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Original Article

Effects of Olfactory Stimulation on Past and Future Thinking in Alzheimer's Disease

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Abstract

Several studies have demonstrated that Alzheimer's disease (AD) is associated not only with difficulty in remembering past events but also with a compromised ability to imagine future ones. Recent empirical research has also demonstrated that odor is an effective cue to alleviate difficulty in remembering past events in AD. We investigated whether odor exposure would help AD patients to imagine future events. To this end, we invited AD patients and control participants to evoke past and future events after odor exposure or without odor. Analysis showed that AD patients and control participants produced more specific and more emotional past and future events after odor exposure than without odor. However, odor exposure did not improve the retrieval time for future thinking in AD participants. This study is the first to demonstrate positive effects of odor exposure on the ability of AD patients to project themselves into the future.

Key words: Alzheimer's disease, autobiographical memory, future thinking, odor, olfactory stimulation

Introduction

Projecting oneself into the future is a human ability that serves in many settings such as decision-making, self-control, planning, and emotion regulation (Boyer 2008; D'Argembeau et al. 2011; Schacter 2012; Miloyan and Suddendorf 2015; Demblon and D'Argembeau 2017). The simulation of future scenarios has a significant adaptive value as it allows the evaluation of the potential consequences of one's actions (Boyer 2008). Several authors have suggested that remembering the past and imagining the future involves common neuroanatomical substrates (Addis et al. 2007, 2009). Research has demonstrated that the default mode network including the medial temporal lobes is robustly engaged in both remembering the past and imagining the future (Addis et al. 2007, 2009; Hassabis et al. 2007).

Both past and future thinking (i.e. respectively the ability to retrieve past personal events and the capacity to project oneself into the future) also rely on similar cognitive processes such as retrieval of contextual details, mental simulation, imagery, and the attribution of personal significance (D'Argembeau et al. 2012). The similarities between past and future thinking have been highlighted by the "constructive episodic simulation hypothesis" (Addis et al. 2007). According to this hypothesis, imagining future scenarios requires the flexible extraction of details from episodic memory and recombining them into a coherent simulation. Therefore, episodic memory can be considered as a core cognitive process that unifies past and future thinking. Not surprisingly, patients with amnesia tend to demonstrate difficulty not only with past thinking but also with future thinking. In a case study, Hassabis et al. (2007) demonstrated that 4 out of 5 amnesic patients with cerebral damage in the region of the hippocampus had difficulty in imagining future experiences. Compared with age-matched controls, they exhibited fewer details and less coherence. In the same vein, patient K.C. (Rosenbaum et al. 2005) and patient D.B. (Klein et al. 2002), who presented severe amnesia, were unable to construct future events.

Both past and future thinking are also impaired in patients with Alzheimer's disease (AD) (Addis et al. 2009; Irish et al. 2012; El

Haj et al. 2015a; Moustafa and El Haj 2018). In a pioneering study, Addis et al. (2009) demonstrated that AD patients exhibited deficits in both remembering the past and imagining the future in terms of personal significance, temporal distance and emotional intensity. Moreover, significant correlations were observed between past and future thinking, providing further evidence of the close linkage between the mental representation of past and future in AD. The same issue was investigated by El Haj et al. (2015a) who invited AD and control participants to evoke past and future events. AD patients retrieved a similar amount of contextual details and a similar amount of self-defining memories as well as similar autonoetic reliving when generating past and future events. Furthermore, they evoked similar themes when generating past and future events. According to El Haj et al. (2015a, 2015b), these findings suggest that the difficulty of AD patients to project themselves into the future may be due to the small amount of information they can retrieve from their episodic memory, resulting in similarities in the generation of past and future events. Future thinking in AD was also investigated by Moustafa and El Haj (2018) who evaluated phenomenological characteristics of both past and future thinking in patients with AD. Compared with control participants, AD patients exhibited poor reliving, mental time travel, visual and auditory imagery, language, and spatiotemporal specificity. However, no significant difference was observed between AD and control participants regarding emotion and importance of future events. That study was the first to demonstrate that AD seems to compromise some phenomenological characteristics of future events, whereas other phenomenological aspects such as emotion seem relatively preserved in the disease. Overall, these studies demonstrate compromise of future thinking in AD.

