74 (205.98)	1696.48 (205.35)	2009.77 (193.87)
Non-rep Visual	1673.29 (208.80)	1733.59 (239.80)	1818.96 (543.25)
Repeated Visual	1611.77 (220.98)	1687.06 (241.82)	1903.01 (385.56)

Figure Captions

Figure 1. Grand Mean waveforms for correct source memory and correct rejections from the test phases of Experiment 1. Dashed lines depict the 300 – 600 ms and 600 – 900 ms time windows.

Figure 2. a) Scalp topographical voltage maps (spherical spline interpolation, 90° equidistant projection) between 400 and 500 ms displaying the difference between correct rejections and hits plus correct source for each condition. *b)* Scalp topographical voltage maps (spherical spline interpolation, 90° equidistant projection) between 600 and 900 ms displaying the difference between correct rejections and hits plus correct source for each condition.

Figure 3. Grand Mean waveforms for visual and auditory hits plus correct source and correct rejections from the test phases of Experiment 1. Dashed lines depict the 400 – 500 ms time window.

Figure 4. a) Grand Mean waveforms for correct source memory from the test phases of Experiment 2. Dashed lines depict the 300 – 600 ms, 600 – 900 ms and 900 – 1200 ms time windows. *b)* Grand Mean waveforms for "no source" trials from the test phases of Experiment 1. Dashed lines depict the 300 – 600 ms, 600 – 900 ms and 900 – 1200 ms time windows.

Figure 5. a) Scalp topographical voltage maps (spherical spline interpolation, 90° equidistant projection) of the learning modality effect (visually minus auditorily learned names for correct and "no source" trials, respectively) of Experiment 2. *b)* Scalp topographical voltage maps (spherical spline interpolation, 90° equidistant projection) of the repetition during learning effect of Experiment 2. (repeated minus non-repeated names for correct and "no source" trials, respectively).

Figure 6. a) Grand Mean waveforms for correct source memory from the test phases of Experiment 3. Dashed lines depict the 300 – 600 ms, 600 – 900 ms and 900 – 1200 ms time windows. b) Grand Mean waveforms for “no source” trials from the test phases of Experiment 3. Dashed lines depict the 300 – 600 ms, 600 – 900 ms and 900 – 1200 ms time windows.

Figure 7. Scalp topographical voltage maps (spherical spline interpolation, 90° equidistant projection) of the learning modality effect (visually minus auditorily learned names for correct and “no source” trials, respectively) of Experiment 3.

