Chemical Senses, 2018, Vol 43, 27–34
doi:10.1093/chemse/bjx064
Original Article
Advance Access publication October 11, 2017

Original Article

From Nose to Memory: The Involuntary Nature of Odor-evoked Autobiographical Memories in Alzheimer's Disease

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Editorial Decision 4 October 2017.

Abstract

Research suggests that odors may serve as a potent cue for autobiographical retrieval. We tested this hypothesis in Alzheimer's disease (AD) and investigated whether odor-evoked autobiographical memory is an involuntary process that shares similarities with music-evoked autobiographical memory. Participants with mild AD and controls were asked to retrieve 2 personal memories after odor exposure, after music exposure, and in an odor-and music-free condition. AD participants showed better specificity, emotional experience, mental time travel, and retrieval time after odor and music exposure than in the control condition. Similar beneficial effects of odor and music exposure were observed for autobiographical characteristics (i.e., specificity, emotional experience, and mental time travel), except for retrieval time which was more improved after odor than after music exposure. Interestingly, regression analyses suggested executive involvement in memories evoked in the control condition but not in those evoked after music or odor exposure. These findings suggest the involuntary nature of odor-evoked autobiographical memory in AD. They also suggest that olfactory cuing could serve as a useful and ecologically valid tool to stimulate autobiographical memory, at least in the mild stage of the disease.

Key words: Alzheimer's disease, autobiographical memory, involuntary memory, odor

Introduction

It is a widely held belief that odors are potent cues for evoking personal autobiographical memories. People frequently report retrieval of long-forgotten scenes and events due to a whiff of a fleeting odor. A smell of coffee may remind one of a vacation during which one sipped a coffee when contemplating the beauty of a natural scene. The smell of a spice may also trigger memories about a journey in the Orient, a dinner at a restaurant, or a family event. Perhaps, the most famous anecdotal report of odor-evoked personal memories is the description by Marcel Proust, reporting retrieval of a long-forgotten scene due to the smell of a madeleine cake soaked in tea. Anecdotal reports about odor efficiency in memory retrieval have been supported by a substantial body of empirical evidence, suggesting that odors serve as potent cues for evoking personal autobiographical memories (Larsson and Willander 2009; Larsson et al. 2014; Saive et al. 2014).

Empirical evidence has suggested that odors are a potent cue for autobiographical retrieval. In a seminal study, Rubin et al. (1984) presented young participants with odors, photographs, or names of common objects, and the participants were asked to describe an autobiographical memory evoked by each cue. Results showed that odors cued memories that had never been thought of or talked about previously. Research also suggests that odor-evoked autobiographical memories may trigger several experiential dimensions such as emotion and mental time travel. The latter dimension refers to the feeling of being brought back in time to the occurrence of the experienced event (Tulving 2002). As for the emotional characteristics of odor-evoked autobiographical memories, empirical evidence has shown that odors are more effective triggers of emotional content than other sensory modalities or even odor labels (Herz 2004; Herz et al. 2004). In a related vein, Herz and Schooler (2002) found that autobiographical memories evoked by odors were more emotional and evocative than those evoked by visual or verbal cues. Mirroring these outcomes, Larsson and Willander (2009) considered emotion as a central aspect of odor-evoked autobiographical memories. The neurobiological basis of these phenomena may be the direct olfactory system projections to the amygdala complex, a brain area that is critical for emotional experience and emotional memory (Cahill et al. 1995). As for the subjective experience of odor-evoked autobiographical memories, research suggests that these memories are associated with strong feelings of being brought back in time to the occurrence of the events (Herz and Schooler 2002; Herz 2004). For instance, Willander and Larsson (2006) found in healthy elderly subjects that odor-evoked autobiographical memories triggered mental time travel better than memories evoked by verbal or visual cues. In addition, odor-evoked autobiographical memories have high specificity. Chu and Downes (2002) found that odor-evoked autobiographical memories are more unique and detailed than memories evoked by other sensory modalities. To conclude, findings support the notion that odor-evoked autobiographical memories are associated with stronger emotions, mental time travel, and specificity than those evoked by visual or verbal cues.