Given the decline in future thinking in AD, we investigated whether it can be alleviated by odor exposure. This aim was based on research demonstrating positive effects of odor exposure on past thinking in AD (El Haj et al. 2017; Glachet et al. 2018, 2019; Glachet and El Haj 2019). For instance, El Haj et al. (2017) investigated the involuntary nature of autobiographical memory as triggered by music and odor. Results demonstrated that odor exposure improved specificity, emotional load and mental time travel of past thinking in AD participants. Odor exposure also resulted in faster retrieval of past thinking in AD participants. The authors hypothesized that retrieving odor-evoked autobiographical memories is based on automatic retrieval of memory rather on generative, requires less cognitive effort.

The superiority of odor over other sensory modalities may be explained by neuroimaging studies demonstrating that 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). This anatomical proximity may provide a more direct access to the spatiotemporal context and the emotional experience associated with odor-evoked memories compared with memories triggered by other sensory modalities (Glachet et al. 2018). In a recent study, Glachet et al. (2019) investigated the effect of odor exposure on the retrieval of recent and remote memories in AD. They found that AD patients produced a higher number and more specific childhood, adulthood, and recent memories after odor exposure than without odor. Taken together, a body of literature strongly suggests odor exposure acts as a potent cue for the retrieval of recent and remote autobiographical memories. These studies have an important clinical implication since odor exposure could assist the retrieval of personal information in AD.

Building on this body of research and bearing in mind the similarities between past and future thinking in AD, the present study extends this literature by assessing whether the positive effect of olfactory stimulation on past thinking in AD is also observed for future thinking. Therefore, we investigated whether odor exposure enhances the specificity, arousal and emotional valence of past and future thinking. Also, and based on studies showing the automatic nature of odor-evoked autobiographical memories (El Haj et al. 2017), we investigated whether odor-exposure results in diminished retrieval time for future events. Participants with mild AD and older adults were invited to generate past and future events after odor exposure and without odor. We posited that the findings would throw light on the effect of olfactory stimulation on future thinking in AD patients.

Materials and methods

Participants

The study included 24 participants at the mild stage of AD and 25 healthy controls. AD participants were recruited from local retirement homes and were diagnosed with probable AD dementia by a neurologist or a geriatrician, based on the National Institute of Aging-Alzheimer Association criteria (McKhann et al. 2011). Control participants were often spouses or relatives of AD patients, or they were recruited from the local community. All participants were French native speakers and reported no auditory or visual impairments. All participants provided written informed consent, were free to participate and could withdraw whenever they wanted. The study was approved by the research ethics committee of the University of Lille.

As shown in Table 1, both groups were matched according to age, sex, and education level. Exclusion criteria for all participants were as follows: history of psychiatric or neurological impairment, drug, and alcohol use. AD participants with dementia in whom memory impairments were not in the foreground (e.g. mixed dementia or frontotemporal dementia) were ineligible. Cognitive and clinical performances of all participants were assessed with the tests described below.

Cognitive and clinical assessment

We evaluated general cognitive efficiency, episodic memory, working memory, and depression. General cognitive efficiency was evaluated with the Mini-Mental State Examination (MMSE) (Folstein et al. 1975) with a maximum score of 30 points. Episodic memory was assessed with the task of Grober and Buschke (1987). Participants were invited to learn and retain 16 words, each belonging to different semantic categories. After an immediate cued recall, there was a 20-s distraction phase followed by a free recall of the 16 words for 2 min. Episodic memory performance was evaluated as the number of words/16 properly recalled during the free recall. Working memory abilities were evaluated by the span task in which participants were asked to repeat a string of single digits in the same order (i.e. forward span), or in the reverse order (i.e. backward span). The length of the string increased by 1 digit at each trial. Scores were expressed as the number of digits properly recalled without error. Depression symptomatology was assessed with the Geriatric Depression Scale (Yesavage 1988; Brink et al. 2013). Participants were asked to indicate if they agreed or disagreed with each of the 15 items. The coding was counterbalanced across items to control response bias. The maximum score was 15 points and the cutoff for definite depression was set at >5/15 points.