Figure 1

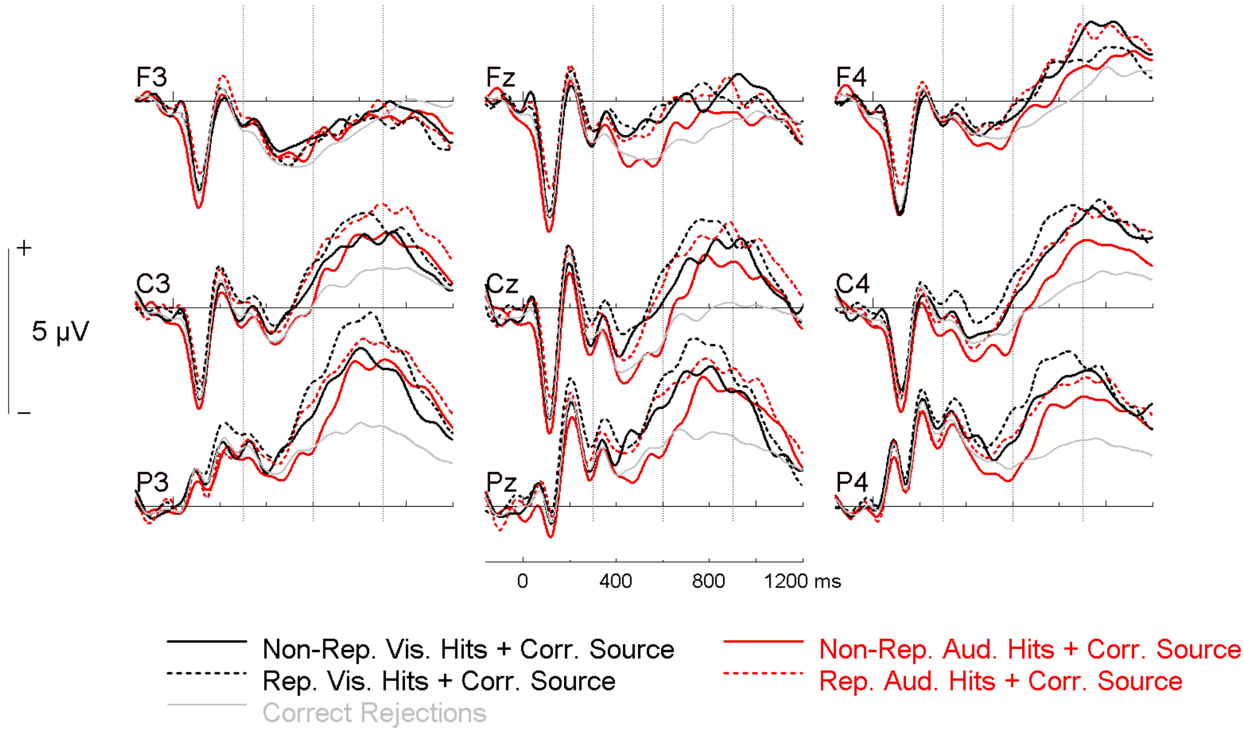

F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
+
5 µV
–
0
400
800
1200 ms
Non-Rep. Vis. Hits + Corr. Source
Rep. Vis. Hits + Corr. Source
Correct Rejections
Non-Rep. Aud. Hits + Corr. Source
Rep. Aud. Hits + Corr. Source

Figure 2

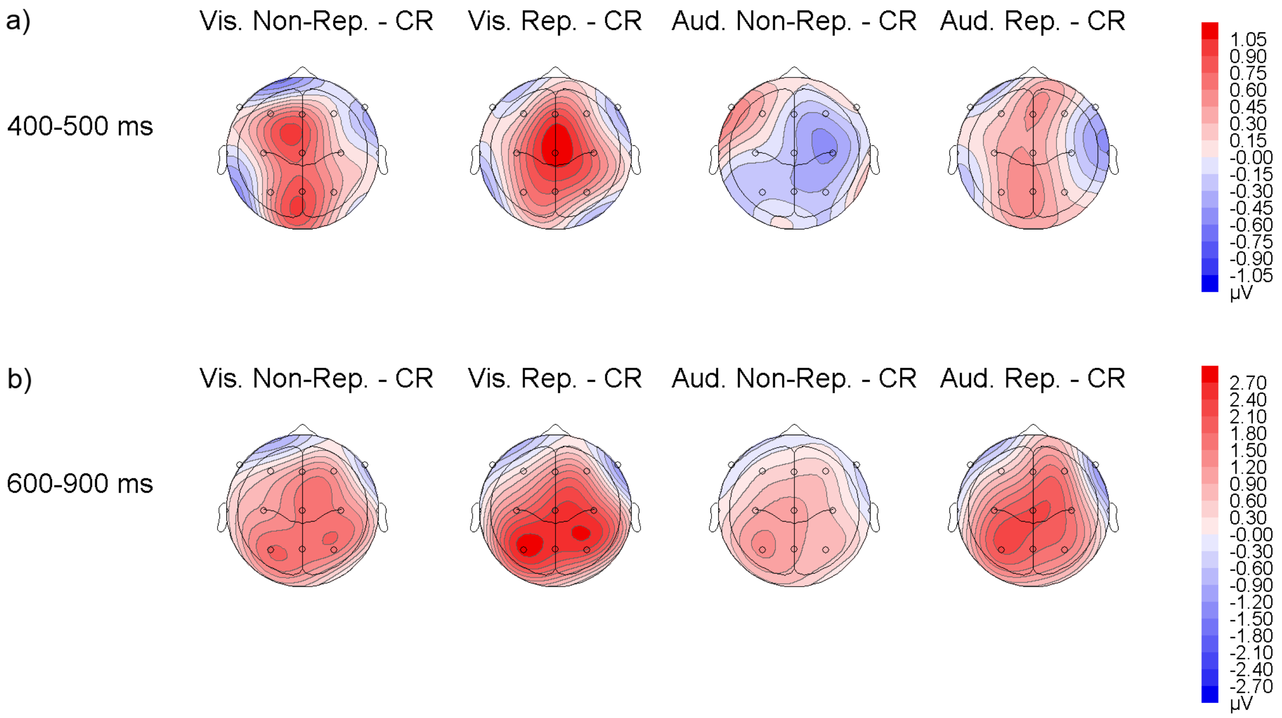

a)
Vis. Non-Rep. - CR
Vis. Rep. - CR
Aud. Non-Rep. - CR
Aud. Rep. - CR
400-500 ms
1.05
0.90
0.75
0.60
0.45
0.30
0.15
-0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-0.90
-1.05
µV
b)
Vis. Non-Rep. - CR
Vis. Rep. - CR
Aud. Non-Rep. - CR
Aud. Rep. - CR
600-900 ms
2.70
2.40
2.10
1.80
1.50
1.20
0.90
0.60
0.30
-0.00
-0.30
-0.60
-0.90
-1.20
-1.50
-1.80
-2.10
-2.40
-2.70
µV