Appearance in response to external cues and strong emotional and subjective experiencing are characteristic features of involuntary memories, that is memories that spontaneously arise without a deliberate effort to retrieve them (Berntsen 2010). Empirical evidence has shown that people frequently experience involuntary memories, especially when they are engaged in automatic activities that require little attention and concentration (Berntsen 2010). Involuntary memories are often more specific than their voluntary counterparts. Interestingly, the decline in memory specificity that is observed for voluntary autobiographical memories in normal aging does not occur for involuntary memories (Schlagman et al. 2009). Involuntary memories are also found to be accompanied by a stronger emotional reaction than their voluntary counterparts, perhaps because we are usually unprepared for the sudden occurrence of involuntary memories (Berntsen 2010). Another phenomenological characteristic of involuntary memories is their subjective reliving, such memories often being associated with mental time travel and vivid recollection of remembered events (Berntsen and Hall 2004).

The specificity, emotion, and mental time travel that characterize involuntary memories are also observed with odor-evoked autobiographical memories. Another feature common to both involuntary and odor-evoked memories is automaticity. Voluntary retrieval is a goal-directed process requiring executive control to monitor the search process, whereas involuntary retrieval is an automatic process instigated by the sensory cue and requiring little executive control (Berntsen 2010). This assumption fits with a 2-mode retrieval model of autobiographical memory, as proposed by Conway (2005). In this model, autobiographical memories can be retrieved generatively or directly. In generative retrieval, autobiographical memories are validated in relation to schematized knowledge and the search process is intentional, iterative, and elaborative. In contrast, in direct retrieval, a cue activates a pattern of highly intertwined autobiographical information, resulting in an effortless and immediate recollection. Thus, effortful selection is bypassed in the direct retrieval mode. It is noteworthy that elemental perceptions (e.g., odors) often trigger direct retrieval (Willander and Larsson 2007; Arshamian et al. 2013), whereas verbal information often activates generative retrieval (Berntsen 2010). A shorter retrieval time has been observed for involuntary than voluntary autobiographical memories, supporting the assumption that involuntary retrieval requires little cognitive control (Schlagman and Kvavilashvili 2008).

Severe autobiographical memory compromise is a defining clinical feature of Alzheimer's disease (AD). A major characteristic of autobiographical memory compromise in AD is overgenerality, that is, the reduced ability to produce specific memories (Greene et al. 1995; Graham and Hodges 1997; Ivanoiu et al. 2006; Leyhe et al. 2009; El Haj et al. 2011, 2012a, 2015c; Irish et al. 2011; Seidl et al. 2011; Barnabe et al. 2012; Müller et al. 2013; De Simone et al. 2016; Kirk and Berntsen 2017). This overgenerality is thought to result in a diminished ability to mentally relive past events and a general feeling of knowing or familiarity that may be expressed by AD patients as a sense of "having experienced this before" (Piolino et al. 2003; Rauchs et al. 2007; Hudon et al. 2009; El Haj et al. 2013b, 2016; El Haj and Antoine 2017b). The decreased ability to retrieve specific autobiographical memories has also been linked with a diminished sense of self (Mograbi et al. 2009; Morris and Mograbi 2013; El Haj and Antoine 2017a). According to the AMAD model (Autobiographical Memory in AD) (El Haj et al. 2015d), owing to autobiographical generality, as well as to anterograde amnesia (i.e., inability to form new memories) and retrograde amnesia (i.e., inability to retrieve old memories), AD patients have limited access to memories that shape their self-knowledge, self-consciousness, and self-image, resulting in a diminished sense of identity. Considering the negative consequences of impairment of autobiographical memory on the sense of identity in AD patients, studies have tried to alleviate this impairment using sensorial cuing.

In a previous study (El Haj et al. 2012a), we investigated the involuntary characteristics of music-evoked autobiographical memories in AD participants who were asked to retrieve personal events in silence and after music exposure. Music-evoked autobiographical memories were found to be more specific, were accompanied by more emotional content, were retrieved faster, and triggered less executive control than memories evoked in silence. These findings were attributed to the involuntary nature of music-evoked autobiographical memories, as compared with effortful voluntary recall (El Haj et al. 2012a). These and related findings on the beneficial effect of music exposure on autobiographical recall in AD (Foster and Valentine 2001; Irish et al. 2006; El Haj et al. 2012a, 2012b, 2013a, 2015c) have potential clinical interest, since sensory cuing may alleviate, to some extent, the autobiographical decline in AD.