Procedures

After the cognitive and clinical assessment, participants were invited to retrieve 1 past event and 1 future event with and without odor

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

		AD (n = 24)	Control (n = 25)
Women/men		18/6[ns]	21/4
Age in years		85.12 (5.68)[ns]	84 (8.5)
Education in years		9.88 (2.09)[ns]	9.12 (1.99)
Depression	Geriatric Depression Scale	2.96 (1.63)[ns]	3.56 (1.96)
General cognitive efficiency	MMSE	20.29 (2.58)***	27.44 (1.89)
Episodic memory	Grober and Buschke	3.46 (1.28)***	7.76 (1.13)
Working memory	Digit span forward	4.29 (.91)***	5.72 (.74)
	Digit span backward	2.29 (.86)***	3.56 (1.96)
Verbal fluency	Phonemic	5.42 (2.86)***	9.24 (2.13)
	Semantic	6.5 (2.59)***	11.76 (2.63)

Note: SDs are given between brackets. Performance on MMSE refers to correct responses/30. Performances on the Grober and Buschke task refer to correct responses/16. Maximum score on depression scale was 15 points.

[ns]Differences between groups were non-significant.

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

exposure. Prior to past and future thinking, they were invited to determine their favorite odor, as described below.

Choice of odorant

Participants were presented with a set of 7 odors (i.e. lemon, orange, grass, cinnamon, chocolate, coffee, coconut, and peach), displayed in bottles of scented oil. These odors were selected as they were found to be easily detected by AD participants and healthy older adults (Tabert et al. 2005) and were even found to be familiar enough to trigger self-related knowledge (Rubin et al. 1984). In our study, participants were invited to move the bottles under their nose and to breathe normally through it. Using the scale developed by Pouliot and Jones-Gotman (2008), participants were asked to rate each odor depending on its olfactory threshold for detection and familiarity. We evaluated the olfactory threshold because AD is widely associated with a decline in olfactory function (Doty et al. 1987; Morgan et al. 1995; Mesholam et al. 1998). Participants used a 5-point Likert scale to indicate whether they were able to detect each odor (1—"I cannot smell anything"; 2—"I smell a slight odor"; 3—"I smell a moderately strong odor"; 4—"I smell a strong odor"; 5—"I smell an extremely strong odor"). They were also asked to indicate on a 5-point Likert scale to what extent each odor was familiar to them (1—"I have never smelled this odor before"; 2—"This smell is slightly familiar to me"; 3—"this smell is moderately familiar to me"; 4—"this smell is very familiar to me"; 5—"this smell is extremely familiar to me"). Based on these 2 scales, we established the odor with the highest threshold and familiarity score for each participant. This odor was then used to trigger past and future thinking in the odor condition.

Past and future thinking

In 1 session, participants were invited to retrieve 1 past and 1 future event after odor exposure. In the second session, they had to retrieve 1 past and 1 future event without odor exposure. Sessions were counterbalanced and separated approximately 1 week apart. The order of past and future thinking was counterbalanced across participants.

In the odor-exposure condition, participants were presented with a bottle of scented oil including the previously chosen odor. They were asked to move the bottle under their nose and to breathe normally through it. Directly after odor exposure, AD and control participants were asked to "recount in detail an event in their lives" or "imagine in detail a future event," regardless of when the event had occurred or might occur. This instruction has been widely used to trigger the generation of autobiographical retrieval of past events (Piolino et al. 2000; Piolino 2008; El Haj et al. 2012a, 2012b, 2013) and future events in AD patients. Participants were allowed 2 min to describe each past and future event. This time limit was adopted to avoid certain biases such as redundancy and distractibility, and is sufficient for autobiographical recollection in most AD patients (Addis et al. 2008; El Haj et al. 2012a, 2012b, 2013, 2017; Glachet et al. 2018). Regarding future events, the experimenter told the participants that they had to imagine events that might reasonably occur in the future. Participants were asked to repeat back the instructions with their own words to ensure their learning. For both past and future events, we asked them to be precise and specific, with events that lasted no more than 24 h, that included details such as the time and place at which the event had occurred or would occur, as well as to describe their feelings and emotions associated with those events. To ensure that participants understood what was required of them, they were asked to repeat the instructions using their own terms. Their autobiographical narratives were recorded using a smartphone and were subsequently transcribed.

