Supplementary Material

Sensory Cueing of Autobiographical Memories in Normal Aging and Alzheimer's Disease: A Comparison Between Visual, Auditory, and Olfactory Information

METHODS

Phase 1: Stimuli Assessment

Two pilot studies were conducted to select our set of experimental stimuli. This behavioral validation consisted in groups of young adults (YA) and older adults (OA) assessing a set of items on two dimensions:

- The Sensory dimension refers to the properties of the sensory (visual, auditory, olfactory) object (e.g., rating the intensity of the coffee fragrance).
- The Conceptual dimension refers to the conceptual object evoked by the sensory object (e.g., rating the evocativeness of the concept "*coffee*").

For the Sensory dimension, we assessed Representativeness, Pleasantness, and Intensity, and for the Conceptual dimension, we assessed Evocativeness, Pleasantness, and Concreteness.

Our goal was to select 3 groups of sensory stimuli (1 group of odorants, 1 group of sounds, and 1 group of pictures) to obtain the most satisfactory matching of mean ratings between groups of participants and modalities, on each dimension and property of the stimuli. For example, we aimed at selecting Odors that were as representative of the real objects as Sounds and Pictures on both the "Conceptual" and "Sensory" dimension, according to both YA and OA.

We consider ecological validity a major concern, especially in laboratory tasks involving sensory stimulation. We therefore paid special attention to Representativeness (i.e., how accurately the sensory stimulus represents the real item), since we reasonably expected visual stimuli to be inherently more related to real objects than auditory and olfactory ones, due to human beings'

visual dominance. For this reason, we choose to prioritize the selection of the best representative sounds and/or odorants.

We were provided with 8 odorants, evoking 8 different items: fresh laundry, apple, fresh-cut grass, coffee, wood fire, toasted bread, wine, and piggery. Following Herz procedure [1], we originally aimed to select an auditory and a visual version for each of these items, so that each item was eventually available in 3 different sensory forms (e.g., a picture of the sea, the sound of the waves, and the smell of the sea).

Pilot 1: Assessment of Items' Sensory Properties

Participants

Twenty-four young adults (18 females, M_{age} 23.9 years, *SD* 3.4) and 25 older adults (19 females, M_{age} 75.1 years, *SD* 6.7) took part in the experiment. All reported normal vision and had no neurological or psychiatric history. Participants gave their written informed consent.

Materials and procedure

We asked participants to rate the 8 items presented in 3 different sensory forms (olfactory, auditory, and visual) so that a total of 24 different sensory stimuli were tested. The stimuli were delivered on a computer using E-Prime® 2.0 software. The stimuli were presented in three different blocks (odor block, sound block, and picture block). Order of presentation of both blocks and stimuli were counterbalanced across subjects. Visual stimuli consisted of 8 digital pictures (640x480 pixels) of the items shown on a black background. Auditory stimuli were 8 recording samples of ecological noises. Each audio file lasted approximatively 10 s and was played through speakers at either side of the computer screen. Olfactory stimuli were 8 fragrances provided by

International Flavors & Fragrances Inc. They were presented by using sniffing sticks (provided by Burghart Messtechnik, Germany) that were handed to the participants by the experimenter following the E-Prime instructions.

For each stimulus, participants were first asked to identify the item by naming it (e.g., [*the smell of/the sound of/the picture of*] the sea). Immediately after the response, the real identity of the item was revealed and participants were then asked to rate the stimulus on 3 scales: representativeness (how accurately the stimulus represented the real item) on a 9-points Likert scale (1 = not at all, 9 = extremely); pleasantness, on an 11-points Likert scale (-5 = extremely unpleasant, 5 = extremely pleasant); intensity (for olfactory and auditory stimuli only), on a 6-points Likert scale (0 = not at all intense, 5 = very intense).

Descriptive statistics and results

For each stimulus, we calculated (i) the percentage of correct responses, (ii) the mean representativeness score, (iii) the mean pleasantness attributed by the participants, and (iv) the mean intensity (exclusively for olfactory and auditory stimuli). Results are reported graphically in Supplementary Figures 1a and 1b.

Pilot 2: Assessment of Items' Conceptual Properties

In Pilot 2, the same 8 items were evaluated on a conceptual dimension.

Participants

A total of 24 young adults (18 females, M_{age} 24.6 years, *SD* 6.7) and 21 older adults (19 females, M_{age} 74.4 years, *SD* 3.6) took part in the experiment. All reported normal vision and had no neurological or psychiatric history. Participants gave their written informed consent.