The present study investigated the potential involuntary nature of odor-evoked and music-evoked autobiographical memories and whether odor and music cuing may alleviate deficits in recollecting autobiographical information in AD. To this end, we asked AD and control participants to retrieve personal events in silence and after odor and music exposure compared with odor- and music-evoked autobiographical memories in terms of specificity, emotion, mental time travel (Chu and Downes 2002; Herz and Schooler 2002; Herz 2004; Herz et al. 2004; Willander and Larsson 2006), speed of retrieval, and executive involvement (El Haj et al. 2012a).

Materials and methods

Participants

We tested 28 participants at the mild stage of AD and 30 healthy controls. The AD participants were recruited from local retirement homes and were diagnosed with probable AD dementia by an experienced neurologist or geriatrician based on the National Institute on Aging-Alzheimer's Association clinical criteria (McKhann et al. 2011). Control participants were independent, living in their own homes, and often spouses or relatives of AD participants. As shown in Table 1, controls were matched to AD participants according to age, sex, and educational level. Exclusion criteria for all participants were other significant psychiatric or neurological illness or history of alcohol or drug use. No participants presented any major visual or auditory acuity limitations that would have prevented them completing the study tasks. Since our procedures dealt with olfactory stimuli, we excluded participants with nasal congestion, upper respiratory infection, or allergic rhinitis symptoms. All participants freely consented to participate and could withdraw whenever they wished, which was the case of 2 AD participants who left the study for health problems (original AD sample, n = 30 participants). All participants provided written informed consent. The study was approved by the local research ethics committee of the University of Lille.

Cognitive and clinical assessments

We administered tests of general cognitive functioning, episodic memory, working memory, and depression. All scores are shown in Table 1.

General cognitive functioning was assessed with the Mini-Mental State Exam (Folstein et al. 1975) and the maximum score was 30 points. Episodic memory was evaluated with the task of Grober and Buschke (1987). The participants had to retain 16 words and after immediate cued recall, there was a 20-s distraction phase during which they had to count numbers aloud. This phase was followed by 2 min of free recall and the score from this phase (out of a maximum of 16) was retained as the episodic score. For working memory assessment, participants had to repeat a string of single digits in the same order (i.e., forward span) or in the inverse order (i.e., backward span). Depression was assessed with the self-report Hospital Anxiety and Depression Scale (Zigmond and Snaith 1983) consisting of 7 items scored on a 4-point Likert scale from 0 (not present) to 3 (considerable). The maximum score was 21 points and the cutoff for definite depression was set at > 10/21 points. Executive function was assessed in terms of verbal fluency (El Haj and Allain 2012), flexibility, and inhibition (Miyake et al. 2000). On the verbal fluency task, participants were given 2 min to generate as many words beginning with the letter P, excluding proper names and variants of the same words. Flexibility was assessed with the Plus–Minus task, with the score referring to the difference between the completion time (in s) for List 3 (alternating between adding and subtracting) minus the average completion time for Lists 1 (adding) and 2 (subtracting). Inhibition was evaluated with the Stroop task, with its score referring to the completion time (in s) for the interference condition minus the average completion time for word reading and color naming.

Experimental procedures

Participants were tested individually in 3 sessions: after odor exposure, after music exposure, and in a control condition. The order of sessions was counterbalanced and there was approximately a 3- to 5-day interval between sessions. In the 3 sessions, participants were asked to "recount, in detail, an event in your (their) life". This simple instruction has been widely used to cue autobiographical recall in AD patients (Fromholt et al. 2003; Piolino et al. 2003; El Haj et al. 2011, 2015a, 2015b; Martinelli et al. 2013). The participants were given 3 min to describe their memories. They were informed of this time limit so that they could structure their memories accordingly and to avoid bias from redundancy or distractibility.

In the odor-exposure condition, the experimenter explained that he was about to open a small bottle of essential oils. Afterwards, he moved the bottle under the participant's nose and asked them to close their eyes and mouth and breathe normally through the nose. This procedure was repeated twice since 2 odors were presented separately, coffee and vanilla. Directly after each odor exposure, the autobiographical instruction was given. Coffee and vanilla were chosen owing to their particular pleasantness, as shown by studies on odor-evoked memories (Rubin et al. 1984; Herz and Cupchik 1995; Chu and Downes 2002; Herz 2004; Miles and Berntsen 2011). The 2 autobiographical evocations after each odor exposure were separated by the verbal fluency task.

