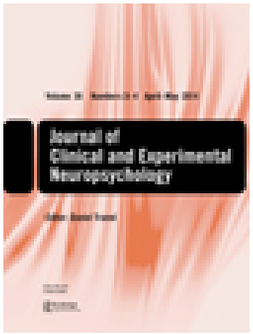

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Alzheimer's disease disrupts domain-specific and domain-general processes in numerosity estimation

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ABSTRACT

Introduction: This study investigated how Alzheimer's Disease (AD) affects numerosity estimation abilities (e.g., finding the approximate number of items in a collection).

Method: Across two experiments, performance from HOA (i.e., Healthy Older Adults; $N = 48$) and AD patients ($N = 50$) was compared on dot comparison tasks. Participants were presented with two dot arrays and had to select the more numerous dot array in comparison tasks. They also took a Simon task and a number-line tasks (i.e., number-line tasks in which they had to indicate the position of a number on a line 0 to 100 or on a line 0 to 1,000 in the number-line task).

Results: In Experiment 1, (a) AD patients obtained significantly poorer performance while comparing collections of dots, especially harder (small-ratio) collections, (b) these deficits correlated with poorer performance on the number-line task for larger numerosities (i.e., 0 to 1,000), and (c) AD patients showed poorer performance on incongruent (where numerosity and area occupied by dots mismatched) than on congruent items (where both features matched), while HOA showed no congruency effects. Experiment 2 showed (a) congruency effects in both groups when convex hull was tested as an incongruent feature, and (b) comparable sequential modulations of congruency effects in both groups.

Conclusions: Our findings showed that numerosity abilities decline in AD patients, and that this decline results from impaired domain-specific processes (i.e., numerosity processing) and domain-general processes (i.e., inhibition). These findings have important implications to further our understanding of how specific and general cognitive processes contribute to numerosity estimation/comparison performance, and how such contributions change during Alzheimer's disease.

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Alzheimer's disease; dot comparison; numerosity processing; inhibition; executive control

Introduction

This study investigated how Alzheimer's disease influences cognitive processes involved in numerosity estimation and comparison (i.e., the ability to find the approximate number of items in a collection or to compare collections of items on the basis of their numerosity). Addressing this issue is important for at least a couple of reasons. First, estimation abilities in general, and numerosity estimation in particular, are important in everyday life (e.g., numerosity estimation abilities are used to estimate the number of fruits in a basket, or to choose the shortest checkout line in a store) of both healthy older adults and AD patients. Second, AD patients experience impairment in many daily life activities, including activities involving numerical estimation (e.g., managing finances, shopping; Collette et al., 2009; Guarino et al., 2019; Jekel et al., 2015; Marshall et al., 2012; Wecker et al., 2000). As a consequence, to provide suitable clinical support for individuals with AD, it is essential that researchers and clinicians first have a detailed and accurate understanding of the numerosity estimation abilities and their underlying processes.

AD is a complex progressive and generalized dementia syndrome. With the disease development, impairments of several domain-general processes are observed, mainly memory, executive, language, and visuo-spatial functions, as well as neuropsychiatric syndromes as hallucinations or delusions. The primary and main characteristic of this dementia is a profound episodic-memory loss in its early clinical course (McKhann et al., 2011). Domain-specific processes, like numerical cognition, are also affected in the early stages of AD (Deloche et al., 1995; Grafman et al., 1989; Mantovan et al., 1999; Marterer et al., 1996; Parlato et al., 1992; Pesenti et al., 1994). Impairment in numerical cognition may represent a reliable hallmark for the diagnosis of Alzheimer's disease (Carlomagno et al., 1999; Deloche et al., 1995; Kaufmann et al., 2002; Mantovan et al., 1999; Marterer et al., 1996).

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In the present study, we aimed at investigating how AD impairs one under-studied numerical activity, namely numerical estimation and comparison. Before presenting the logic of the present work, we briefly review previous relevant findings on AD and numerical estimation and comparison abilities and on main effects on numerosity estimation performance in healthy participants.