Materials and procedure

Participants filled out a 5-minute questionnaire developed specially for this study. They were asked to rate the most common descriptors (i.e., words) related to each sensory form in which each item was presented in Pilot 1 on several dimensions. For instance, in Pilot 1, we asked participants to evaluate the item "Coffee" by presenting it in the odor form (i.e., the smell of coffee), in the auditory form (i.e., the noise made by a coffee machine) and in the visual form (i.e., a picture of a cup of coffee). Then, in Pilot 2, we asked our participants to evaluate the following descriptors: "*Coffee*", "*Coffee machine*" and "*Cup of coffee*". However, in some cases, the same descriptor could be easily associated with two or more sensory forms; this was the case for the item "Wood fire" or "Apple". Thus, a total of 17 descriptors was evaluated (see Supplementary Table 1).

Supplementary Table 1. Descriptors (i.e., words) linked to each sensory stimulus

Item	Olfactory version	Auditory version	Visual version
LAUNDRY	Laundry	Washing machine	Detergent bottle
APPLE	Apple	Apple	Apple
FRESH-CUT GRASS	Fresh-cut grass	Lawnmower	Lawnmower
COFFEE	Coffee	Coffee machine	Cup of coffee
WOOD FIRE	Wood fire	Wood fire	Wood fire
TOASTED BREAD	Toasted bread	Bread	Bread
WINE	Wine	Bottle of wine	Bottle of wine
PIG	Piggery	Pig	Pig

Participants were asked to rate each descriptor on 4 dimensions: evocativeness (the number of memories each descriptor evokes), on a 4-alternative forced-choice label scale (options: "None", "Just one", "A few" and "A lot"); concreteness, on a 6-points Likert scale (0 = "Not concrete at all", 5 = "Very concrete"); pleasantness, on an 11-points Likert scale (-5 = extremely unpleasant, 5 = extremely pleasant).

Descriptive statistics and results

Participants' responses for the evocativeness assessment were coded using a 4-points scale. We attributed 0 points to the response "None"; 1 point to "Just one"; 2 points to "A few"; 3 points to "A lot". For each stimulus, we computed mean scores for evocativeness, concreteness and pleasantness. Results are reported graphically in Supplementary Figure 2a and 2b.

Phase 2: Stimuli Selection

As expected, regarding items' olfactory forms on a sensory dimension, perfect Representativeness was extremely hard to achieve. Thus, as stated above, we prioritized the selection of the best representative olfactory stimuli. We decided to exclude olfactory stimuli that obtained ≤ 50% correct responses at the identification task and a mean rating score ≤ 5 on the Representativeness scale (Supplementary Figure 1a and 1b).

We also decided to break the link across the items' sensory forms, i.e., we took the liberty to select different items for each modality. We kept the 4 olfactory stimuli with the best Representativeness score. After several trials, we considered the selection presented in Table 3 as the most relevant one. In this final selection, Auditory and Visual stimuli shared the same item selection and stimulus descriptors (i.e., bread, apple, wood fire, and wine). The link across the different sensory forms was preserved only for the item "Apple".

Supplementary Table 2. Final selection of stimuli

Olfactory Stimuli	Auditory Stimuli	Visual Stimuli
Laundry	Bread cutting sound	A picture of typical French bread
Apple	Apple crunch sound	A picture of an apple
Fresh-cut grass	Sound of wood cracking	A picture of a wood fire
Coffee	Wine bottle opening sound	A picture of a bottle of wine

Inferential statistics

Regarding Sensory dimension, we conducted a repeated measures ANOVA on participants' responses with Group (YA versus OA) as the between-subjects factor and Sensory form (Olfactory versus Auditory versus Visual) as the within-subjects factor for each variable. Post-hoc tests were performed when main effects or interactions were observed.

Regarding the Conceptual dimension, since presently auditory and visual stimuli shared the same stimulus descriptors (i.e., bread, apple, wood fire and wine, as stated above), we conducted a 2 x 2 repeated measures ANOVA on participants' responses with Group (YA versus OA) as the between-subjects factor and Sensory form (Olfactory versus Auditory/Visual) as the within-subjects factor for each variable (i.e., property). Post-hoc tests were performed when main effects or interactions were observed.

To put it simple, we report only results for the ANOVA (main effects and interactions). Please refer to Supplementary Table 3 for means, standard errors and *p* values obtained from the post-hoc analyses. Properties for the sensory dimension were Representativeness, Pleasantness and Intensity, and the Conceptual dimension, Evocativeness, Pleasantness and Concreteness.