Table 1. Demographic, cognitive, clinical, and executive characteristics of AD and control participants

		AD (n = 28)	Controls (n = 30)
Women/men		20/8[n/s]	22/8
Age in years		73.25 (6.71)[n/s]	71.75 (8.05)
Education in years		8.71 (3.03)[n/s]	9.33 (2.25)
General cognitive functioning	Mini-Mental State Examination	22.54 (1.64)***	28.17 (1.51)
Episodic memory	Grober and Buschke	6.11 (2.31)***	10.63 (3.31)
Working memory	Forward span	4.89 (1.20)**	6.33 (1.73)
	Backward span	3.57 (1.17)***	4.97 (1.38)
Depression	Hospital Anxiety and Depression Scale	8.75 (1.11)***	7.03 (1.99)
Executive function	Verbal fluency	17.36 (5.36)***	23.13 (5.26)
	Flexibility	12.61 (5.88)***	5.48 (1.95)
	Inhibition	64.36 (6.71)***	35.53 (9.84)

Note: Standard deviations are given between brackets. Performance on Mini-Mental State Examination refers to correct responses/30. Performance on Grober and Buschke task refers to correct responses/16. Performance on forward and backward spans refers to number of correctly repeated digits. Maximum score on depression scale was 21 points. Performance on verbal fluency refers to number of correctly generated words. Flexibility and inhibition scores refer to completion time in seconds.

[n/s]differences between groups were nonsignificant.

Differences between groups were significant at **P < 0.001, ***P < 0.001.

In the music-exposure condition, an autobiographical instruction was provided after exposure to 2 pieces of music, Vivaldi's "Spring" movement from the "Four Seasons" and the French song "la Bohème", performed and composed by Charles Aznavour and written by Jacques Plante. The former piece has been widely used in studies on music-evoked autobiographical memory in AD (Foster and Valentine 2001; Irish et al. 2006; El Haj et al. 2012a, 2012b, 2013a, 2015c), and the latter was chosen for its considerable popularity with French-speaking AD patients (Basaglia-Pappas et al. 2013). Furthermore, we wished to compare the effects of music with lyrics (the "Four Seasons") and without lyrics ("la Bohème"). Music was played ambiently. Because the experiment was performed in various places (i.e., participants' homes or rooms in retirement homes) with various acoustic characteristics, the volume level was adjusted during each session. As in the odor-exposure session, the 2 autobiographical evocations after each music exposure were separated by an executive task (i.e., the Plus-Minus task).

In the control condition, autobiographical instruction was also provided twice, but in silence with odor-free air. Prior to the session, rooms were aerated to provide an odor-neutral environment. During the control session, all windows and doors were closed to provide a quiet environment. Similar precautions were also taken for the odor- and music-exposure sessions. The 2 autobiographical evocations were separated by the Stroop task.

Evaluation of autobiographical specificity

Autobiographical performance was scored with the TEMPau scale (Test Episodique de Mémoire du Passé) (Piolino et al. 2004, 2006, 2007; Rauchs et al. 2007), an instrument based on classic autobiographical evaluations (Kopelman et al. 1989) and adapted in French. Ranging from 0 to 4 points, the scale allows a comprehensive evaluation of autobiographical specificity (single vs. repeated memory) by evaluating contextual characteristics, such as the presence of spatiotemporal details and internal characteristics such as the presence of phenomenological details (perceptions, thoughts, and feelings). We attributed 0 if the participant was unable to produce any memory or if she/he gave only general information about a theme (e.g., "my father"); 1 point if the memory depicted a repeated or extended event (e.g., "my father used to drink coffee"); 2 points if the memory was situated in time and/or in space (e.g., "my father used to drink coffee in the backyard"); 3 points if the memory was specific, lasting less than 24 h and situated in time and space (e.g., "one morning on a summer vacation in the mountain, my father was not able to find a grocery to buy coffee"); 4 points if the memory was specific, situated in time and space, and included internal sensory-perceptual-affective details (e.g., "my father was bit nervous without his morning coffee"). Since 2 memories were assessed, the specificity score referred to the sum of the 2 scores, the maximum score being 8 points.

To prevent scoring bias, events were also rated and categorized by an independent rater who was blind to the hypotheses. Using Cohen's Kappa coefficient (k) (Brennan and Prediger 1981), high inter-rater agreement coefficient was obtained (K > 0.87). Disagreements were discussed until a consensus was reached.