Evaluation of specificity

Specificity of both past and future events was measured by the experimenter using the narratives. Performance was scored on the TEMPau scale (Test Episodic de Mémoire du Passé) (Piolino et al. 2002), an instrument based on classic autobiographical memory evaluation (Kopelman et al. 1989) that is widely used as a reliable measure of autobiographical memory in AD (D'Argembeau et al. 2003; El Haj et al. 2012a, 2012b, 2013, 2015a, 2017; Glachet et al. 2018), and has been adapted in French. For each memory, we attributed zero if there was no memory or only general information about a theme (i.e. I was child). One point was attributed for an extended event without spatiotemporal context (i.e. I played music every week); 2 points for an extended event situated in time and space (i.e. I played music every Monday and Thursday at the local stadium); 3 points for a specific event lasting less than 24 h, and situated in time and space (i.e. It was the first time I played with the local orchestra); and 4 points for a specific memory with phenomenological details such as feelings, thoughts, visual imagery, and emotion (i.e. I felt stressed but very happy). The maximum score for each memory was 4 points.

Evaluation of emotion

Emotions associated with past and future events were rated by the participants after autobiographical recall. We used the Self-Assessment Manikin (SAM) (Lang 1980), which allows the evaluation of the arousal and emotional valence associated with each past and future event, after odor exposure and without odor. Participants used a 5-point Likert scale to rate the arousal and valence of their past and future events compared with a pictorial representation. Regarding arousal, they were instructed to use the very calm SAM rating if the content of the event included no arousal, the extremely excited representation if the memory included extreme emotions, and to use intermediate SAM ratings for events including intermediate levels of arousal (1—"I feel very calm"; 5—"I feel very excited"). For emotional valence, they were instructed to use the extremely happy SAM rating if the event involved very positive content, the extremely unhappy SAM one if the content of the event was very negative, and to use the intermediate SAM rating for events including intermediate positive or negative emotions (1—"I feel extremely sad"; 5—"I feel extremely happy"). The maximum score for arousal and valence was 5 for each.

Evaluation of reaction time

The reaction time was evaluated with respect to the latency between the end of the instruction for both past and future events, and the beginning of the narrative. Reaction time was scored according to the recording of the narrative.

Statistical analysis

We compared differences between AD and control participants regarding specificity, arousal and emotional valence, and reaction time of past and future thinking with and without odor exposure. Owing to the non-normal distribution of the data, non-parametric tests were conducted. Between-group comparisons were performed with the Mann–Whitney *U* test, and within-group comparisons were assessed using the Wilcoxon sign rank test. Results are reported with effect size, Cohen's d = .2, refers to a small effect size, Cohen's d = .5, a medium effect size, and Cohen's d = .8, a large effect size (Cohen 1998). Effect sizes were calculated for non-parametric tests according to the recommendations of Rosenthal and DiMatteo (2001) and Ellis (2010).

Results

Autobiographical specificity for past and future events

As shown in Figure 1, between-group comparison revealed a significant difference between AD and control participants in the odor-free condition regarding the autobiographical specificity for past events (Z = –5.39, P < 0.001, Cohen's d = 2.34), with means of 1.5 (standard deviation [SD] = .88, Mdn = 1.5) and 3.36 (SD = .7, Mdn = 3), respectively. A significant difference was also found between AD and control participants regarding the autobiographical specificity for future events (Z = –3.87, P < 0.001, Cohen's d = 1.25), with means of 1.17 (SD = .87, Mdn = 1) and 2.4 (SD = 1.08, Mdn = 2), respectively. Between-group analysis also revealed significant differences between AD and control participants in past events after odor exposure (Z = –5.36, P < 0.001, Cohen's d = 1.79), with means of 2.33 (SD = 1.05, Mdn = 3), and 3.38 (SD = .5, Mdn = 4), respectively, and future events (Z = –3.56, P < 0.001, Cohen's d = 1.1), with means of 1.79 (SD = .72, Mdn = 2), and 2.84 (SD = 1.14, Mdn = 3), respectively.

Within-group analysis revealed higher specificity after odor exposure for past events in AD participants (Z = 3.38, P = 0.001, Cohen's d = 1.9) and control participants (Z = 2.16, P = 0.03, Cohen's d = .96). We also found higher specificity after odor exposure for future events in AD participants (Z = 2.69, P = 0.007, Cohen's d = 1.31), but not in control participants (Z = 1.3, P > 0.05, Cohen's d = .54).