Figure 3

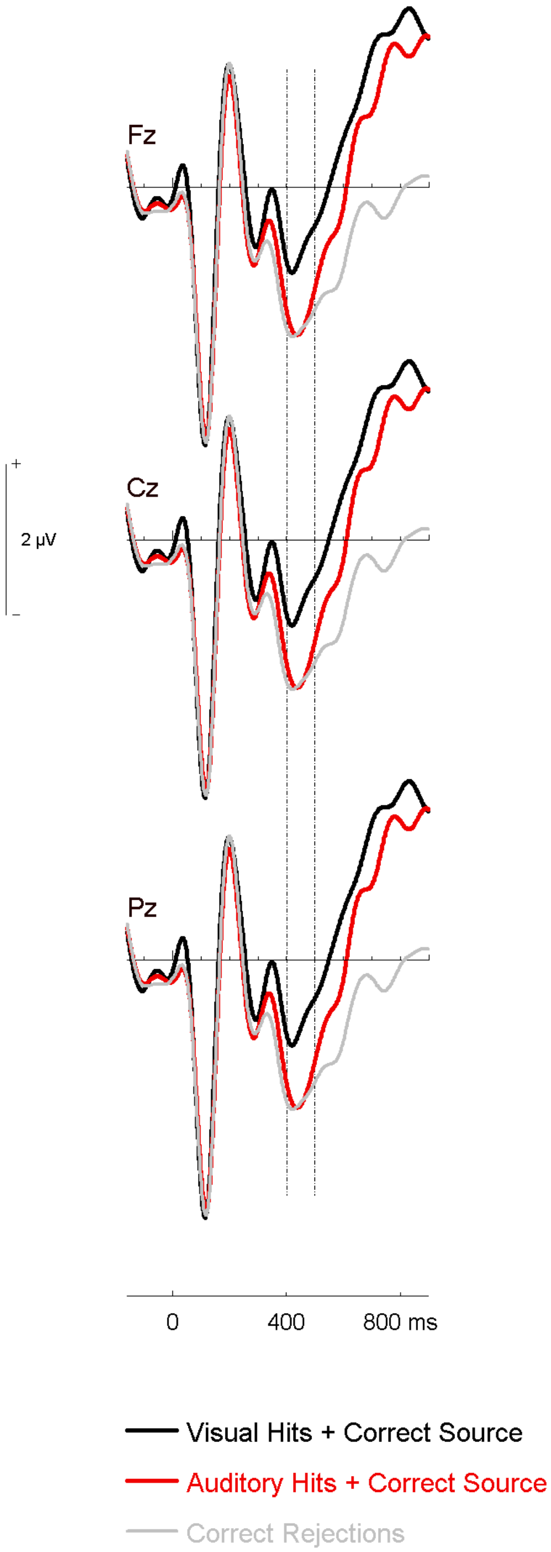

Fz
Cz
Pz
+
2 µV
–
0
400
800 ms
Visual Hits + Correct Source
Auditory Hits + Correct Source
Correct Rejections