Evaluation of emotion, mental time travel, and retrieval time

After autobiographical retrieval, participants rated the emotional content of their evoked memories on a 5-point scale (−2 = very negative, 0 = neutral, and 2 = very positive). They also rated the following statement: "I feel that I traveled back to the time it happened" on a 5-point scale (0 = not at all, 1 = slightly, 2 = moderately, 3 = quite a bit, and 4 = extremely). The latter statement replicated a French short version (El Haj et al. 2016) of the Autobiographical Memory Questionnaire (Rubin et al. 2003). As for automaticity, retrieval time was defined as the amount of time in s between the end of the autobiographical instruction and the start of memory generation, retrieval time being measurable as an identifiable interval within the whole recording period. The scores of emotion, mental time travel, and retrieval time were the mean of the scores for the 2 memories.

Results

We compared autographical characteristics (i.e., specificity, emotion, mental time travel, and retrieval time) between AD and control participants separately for each experimental condition (i.e., control condition, after music, and after odors). We then compared the same characteristics across the 3 experimental conditions separately for AD and control participants. Next, we transformed all raw specificity and executive data to z scores, calculated a global executive z score from the mean of z scores of the 3 executive measures (i.e., fluency, flexibility, and inhibition) and performed stepwise regression analysis to determine whether executive function predicts autobiographical specificity, separately for the 3 experimental conditions and for AD and control participants. Since the specificity, emotion, and mental time travel scores were ordinal, nonparametric tests were used. They were also used for retrieval time owing to the non-normal distribution shown by the Kolmogorov–Smirnov test. For all tests, significance was set as $P \leq 0.05$, with P-values between 0.051 and 0.099 being considered as trends.

Autobiographical deficits in AD participants

Scores for all autobiographical characteristics are shown in Table 2. Compared with controls, AD participants showed less specificity in the control condition ($Z = -4.61$, $P < 0.001$), after music exposure ($Z = -3.22$, $P < 0.01$), and after odor exposure ($Z = -3.68$, $P < 0.001$). AD participants also showed less emotional experience in the control condition ($Z = -2.24$, $P < 0.05$), but no significant differences were observed between AD and control participants after music exposure ($Z = -1.29$, $P > 0.01$) or after odor exposure ($Z = -0.69$, $P > 0.01$). The same pattern was observed for mental time travel, since significant differences were shown between AD and control participants in the control condition ($Z = -2.74$, $P < 0.01$), but not after music exposure ($Z = -1.68$, $P > 0.01$) or odor exposure ($Z = -1.63$, $P > 0.01$). As for retrieval time, longer intervals were observed for AD than for control participants in the control condition ($Z = -4.09$, $P < 0.001$), both after music exposure ($Z = -3.61$, $P < 0.001$) and odor exposure ($Z = -3.04$, $P < 0.001$).

Higher memory specificity after odor exposure in AD participants

For AD participants, Friedman's repeated measures analysis of variance showed significant variation in specificity across the 3 experimental conditions, χ^2 (2, $N = 28$) = 15.32, $P < 0.001$. Post hoc analysis with Wilcoxon signed-rank tests showed higher specificity after odor exposure than in the control condition ($Z = -3.22$, $P < 0.001$) and after music exposure than in the control condition ($Z = -3.20$, $P < 0.001$), but no significant differences between odor exposure and music exposure ($Z = -1.42$, $P > 0.01$). For control participants, Friedman's repeated measures analysis of variance showed no significant variations of specificity across the 3 experimental conditions, χ^2 (2, $N = 30$) = 1.55, $P > 0.01$.

Table 2. Characteristics of autobiographical memories generated by AD and control participants in control condition, after music exposure, and after odor exposure

		AD	Controls
Specificity	Control condition	4.36 (1.44)***	7.46 (0.51)
	Music	3.11 (0.92)**	3.77 (0.57)
	Odor	3.29 (0.76)***	3.90 (0.30)
Emotion	Control condition	0.71 (1.48)*	1.53 (0.90)
	Music	1.46 (0.92)[n/s]	1.70 (0.89)
	Odor	1.43 (0.96)[n/s]	1.63 (0.67)
Mental time travel	Control condition	2.12 (1.21)**	3.03 (1.22)
	Music	3.07 (1.12)[n/s]	3.60 (0.62)
	Odor	3.11 (1.03)[n/s]	3.57 (0.63)
Retrieval time	Control condition	31.13 (9.91)***	20.25 (7.78)
	Music	24.82 (11.72)***	15.41 (6.81)
	Odor	14.52 (10.36)***	7.42 (3.25)

Note: maximum specificity score was 8 points. Emotion was rated on a 5-point scale (−2 = very negative, 2 = very positive). Mental time travel rating was rated on a 5-point scale (0 = not at all, 4 = extremely). Retrieval time was calculated in s.