Arousal and emotional valence for past and future events

Results regarding arousal and emotional valence are presented in Figures 2 and 3, respectively. Between-group analysis revealed no significant difference between AD and control participants for arousal associated with past events in the odor-free condition (Z = –.90, P > 0.05, Cohen's d = .31), with means of 3.37 (SD = 1.13, Mdn = 4), and 3.68 (SD = .85, Mdn = 4), respectively. We found no difference in the odor-free condition between AD and control participant regarding arousal for future events (Z = –.19, P > 0.05, Cohen's d = .03), with means of 3.08 (SD = 1.35, Mdn = 3), and 3.12 (SD = 1.09, Mdn = 3), respectively. No significant difference was found after odor exposure between AD and control participants regarding arousal for past events (Z = .79, P > 0.05, Cohen's d = .2), with means of 4.29 (SD = .75, Mdn = 4), and 4.44 (SD = .71, Mdn = 5), respectively, and for future events (Z = .14, P >

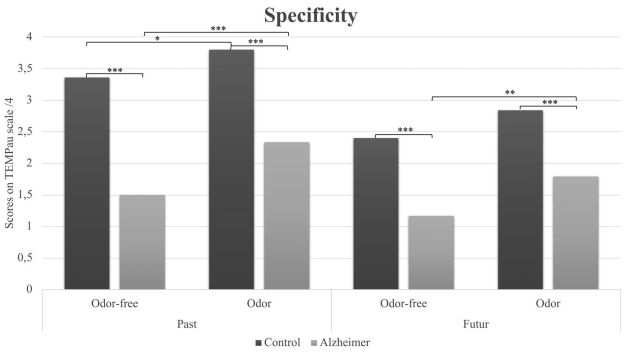

Figure 1. Specificity scores observed in AD participants and control participants for past and future events after odor exposure and without odor. *Note*: Differences between odor and odor-free conditions were significant at: *P < 0.05, **P < 0.01 and ***P < 0.001.

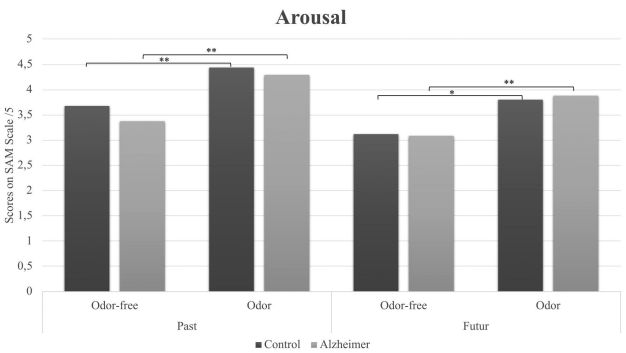

Figure 2. Scores on arousal scale observed in AD participants and control participants for past and future events after odor exposure or without odor. *Note*: Differences between odor and odor-free conditions were significant at: *P < 0.05 and **P < 0.01.

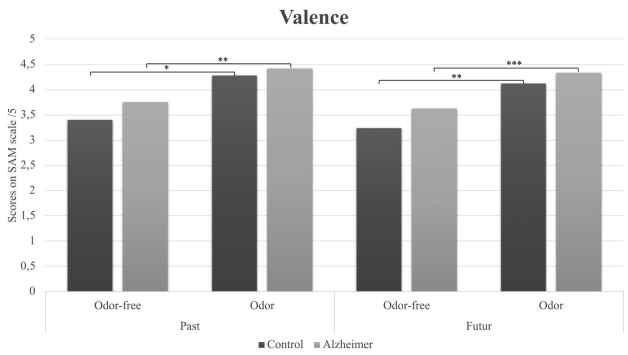

Figure 3. Scores on valence scale observed in AD participants and control participants for past and future events after odor exposure or without odor. *Note*: Differences between odor and odor-free conditions were significant at: **P* < 0.05, ***P* < 0.01, and ****P* < 0.001.