Figure 4

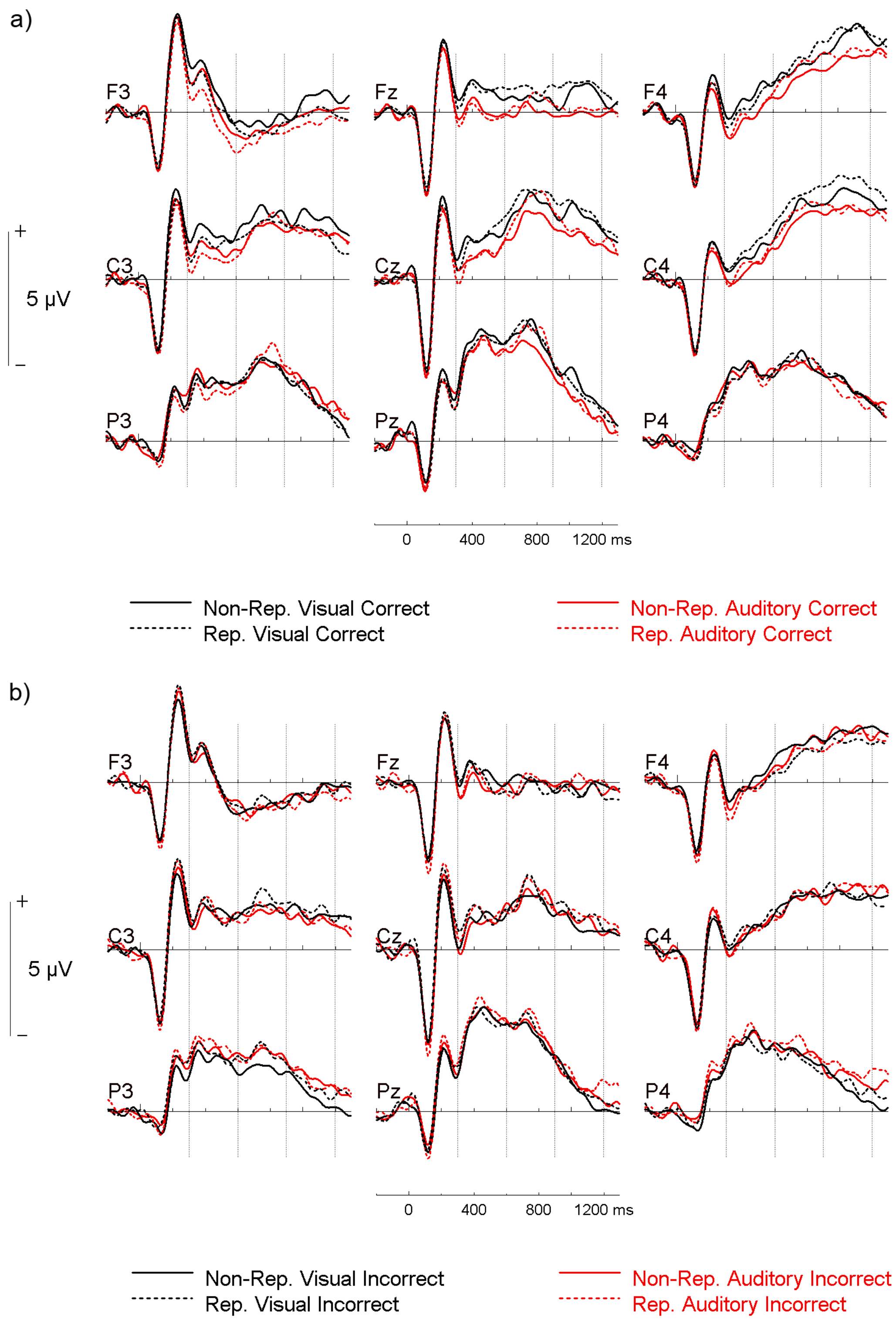

a)
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
+
5 µV
–
0
400
800
1200 ms
Non-Rep. Visual Correct
Rep. Visual Correct
Non-Rep. Auditory Correct
Rep. Auditory Correct
b)
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
+
5 µV
–
0
400
800
1200 ms
Non-Rep. Visual Incorrect
Rep. Visual Incorrect
Non-Rep. Auditory Incorrect
Rep. Auditory Incorrect