[n/s]differences between groups were nonsignificant.

Differences between groups were significant at *$P < 0.05$, **$P < 0.001$, ***$P < 0.001$.

For convenience, we report the means of specificity for memories evoked by coffee and those evoked by vanilla. No significant differences were observed for specificity of memories evoked by coffee and those evoked by vanilla in AD (*M* coffee = 2.31, *M* vanilla = 2.05, $Z = -0.42$, $P > 0.01$) or control participants (*M* coffee = 3.52, *M* vanilla = 3.94, $Z = -0.61$, $P > 0.01$).

Higher emotion after odor exposure in AD participants

A trend toward significant variation in emotion across the 3 experimental conditions was observed, χ^2 (2, $N = 28$) = 5.93, $P = 0.053$. Post hoc analysis showed higher emotion after odor exposure than in the control condition ($Z = -2.13$, $P < 0.05$) and after music exposure than in the control condition ($Z = -2.58$, $P = 0.01$), but no significant differences between odor exposure and music exposure ($Z = -0.27$, $P > 0.01$). For control participants, Friedman's repeated measures analysis of variance showed no significant variations in emotion across the 3 experimental conditions, χ^2 (2, $N = 30$) = 1.42, $P > 0.01$

Higher mental time travel after odor exposure in AD participants

Significant variations in mental time travel were observed across the 3 experimental conditions, χ^2 (2, $N = 28$) = 11.59, $P < 0.01$. Post hoc analysis showed higher mental time travel after odor exposure than in the control condition ($Z = -3.08$, $P < 0.01$) and after music exposure than in the control condition ($Z = -2.68$, $P < 0.01$), but no significant differences between odor exposure and music exposure ($Z = -0.09$, $P > 0.01$). For control participants, Friedman's repeated measures analysis of variance showed no significant variations in mental time travel across the 3 experimental conditions, χ^2 (2, $N = 30$) = 3.80, $P > 0.01$.

Shorter retrieval time after odor exposure in AD participants

Significant variations in retrieval time were observed across the 3 experimental conditions, χ^2 (2, $N = 28$) = 26.00, $P < 0.001$. Post hoc analysis showed shorter retrieval time after odor exposure than in the control condition ($Z = -4.05$, $P < 0.001$), after music exposure than in the control condition ($Z = -2.05$, $P < 0.05$), and after odor exposure than after music exposure ($Z = -3.44$, $P < 0.001$). For control participants, significant variations in retrieval time were observed across the 3 experimental conditions, χ^2 (2, $N = 30$) = 44.89, $P < 0.001$. Post hoc analysis showed shorter retrieval time after odor exposure than in the control condition ($Z = -4.78$, $P < 0.001$), after music exposure than in the control condition ($Z = -3.14$, $P < 0.05$), and after odor exposure than after music exposure ($Z = -4.49$, $P < 0.001$).

Executive function does not predict memory after odor exposure

To assess the putative contributions of executive function to autobiographical memory as evoked in the 3 experimental conditions, we carried out 3 sets of regression analyses separately for the 3 experimental conditions and for AD and control participants. In the first set, autobiographical specificity in the control condition (in *z* score) was used as the dependent variable, whereas the predictor variable was the mean *z* score of executive function. Executive function predicted autobiographical memory significantly in the control condition, accounting for 24.7% ($P < 0.01$) of its variance in AD participants and 25.4% ($P < 0.01$) in controls. In the second set of analyses, autobiographical recall after music exposure was the dependent variable and the mean executive function *z* score was the predictor variable. Executive function did not predict music-evoked autobiographical memory either in AD participants ($P > 0.01$) or in controls ($P > 0.01$). A similar pattern was observed in the third set: executive function did not predict odor-evoked autobiographical memory either in AD participants ($P > 0.01$) or in controls ($P > 0.01$).