RESULTS

Sensory Dimension

Representativeness

The ANOVA showed a main effect of Group ($F_{(1,141)} = 36.3$; $p < 0.001$; $\eta^2_p = 0.20$), as YAs rated our stimuli higher than OAs on this variable. We also observed a main effect of Sensory form ($F_{(2,141)} = 49.6$; $p < 0.001$; $\eta^2_p = 0.41$). Pictures were still judged to best represent real objects, followed by Sounds and Odors. All pairwise comparisons were significant. An interaction between

Group and Sensory form was also found ($F_{(2, 141)} = 13.7$; $p < 0.001$; $\eta^2_p = 0.16$). Again, almost all the pairwise comparisons were significant. However, interestingly, YAs only perceived a difference between Odors and Pictures in their representativeness of the real objects. Lastly, YAs and OAs did not differ in their assessment of Pictures' representativeness.

Pleasantness

The ANOVA showed a main effect of Group ($F_{(1,141)} = 8.38$; $p < 0.01$; $\eta^2_p = 0.05$) revealing that OA judged our stimuli as globally more pleasant than YA. We also observed a main effect of Sensory form ($F_{(2,141)} = 13.41$; $p < 0.001$; $\eta^2_p = 0.15$). Pictures were still rated as the most pleasant sensory form, followed again by Odors and Sounds[1]. However, this time[1], post-hoc analysis revealed that Sounds were rated as significantly less pleasant than Pictures only, while no differences were observed when comparing with Odors. The significant interaction between Group and Sensory form ($F_{(2, 141)} = 7.13$; $p < 0.01$; $\eta^2_p = 0.09$) and subsequent post-hoc results' analysis showed that: (i) Sounds were now[1] judged as pleasant as Odors, but not Pictures, by OA, while they were still rated as less pleasant than both Odors and Pictures by YA, (ii) Odors were as pleasant as Pictures for YA and (iii) there was still[1] no differences between YA and OA in rating our Odors pleasantness.

Intensity

The ANOVA performed on Odors' and Sounds' intensity showed no main effects nor interaction (all $F < 2$; all $p > 0.1$).

[1] When compared to the result on the initial selection

Conceptual Dimension

Evocativeness

The ANOVA showed a main effect of Group ($F_{(1,88)} = 25.7$; $p < 0.001$; $\eta^2_p = .22$) as OA judged our overall set of stimuli globally more evocative than YA. However, this time[1] we observed no other main effect or interaction (all $F < 1$; all $p > .1$), suggesting that the Sensory forms shared an equivalent degree of evocativeness across groups.

Pleasantness

The ANOVA showed a main effect of Group ($F_{(1,88)} = 30.6$; $p < 0.001$; $\eta^2_p = 0.25$), as OAs judged our stimuli as more pleasant than YAs. No other main effects or interactions (all $F < 2$; all $p > 0.1$) were observed, indicating that all Sensory forms were perceived as equally pleasant across groups.

Concreteness

The ANOVA showed no main effects nor interactions (all $F < 2$; all $p > 0.1$), suggesting that all stimuli were perceived as equally concrete across groups and Sensory forms.

General Discussion

Our final selection displays two critical strengths: (i) on the Sensory dimension, Sounds were perceived equally pleasant as Odors, (ii) perfect inter-modality matching was obtained in the Conceptual dimension, for each property (Evocativeness, Pleasantness and Concreteness), separately for YAs and OAs.

Setting aside the differences in Representativeness driven by visual dominance, we found noteworthy that our Olfactory and Auditory stimuli were still judged as equally representative of the real items by YAs (i.e., in young, normal cognition). Moreover, importantly, Odors and Sounds showed no significant differences in Intensity in the Sensory dimension, for both groups, nor in Pleasantness, regardless of the dimension.

In sum, after a long phase of pretesting, the final selection was the most satisfactory for our inter-subject design. In the Sensory dimension, overall, our stimuli were considered as mildly to highly representative of the real items, as well as mildly pleasant and intense. Importantly, Odors and Sounds were rated similarly on Pleasantness across our participants but also on Representativeness by YAs. They were also perceived as equally intense by both YAs and OAs. In the Conceptual dimension, perfect inter-modality matching was obtained for each property (i.e., Evocativeness, Pleasantness and Concreteness), and separately for YAs and OAs. Our stimuli were perceived as mildly concrete, mildly pleasant and evocative across the different sensory forms.