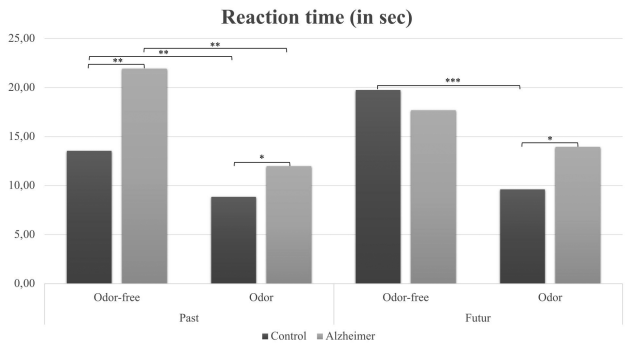

Figure 4. Reaction time in seconds observed in AD participants and control participants for past and future events after odor exposure and without odor. *Note*: Differences between odor and odor-free conditions were significant at: **P* < 0.05, ***P* < 0.01, and ****P* < 0.001.

0.05, Cohen's *d* = .09), with means of 3.88 (SD = .9, Mdn = 4), and 3.8 (SD = .91 Mdn = 4), respectively.

Regarding emotional valence, we found no significant difference between AD and control participants for past events in the odor-free condition (*Z* = .61, *P* > 0.05, Cohen's *d* = .29), with means of 3.75 (SD = .94, Mdn = 4), and 3.4 (SD = 1.41, Mdn = 4), respectively. AD and control participants reported the same emotional valence for future events in the odor-free condition (*Z* = 1.1, *P* > 0.05, Cohen's *d* = .41), with means of 3.63 (SD = .82, Mdn = 4) and 3.24 (SD = 1.05, Mdn = 4), respectively. Between-group analysis revealed no significant difference between AD and control participants regarding emotional valence for past events evoked after odor exposure (*Z* = .49, *P* > 0.05, Cohen's *d* = .13), with means of 4.42 (SD = 1.06, Mdn = 4) and 4.28 (SD = 1.1, Mdn = 5), respectively. No significant difference was found between AD and control participants regarding emotional valence for future events after odor exposure (*Z* = .35, *P* > 0.05, Cohen's *d* = .22), with means of 4.33 (SD = .76, Mdn = 4.5) and 4.12 (SD = 1.13, Mdn = 4), respectively.

The Wilcoxon signed-rank test revealed higher arousal for past events after odor exposure than without odor in both AD participants (*Z* = 3.07, *P* = 0.002, Cohen's *d* = 1.61) and control participants (*Z* = 2.82, *P* = 0.005, Cohen's *d* = 1.37). AD and control participants reported higher arousal for future events after odor exposure than without odor with (*Z* = 2.19, *P* = 0.002, Cohen's *d* = .99) and (*Z*= 2.63, *P* = 0.009, Cohen's *d* = 1.24), respectively. AD and control participants reported more positive past events after odor exposure than without odor with (*Z* = 2.44, *P* = 0.01, Cohen's *d* = 1.15) and (*Z* = 2.23, *P* = 0.025, Cohen's *d* = .99), respectively. AD and control participants also reported more positive future events after odor exposure compared with the odor-free condition with (*Z* = 3.53, *P* < 0.001, Cohen's *d* = 2.08) and (*Z* = 2.81, *P* = 0.005, Cohen's *d* = 1.36), respectively.

Reaction times for past and future events

As shown in Figure 4, reaction time was shorter in control participants than in AD participants for past events evoked without odor (*Z* = 2.81, *P* = 0.005, Cohen's *d* = .65), with means of 21.96 (SD = 12.77, Mdn = 20) and 13.56 (SD = 13.16, Mdn = 10), respectively. There was no significant difference in reaction time between AD and control participants for future events evoked without odor (*Z* = .26, *P* > 0.05, Cohen's *d* = .14), with means of 17.71 (SD = 13.51, Mdn = 12) and 19.76 (SD = 17.57, Mdn = 13), respectively. Control participants had shorter reaction times than AD participants regarding past events evoked after odor exposure (*Z* = 2.54, *P* = 0.011, Cohen's *d* = .28), with means of 12 (SD = 8.54, Mdn = 11) and 8.88 (SD = 12.97, Mdn = 4), respectively. Reaction times were also shorter in control participants than in AD participants for future events evoked after odor exposure (*Z* = 2.12, *P* = 0.034, Cohen's *d* = .45), with means of 13.96 (SD = 9.27, Mdn = 12.5) and 9.64 (SD = 10.02, Mdn = 6), respectively.