We also carried out correlation analysis between the mean *z* score of executive function and retrieval time. In AD participants, significant correlations were found between executive function and retrieval time of autobiographical memory in the control condition (r = −0.45, $P < 0.05$), but not of music-evoked autobiographical memory ($r = -.21$, $P > 0.01$) or odor-evoked autobiographical memory ($r = -.11$, $P > 0.01$). A similar pattern was observed in the control participants, significant correlations being found between executive function and retrieval time of autobiographical memory in the control condition ($r = -.47$, $P < 0.05$), but not of music-evoked autobiographical memory ($r = -0.19$, $P > 0.01$) or odor-evoked autobiographical memory ($r = -.13$, $P > 0.01$). The negative correlation meant that the better executive function was, the shorter the retrieval time.

Discussion

In light of research suggesting the beneficial effects of music exposure on autobiographical memory in AD, we assessed whether such benefits would also be observed for odor exposure. We further investigated whether odor exposure would cue involuntary memory like the involuntary nature of music-evoked autobiographical memory in AD. We found that memories retrieved after odor and music exposure in AD participants had higher specificity, emotional experience, mental time travel, and shorter retrieval time than in the control condition. The beneficial effects of odor and music exposure on autobiographical characteristics were similar, except for retrieval time which was much shorter after odor exposure than music exposure. Interestingly, no significant variations were observed in control participants for autobiographical characteristics across the 3 experimental conditions, except for retrieval time which was likewise much improved after odor exposure than music exposure. Finally, regression analyses suggested that executive function may be involved in memories evoked in the control condition, but not in memories evoked after music or odor exposure. Collectively, these findings imply the involuntary nature of odor-evoked autobiographical memory.

The empirical evidence reviewed in the introduction strongly suggests that odors function as a potent cue for autobiographical retrieval (Larsson et al. 2014; Saive et al. 2014). The present findings, which have greater autobiographical specificity and involved richer emotional reliving with odor-evoked autobiographical memories than control memories, replicate in AD participants the findings of previous research in younger adults (Herz and Schooler 2002; Herz 2004). Interestingly, odor exposure "filled" the emotional gap that was observed in the control condition between AD and control participants. The same assumption can be made for mental time travel since the difference between AD and control participants in the control condition disappeared after odor exposure. Furthermore, odor-evoked autobiographical memories in AD participants triggered higher mental time travel than memories evoked in the control condition, replicating research showing strong feelings of being brought back in time by odor-evoked memories (Herz and Schooler 2002; Herz 2004). Interestingly, emotional experience and mental time travel are features of involuntary memories, as observed for odor-evoked memories in our AD participants (Berntsen and Hall 2004; Berntsen 2010).

Another involuntary characteristic revealed by our data on odor-evoked autobiographical memories is relative automaticity. These memories triggered shorter retrieval times than memories evoked in the control condition, an outcome that was observed for both AD and control participants. Odor-evoked autobiographical memories were not significantly associated with executive involvement, unlike memories evoked in the control condition. Together, these findings suggest that retrieving odor-evoked autobiographical memories requires less effort than voluntarily remembering events from the past. The notion of automaticity as observed in our study fits with the assumption of Berntsen (2010), who defines voluntary retrieval as a goal-directed process requiring executive control to monitor the search process and involuntary retrieval as an automatic process instigated by sensory cues (including odors), requiring little executive control. Prior research has shown shorter retrieval time for involuntary (Schlagman and Kvavilashvili 2008) and music-evoked autobiographical memories (El Haj et al. 2012a) compared with their voluntary autobiographical counterparts. In both AD and control participants, our findings of shorter retrieval time for odor-evoked than for music-evoked memories, and shorter retrieval time for odor- and music-evoked memories than for their voluntary counterparts, strongly suggest that odor-evoked retrieval is involuntary and requires little cognitive control.