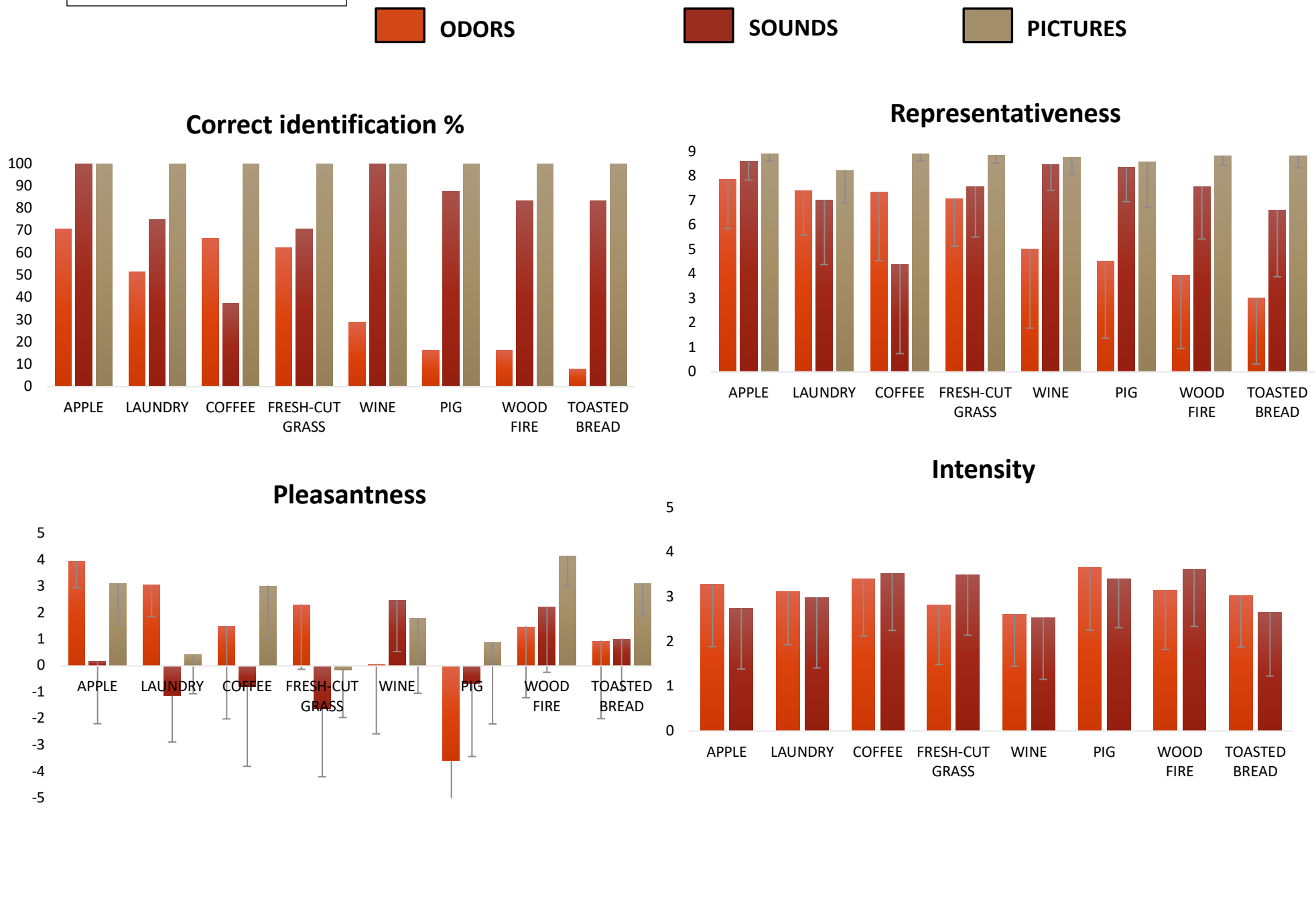
Supplementary Table 3. Means, standard errors and p values obtained from the post-hoc analyses following the ANOVA on the final selection of stimuli

Selection 2 - Main effects								
Sensory								
	YA	**OA**	**Odors versus Sounds**		**Odors versus Picture**		**Sounds versus Pictures**	
Representativeness	8.0±0.1	6.5±0.1	5.8±0.2	7.1±0.2	5.8±0.2	8.8±0.2	7.1±0.2	8.8±0.2
	p = 0.000		p = 0.000		p = 0.000		p = 0.000	
Pleasantness	2.4±0.1	3.0±0.1	2.5±0.1	2.1±0.1	2.5±0.1	3.5±0.1	2.1±0.1	3.5±0.1
	p = 0.003		N.S.		p = 0.001		p = 0.000	
Intensity	3.0±0.1	3.2±0.1	3.1±0.1	3.1±0.1				
	N.S.		N.S.					
Conceptual								
	YA	**OA**	**Odors versus Sounds/Pictures**					
Concreteness	3.9±0.1	4.1±0.1	3.9±0.1		4.1±0.1			
	N.S.		N.S.					
Pleasantness	2.3±0.1	3.5±0.1	2.7±0.1		2.1±0.1			
	p = 0.000		N.S.					
Memory evocativeness	1.7±0.0	2.3±0.0	2.05±0.0		2.09±0.0			
	p = 0.000		N.S.					