Figure 5

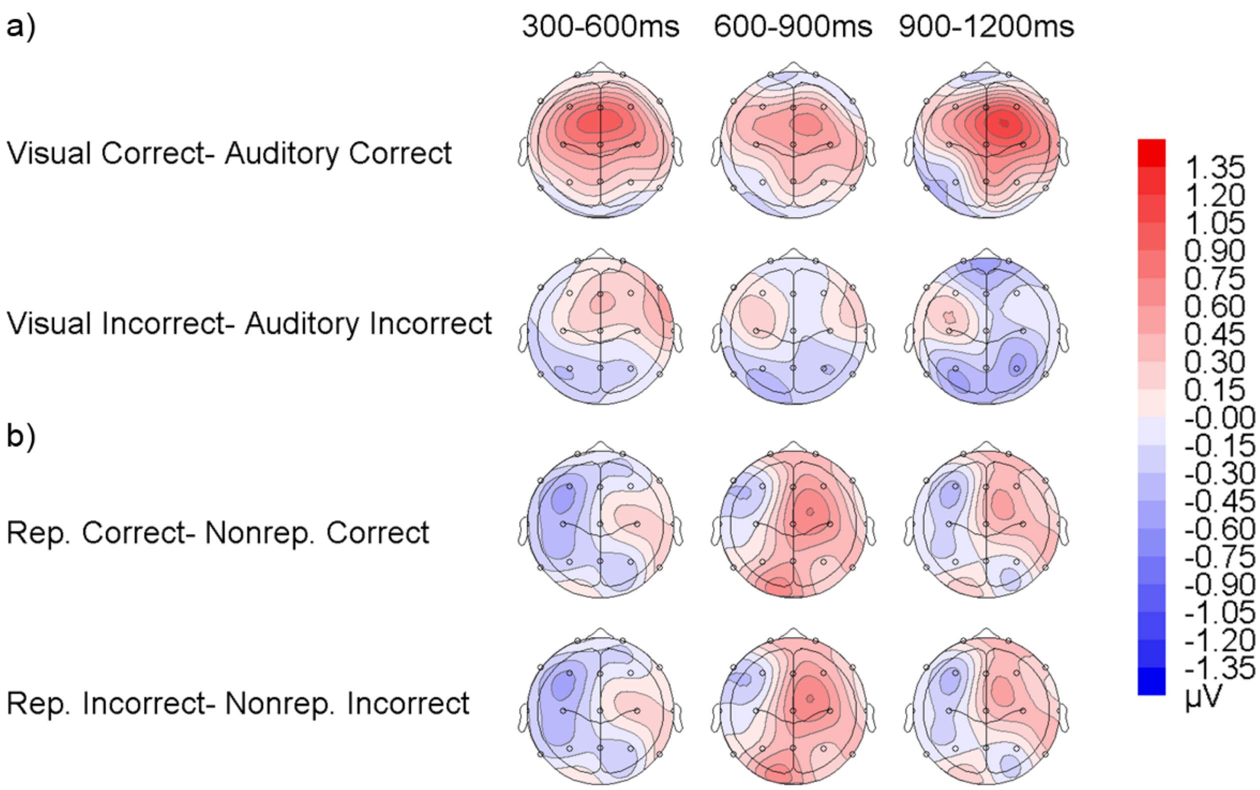

a)
300-600ms
600-900ms
900-1200ms
Visual Correct- Auditory Correct
Visual Incorrect- Auditory Incorrect
b)
Rep. Correct- Nonrep. Correct
Rep. Incorrect- Nonrep. Incorrect
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
-0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-0.90
-1.05
-1.20
-1.35
μV