The Wilcoxon signed-rank test revealed shorter reaction times for past events evoked after odor exposure than in the odor-free condition in AD participants (*Z* = −3.24, *P* = 0.001, Cohen's *d* = 1.77) and control participants (*Z* = −2.42, *P* = 0.001, Cohen's *d* = 1.11). We found no difference in reaction time for future events in AD participants after odor exposure compared with the odor-free condition (*Z* = −1.29, *P* > 0.05, Cohen's *d* = .56). However, control participants had shorter reaction times for future events evoked after odor exposure than without odor (*Z* = −3.65, *P* < 0.001, Cohen's *d* = 2.14).

Discussion

Considering studies demonstrating a beneficial effect of odor on the retrieval of autobiographical memories, we investigated whether odor exposure would enhance future thinking in mild AD. To this end, we invited AD patients and control participants to evoke past and future events after odor exposure and without odor. Our analysis showed a positive effect of odor exposure on the ability of AD patients to produce past and future events. Past thinking during odor exposure was more specific, more emotional and retrieved faster than in the odor-free condition in both AD patients and control participants. However, we found no effect of odor exposure on the retrieval time for future events in AD patients. Considering previous studies demonstrating a positive effect of odor exposure on autobiographical memory in young adults (Herz and Cupchik 1992; Chu and Downes 2000; Herz and Schooler 2002; Herz et al. 2004), and in AD (El Haj et al. 2017; Glachet et al. 2018, 2019; Glachet and El Haj 2019), our study is the first to demonstrate the beneficial effect of odor exposure on past and future thinking in AD.

Our findings replicate previous research demonstrating that autobiographical memory deficit in AD can be somewhat alleviated by odor presentation, allowing AD patients to produce more specific autobiographical memories (El Haj et al. 2017; Glachet et al. 2018, 2019). The ability of odor to enhance autobiographical specificity has been associated with the neuronal proximity between the olfactory bulb and the limbic system (Larsson et al. 2014). Moreover,

odor-evoked autobiographical memories have been associated with the activation of the amygdalo-hippocampal complex (Arshamian et al. 2013), which is involved in the retrieval of specific and emotional memories. This anatomical proximity may provide a more direct access to the spatiotemporal details that form of autobiographical memory, resulting in specific odor-evoked autobiographical memories (Glachet et al. 2018). Our findings also replicate previous studies demonstrating that odor exposure enhances the emotional and phenomenological properties of past thinking in AD (El Haj et al. 2017; Glachet et al. 2018; Glachet and El Haj 2019). Another important characteristic of odor-evoked autobiographical memories is their relative automaticity, which is mainly associated with short retrieval times (El Haj et al. 2012a, 2017). Our study replicates previous findings demonstrating that odor-evoked autobiographical memories were retrieved faster than memories evoked without odor (El Haj et al. 2017; Glachet et al. 2018), suggesting the automatic nature of odor-evoked autobiographical memories. This latter result can be interpreted in terms of the executive control involved in the retrieval of voluntary and involuntary autobiographical memories. El Haj et al. (2017) found that odor-evoked autobiographical memories were not associated with executive involvement, unlike memories evoked in an odor-free condition. This interpretation fits with the assumption of Berntsen (2010), who defined voluntary recall as a complex and goal-directed process requiring executive control, and involuntary recall as an automatic process generally by with sensory cues (e.g. odors) and requiring little executive control. This interpretation may explain why we observed shorter reaction times during the retrieval of odor-evoked autobiographical memories in both AD patients and control participants.

Building on research demonstrating a positive effect of odor on the retrieval of autobiographical memories in AD (El Haj et al. 2017; Glachet et al. 2018, 2019), we investigated whether odor exposure improves future thinking in mild AD. There is a general view that what we can retrieve about the past influences our ability to project ourselves into the future. The present study is the first to demonstrate that odor exposure enhances not only the specificity of past events, but also the ability of AD patients to envisage detailed future scenarios. This finding can be interpreted in the light of the constructive episodic simulation hypothesis, according to which past and future thinking are subsumed by a similar representation from episodic memory (Addis et al. 2007; Schacter and Addis 2007). Episodic memory is deeply impaired in AD (Irish et al. 2006; Ivanoiu et al. 2006; Leyhe et al. 2009; Seidl et al. 2011; El Haj et al. 2015b, 2015c), providing little available information for the construction of specific future events (El Haj et al. 2015a). In the present study, odor exposure enhanced the specificity of future events in both AD patients and control participants. A possible explanation is that odor exposure may provide access to more information from episodic memories. Thus, odor-evoked future events may involve a more direct access to the phenomenological details stored in episodic memory, allowing for the construction of specific future events.