Selection 2 – Interactions												
Sensory												
	YA						**OA**					
	O versus S		**O versus P**		**S versus P**		**O versus S**		**O versus P**		**S versus P**	
Representativeness	7.4±0.2	7.8±0.2	7.4±0.2	8.8±0.2	7.8±0.2	8.8±0.2	4.3±0.2	6.5±0.2	4.3±0.2	8.8±0.2	6.5±0.2	8.8±0.2
	N.S.		p = 0.01		N.S.		p = 0.000		p = 0.000		p = 0.000	
Pleasantness	2.6±0.2	1.4±0.2	2.6±0.2	3.0±0.2	1.4±0.2	3.0±0.2	2.4±0.2	2.7±0.2	2.4±0.2	3.9±0.2	2.7±0.2	3.9±0.2
	p = 0.02		N.S.		p = 0.001		N.S.		p = 0.001		p = 0.01	
Intensity	3.1±0.2	2.8±0.2					3.0±0.2	3.4±0.2				
	N.S.						N.S.					

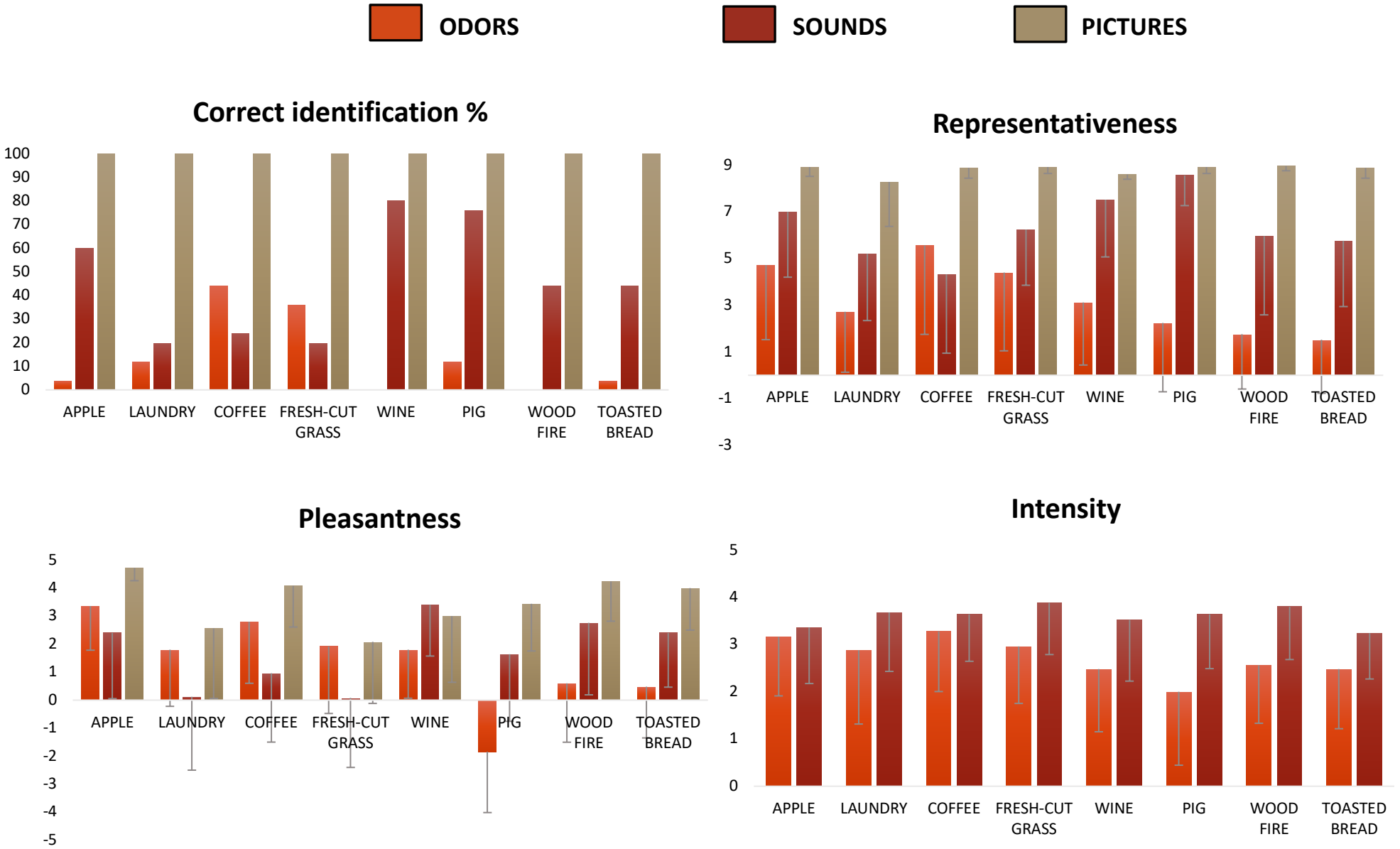
Supplementary Figure 1a

YA – SENSORY DIMENSION

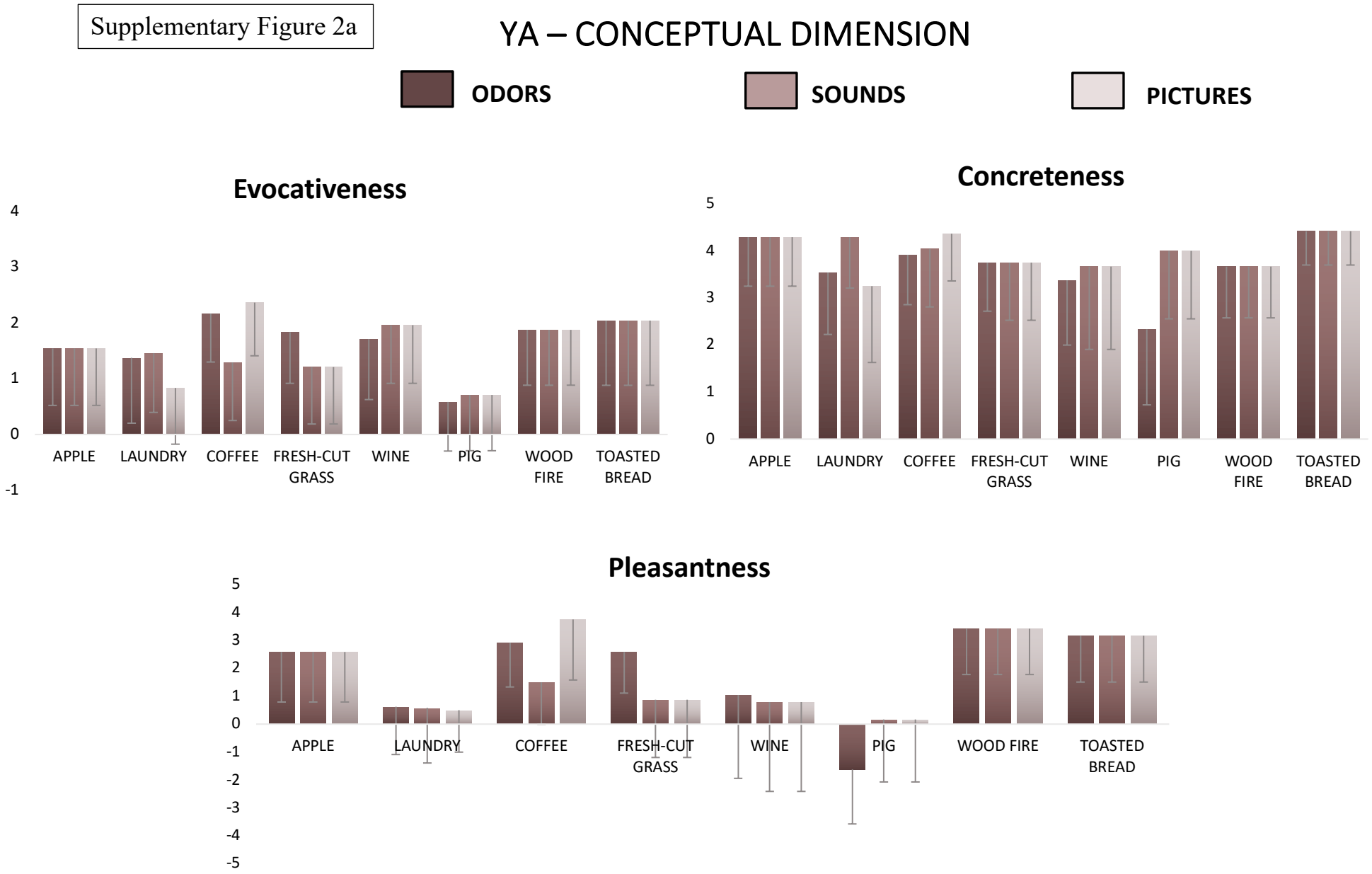


Supplementary Figure 1b

OA – SENSORY DIMENSION



Supplementary Figure 2a

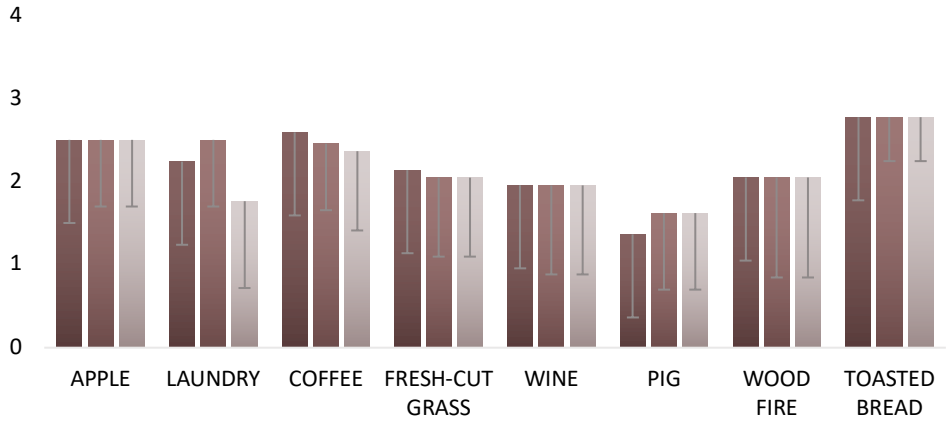


Supplementary Figure 2b

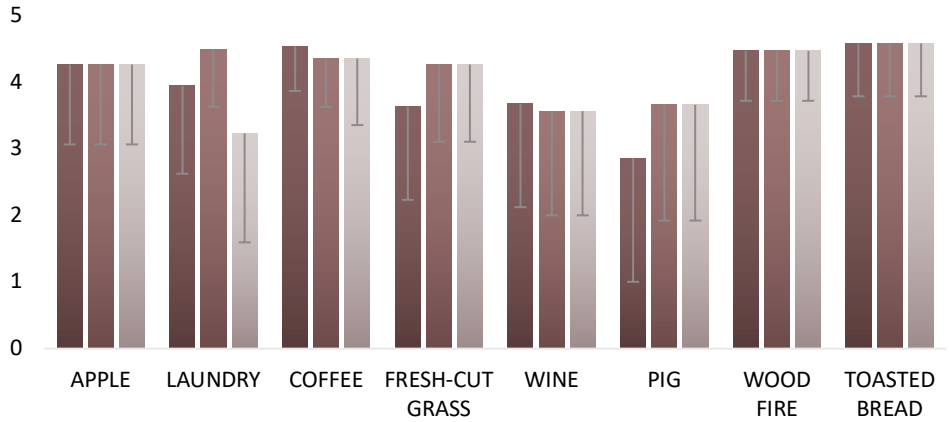
OA – CONCEPTUAL DIMENSION

ODORS SOUNDS PICTURES

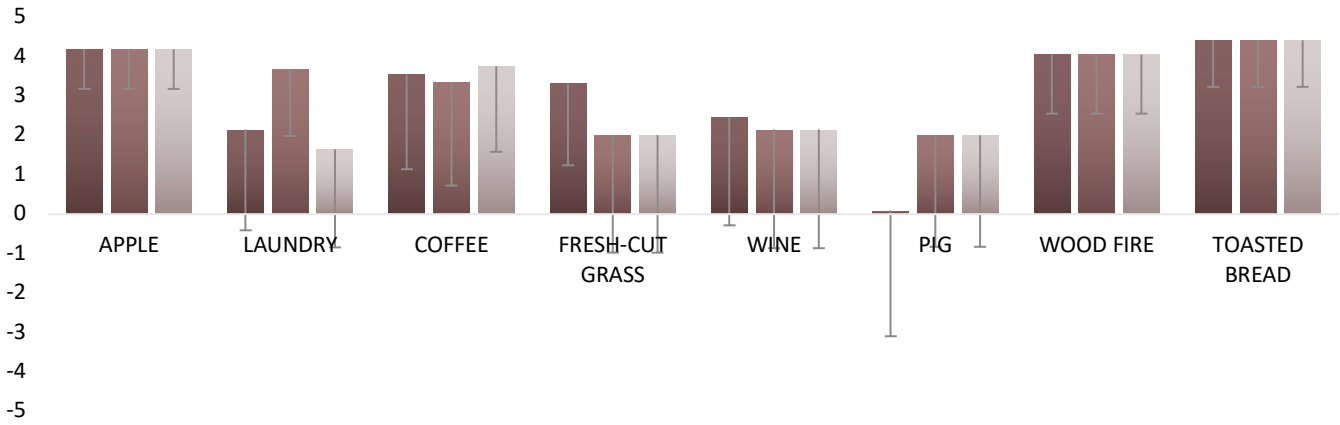
Evocativeness



Concreteness



Pleasantness



SUPPLEMENTARY RESULTS