Figure 6

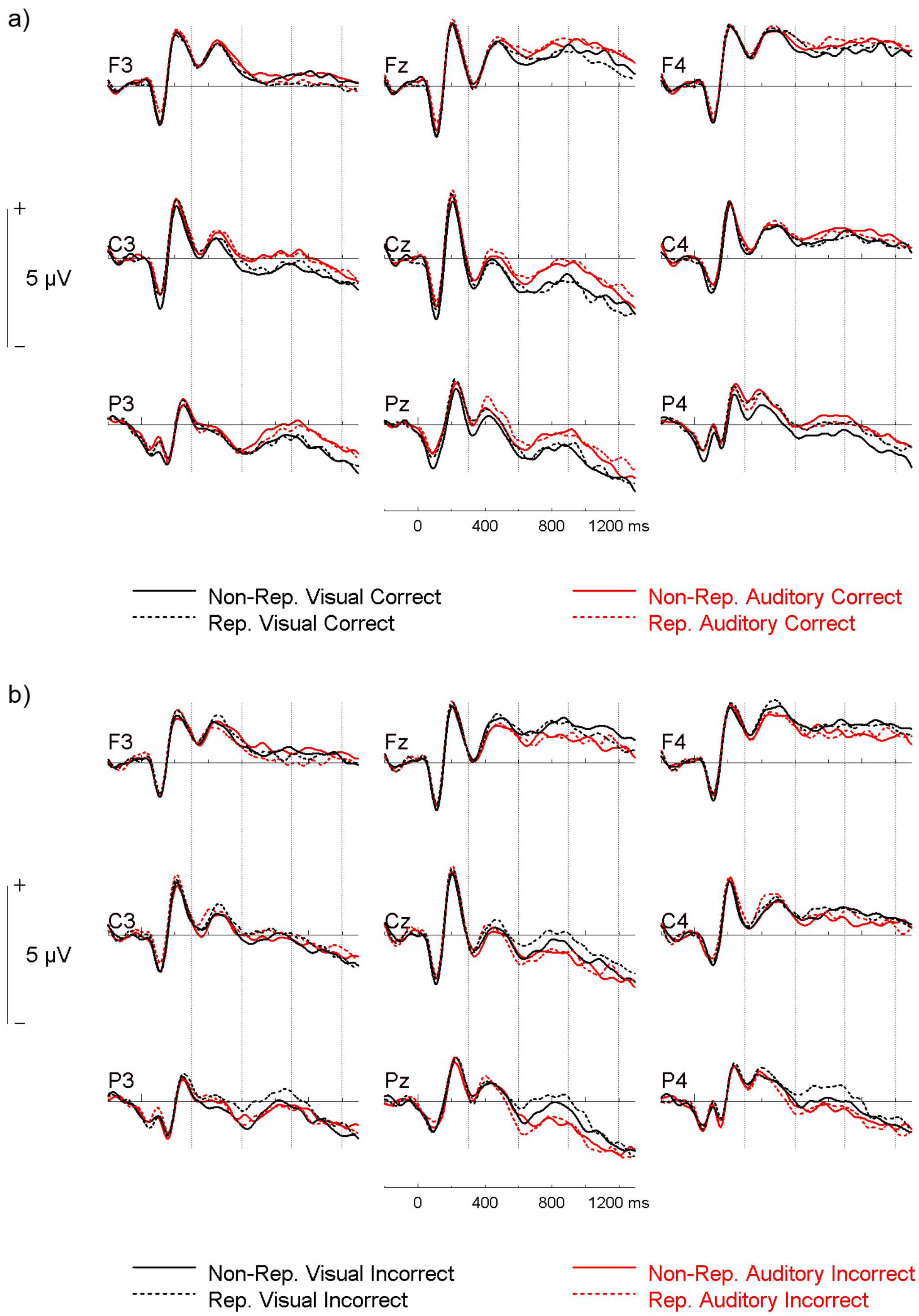
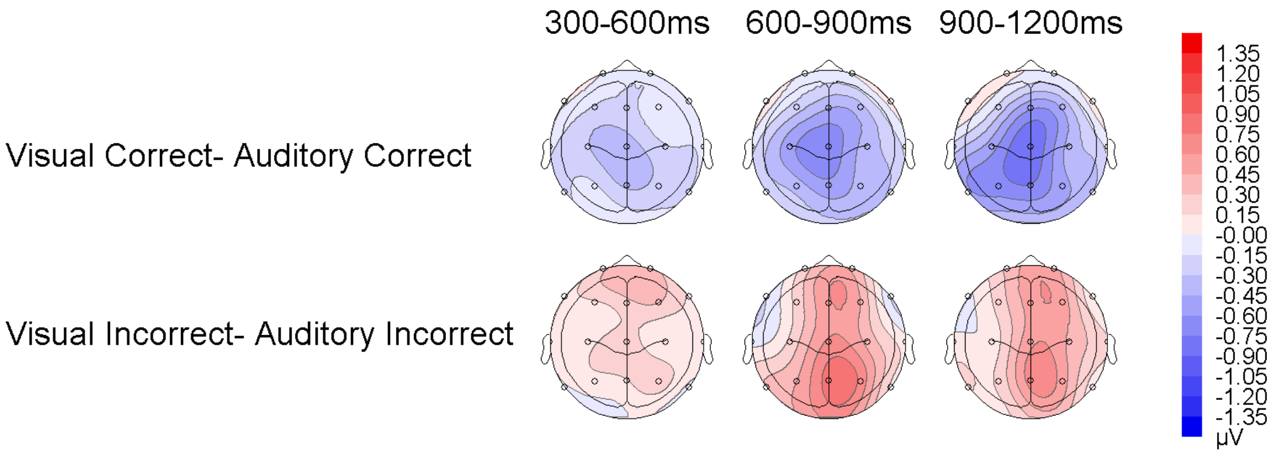

a)
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
+
5 µV
–
0
400
800
1200 ms
Non-Rep. Visual Correct
Rep. Visual Correct
Non-Rep. Auditory Correct
Rep. Auditory Correct
b)
F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
+
5 µV
–
0
400
800
1200 ms
Non-Rep. Visual Incorrect
Rep. Visual Incorrect
Non-Rep. Auditory Incorrect
Rep. Auditory Incorrect

Figure 7


300-600ms
600-900ms
900-1200ms
Visual Correct- Auditory Correct
Visual Incorrect- Auditory Incorrect
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
-0.00
-0.15
-0.30
-0.45
-0.60
-0.75
-0.90
-1.05
-1.20
-1.35
µV