Furthermore, we found that odor exposure resulted in more positive autobiographical memories and future events in both AD patients and control participants. This finding is consistent with previous research demonstrating that odors are more powerful triggers of emotional content than other sensory modalities in healthy adults (Herz and Schooler 2002; Herz et al. 2004) and AD patients (El Haj et al. 2017; Glachet and El Haj 2019). The present study extends those findings by demonstrating that AD patients report more positive future events after odor exposure than without odor, and has an important clinical implication since odor could help AD patients to envisage more positive future scenarios. Since we did not evaluate the well-being of AD patients after generating past and future events, it would be of interest to investigate whether the evocation of positive odor-evoked future events influences the well-being of patients more than in an odor-free condition.

The present study contributes to the literature demonstrating similarities between past and future thinking in AD. In the odor-free condition, our analysis demonstrated a lower specificity in AD patients than in control participants, reflecting their reduced ability to produce detailed events in both past and future scenarios. These findings fit with previous research demonstrating the difficulty that AD patients experience in projecting themselves into the future, as well as their reduced ability to imagine phenomenological details associated with future events (Moustafa and El Haj 2018). Their difficulty in generating future scenarios is consistent with several studies of populations with episodic memory deficits, such as older adults (Addis et al. 2008) and amnesic patients (Hassabis et al. 2007), who also experience difficulty in generating future events. The well-known hippocampus-dependent memory impairment in AD and amnesic patients (Hassabis et al. 2007) may lead to drawing repeatedly on the same general past events, resulting in a greater similarity between past and future thinking. Addis et al. (2009) suggested that the hippocampus may have an important role not only in remembering autobiographical memories, but also in producing original future scenarios. Since the hippocampus is a prime site of neuropathology in AD, it is not surprising that our AD participants generated fewer autobiographical details than control participants when producing past and future events. To illustrate this issue, a study by Moustafa and El Haj (2018) demonstrated that, unlike control participants, AD patients evoked similar themes when generating past and future events, suggesting that they found it difficult to mentally "try out" alternative scenarios in the construction of future events, without repeating the same schemes of past events.

While displaying poor specificity, AD patients demonstrated high ratings for emotion associated with past and future events. In other words, we found no difference between AD patients and control participants regarding the arousal and the emotional valence of past and future thinking. These findings echo those by Sundstrøm (2011) who found better recall of emotional items than neutral items in AD patients. In a similar vein, Kalenzaga et al. (2013) asked AD patients to describe themselves with emotional and neutral adjectives. After an encoding phase, they observed a better recall of emotional adjectives than neutral adjectives. In the present study, AD participants were invited to rate the arousal and the emotional valence of their own autobiographical memories or future scenarios. Consistent with previous studies (Sundstrøm 2011; Kalenzaga et al. 2013), our findings suggest that AD patients can experience prolonged emotional states that persist, even if the event that originally caused the emotion has faded from their memory (Guzmán-Vélez et al. 2014). Regarding future scenarios, the high emotional rating observed in our AD participants may be due to the repetition of the emotional value associated with past scenarios. This hypothesis fits with studies suggesting striking similarities between remembering the past and imagining the future in AD (Addis et al. 2009; El Haj et al. 2015a, 2015b, 2015c; Moustafa and El Haj 2018).

One limitation of our study is the evaluation of only one past and future event per participant. Future research should investigate this issue with a larger panel of autobiographical memories and future events, taking the fatigability of AD participants into account. Moreover, we did not evaluate the executive processes involved in the generation of future scenarios, which may explain why our

AD participants did not benefit from odor exposure regarding the reaction time for future events. Finally, it would be of interest to evaluate the effect of odor exposure on the phenomenology of future scenarios.

In conclusion, the present study replicates previous research demonstrating the positive effects of odor exposure on past thinking in AD. Odor exposure may result in specific and emotional future thinking. In other words, olfactory stimulation may alleviate the difficulty that AD patients experience when they attempt to project themselves into the future. These results have important clinical implications since odor can be used as a tool to enhance future thinking in AD patients.

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Conflict of interest

No potential conflict of interest is reported by the authors.

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