Stimuli Sensory Properties Assessment (see Methods)

Representativeness

As expected, the ANOVA conducted with Type of sensory stimulation (Olfactory/Auditory/Visual) and Group (AD/OA/YA) as between-subjects factors for the Representativeness assessment showed a large main effect of Type of sensory stimulation ($F_{(2,170)} = 43.9$; $p < 0.001$; $\eta^2_p = 0.34$). Not surprisingly, Pictures best represented real objects (mean = 6.60 ± 0.83), followed by Sounds (mean = 5.81 ± 1.31) and Odors (mean = 4.89 ± 2.04). Statistically, each pairwise comparison was highly significant (Tukey's post-hoc test, all $p_s <$ 0.000, all ds > 0.70). A trend for Group ($F_{(2,170)} = 2.64$; $p = 0.07$; $\eta^2_p = 0.03$) was also observed. However, crucially, no interaction between Group and Type of sensory stimulation was found ($F_{(4, 170)} = 1.45$; $p = 0.21$; $\eta^2_p = 0.03$), indicating that, overall, our 3 groups of participants perceived a similar magnitude of association between the different sensory stimuli and the real objects they were meant to represent.

Pleasantness

The ANOVA conducted with Type of sensory stimulation (Olfactory/Auditory/Visual) and Group (AD/OA/YA) as between-subjects factors on our stimuli's pleasantness showed a main effect of Type of sensory stimulation ($F_{(2,170)} = 6.97$; $p = 0.001$; $\eta^2_p = 0.07$). Tukey's post-hoc tests revealed that, overall, Pictures were rated as significantly more pleasant (mean = 3.34 ± 2.00) than Sounds (mean = 2.47 ± 2.31, $p = 0.001$, d = 0.40) and Odors (mean = 2.63 ± 2.45, $p =$ 0.01, d = 0.31) while no differences were observed between Odors and Sounds ($p > 0.1$). There was also a main effect of Group ($F_{(2,170)} = 23.84$; $p < 0.001$; $\eta^2_p = 0.21$) driven by YA rating our

whole set of stimuli as generally less pleasant (mean = 1.82 ± 2.62) than OA and AD patients (mean = 3.39 ± 2.13 and 3.23 ± 1.69 respectively, all $p_s < 0.001$, all d_s absolute values > 0.60). No differences were observed between OA and AD patients ($p > 0.1$). Also, no interaction between Group and Type of sensory stimulation was found ($F_{(4, 170)} = 1.67$; $p = 0.15$; $\eta^2_p = 0.03$).

Intensity

The ANOVA performed on Odors and Sounds intensity with Type of sensory stimulation (Olfactory/Auditory) and Group (AD/OA/YA) as between-subjects factors showed no main effects (all $p_s > 0.1$). Our stimuli shared a similar perceived intensity across our groups (mean = 4.02 ± 1.16, 3.79 ± 1.16, and 3.61 ± 1.05 for YA, OA, and AD patients, respectively) and both sensory modalities (mean = 3.75 ± 1.09 and 3.86 ± 1.17 for Odors and Sounds, respectively). However, a statistically significant interaction between Group and Type of sensory stimulation was observed ($F_{(2, 114)} = 5.12$; $p = 0.007$; $\eta^2_p = 0.08$). Tukey's post-hoc tests revealed that this was exclusively driven by YA perceiving Odors as significantly more intense (mean = 4.32 ± 0.90) than OA (mean = 3.55 ± 1.04, $p = 0.05$, d = 0.79) and AD patients (mean = 3.40 ± 1.10, $p = 0.01$, d = 0.92).

REFERENCE

[1] Herz RS (2004) A naturalistic analysis of autobiographical memories triggered by olfactory visual and auditory stimuli. *Chem Senses* **29**, 217–224.