How odor might serve as a retrieval cue for autobiographical memory can be discussed within the framework of the encoding specificity of memory hypothesis (Tulving and Thomson 1973), according to which salient sensory elements of the encoding context are processed along with the target information as part of a memory trace. These contextual elements may then serve as retrieval cues for the target information when the same context is reinstated at testing. Research supports this hypothesis for odors. In a pioneering study by Cann and Ross (1989), subjects processed a series of photographs in the presence of ambient odors. Results demonstrated better memory of the photographs when the odors present during learning and testing sessions were matched than when they mismatched. These outcomes were replicated by another study showing that odors presented during both learning and testing sessions improved the recall of a list of words compared with a no-odor control condition (Schab 1990). Although these studies link the effectiveness of odors as memory retrieval cues with their presence during encoding, it is difficult to assume that the positive effect of odors, as observed in our study, is due to their presence during memory encoding. Our participants were invited to retrieve any event that came to mind and were not instructed to retrieve memories that they were reminded of by the odor/music stimuli. Even if invited to retrieve memories related with the odors, it is very difficult to ensure that the retrieved memories are related to the cues, especially in AD patients. Note that one advantage of instructing participants to retrieve any memory rather than memories related with a specific odor is the retrieval of more memories, as AD patients may find it very difficult to retrieve memories related to a specific cue. In our study, the instruction to retrieve any memories may have contributed significantly to the fact that all AD and control participants succeeded in retrieving memories. Another interpretation of this success is that participants were invited to retrieve only 2 memories. Furthermore, any general information (e.g., "in my childhood") was considered as an event.

Considering our control participants, we found no significant variations in their autobiographical characteristics across the 3 experimental conditions except for retrieval time. This does not support previous research showing the positive effects of involuntary retrieval on autobiographical reliving in normal aging. A study found less specificity for voluntary memories in older than in younger participants, an effect than was not observed for involuntary memories (Schlagman et al. 2009). The absence in our control participants of any benefit from exposure to odors or music on autobiographical specificity can be attributed to a ceiling effect: they were able to easily retrieve and mentally relive 2 specific memories from their autobiographical database without any cues. Another explanation of the lack of benefit from exposure to odors or music in the controls is that the sensitivity of our specificity scale was too low to detect differences in the quality of the memories they retrieved. The same may be said for the emotion and mental time travel scales.

From a neuroanatomical point of view, odors are intimately linked with the limbic system, since the amygdala is located only one synapse away from the olfactory receptors (Larsson et al. 2014). Moreover, odor-evoked memories have been associated with activation in the amygdala and hippocampal regions (Arshamian et al. 2013), a fact that is particularly relevant since these regions are preferentially targeted by the neuropathological processes of AD (Pennanen et al. 2004). In a study by Royet et al. (2011), activity in the hippocampus was associated with correct recognition of odors, and decreased activation of the anterior hippocampus was observed with correct recognition and rejection. These outcomes led some authors to suggest that better odor recognition memory is associated with less activation in the hippocampus (Saive et al. 2014). Further evidence of hippocampal involvement in odor memory comes from research showing poor odor recognition in patients with hippocampal lesions (Levy et al. 2004). Moreover, hippocampal activation was observed during retrieval of odor-evoked autobiographical memories and did not vary as a function of memory remoteness, suggesting a permanent role of the hippocampus in the retrieval of odor-evoked autobiographical memories (Arshamian et al. 2013). Interestingly, hippocampal activation is observed in both voluntary and involuntary autobiographical memories, although voluntary memories also tend to activate the dorsal frontal regions that are associated with cognitive control (Hall et al. 2014).

One limitation of our study is that olfactory function was not assessed in any of the participants. Another potential limitation is the subjective assessment of emotion, resulting in a clear trend toward positive memories. Future research should assess the emotional characteristics of odor-evoked autobiographical memories using galvanic skin response recordings, a noninvasive technique that has been applied in AD studies (Irish et al. 2006). A wider variety of odors than the two we used could also be studied.

Regardless of these limitations, our findings are intriguing since they highlight olfactory cuing as a useful and ecologically valid tool for stimulating autobiographical memory in AD, at least in the mild stage of the disease and for emotionally positive memories. Research on autobiographical rehabilitation in AD has long been focused on music. By showing that odors are similarly potent cues, this study paves the way for clinical and experimental research on odor-evoked autobiographical memory in AD.

Funding

Dr El Haj, Dr Gandolphe, and Pr Antoine were supported by the LABEX (excellence laboratory, program investment for the future) DISTALZ (Development of Innovative Strategies for a Transdisciplinary approach to Alzheimer disease). Dr El Haj was supported by the EU Interreg 2 Seas Programme 2014–2020 (cofunded by the European Regional Development Fund). Dr Kapogiannis was supported by the Intramural Research Program of the National Institute on Aging, NIH.

Conflict of interests

The authors declare no conflict of interest.

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