Previous findings on AD patients' numerosity estimation

Several studies aimed at determining group-related differences on different numerical components in AD. They commonly reported heterogeneous profiles of numerical skills deterioration (e.g., Cappelletti et al., 2012; Girelli & Delazer, 2001; Kaufmann et al., 2002). Indeed, number, or numerosity knowledge can be intact even when other arithmetic knowledge and calculation abilities are grossly impaired. For instance, Kaufmann et al. (2002) tested HOA and AD patients on basic numerical and arithmetic processing. They compared HOA and AD patients in number comprehension (i.e., transcoding abilities, comprehension/production of operation signs, number sequences), arithmetic (i.e., written problems including facts and rules), and basic numerical tasks (i.e., dot counting of smaller collections and number comparison tasks). Results showed that accuracy in dot counting and distance effects in number comparison (i.e., better performance to determine which number is the largest of two numbers when the distance between numbers is large *vs*. small) were preserved in AD patients. However, AD patients committed more errors than controls in both arithmetic fact retrieval and written calculation. These findings showed that basic number knowledge is well preserved in early AD (i.e., an intact representation and manipulation of number magnitude), while arithmetic processes are impaired (see Cappelletti et al., 2012, for similar results; Girelli & Delazer, 2001, for a review).

To our knowledge, only one study investigated approximate estimates abilities in AD. Gandini et al. (2009) asked HOA and AD patients to provide a quick and rough estimate of collections including 20–65 dots. Data showed that AD patients provided poorer estimates than controls. However, we ignore the origins of AD-related decline in numerosity estimation abilities. One important goal of this study is to investigate the mechanisms responsible for AD's poorer numerosity estimation performance. Following previous studies that found that numerosity estimation crucially involves both domain-general (e.g., inhibition) and domain-specific (e.g., numerical) processes (e.g., Barth et al., 2005; Gebuis & Reynvoet, 2012; Gilmore et al., 2016; Halberda et al., 2008), we examined here how both such domain-general and domain-specific mechanisms contribute to AD patients' difficulties in numerosity estimation.

Previous findings on numerosity estimation in healthy participants

Several factors have been found to crucially influence healthy participants' performance in numerosity estimation and numerosity comparison tasks. These include numerical (e.g., numerosity or number of dots included in a collection) and visual features (e.g., convex hull, corresponding to "the smallest contour around the dot collections") of collection of dots (see Leibovich et al., 2017, for a review).

First, participants' speed and accuracy in dot comparison tasks may depend on numerical features of dot collections (e.g., DeWind & Brannon, 2016; Gebuis & Reynvoet, 2012; Smets et al., 2014). For example, healthy participants (i.e., children, young and older participants) are faster on so-called large-ratio collections such as when comparing arrays of 24 and 12 dots than on so-called small-ratio collections such as when comparing arrays of 24 and 20 dots (e.g., Barth et al., 2005; Halberda & Feigenson, 2008; Halberda et al., 2008). As another example, participants are faster on smaller than on larger collections such as when comparing collections including 1 to 8 dots versus collections of 10 to 80 dots (e.g., Clayton & Gilmore, 2015; Revkin et al., 2008). Such findings have been explained within the Approximate Number System theory (ANS; Dehaene, 1997, p. 5). According to the ANS theory, comparing collections of dots relies on retrieving approximate representations of numerosities from long-term memory. These representations vary according to a normal distribution with a mean n and a standard deviation wn, where w is the Weber fraction. Distributions of two numerosity representations are more precise for small than for larger numerosities and overlap less for larger-ratio collections than for small-ratio collections. These lead participants to be faster at comparing smaller than larger numerosities and larger-ratio collections (i.e., 8 *vs*. 16 dots) than smaller-ratio collections (i.e., 8 *vs*. 10 dots).

However, the ANS theory assumptions that a sense of number is innate and that non-symbolic numerosity is processed independently of visual features (i.e., continuous magnitudes) are still debated. In a recent review, Leibovich et al. (2017) proposed an alternative hypothesis according to which it is impossible to isolate the

processing of numerosity independent of visual features (see also Leibovich & Henik, 2013). Indeed, previous studies found that performance in dot comparison tasks was also influenced by visual features of dots, such as cumulative surface area covered by the dots, convex hull (i.e., smallest contour around the dot array), average dot size, density of the dots, distance between dots, etc. For instance, participants are faster on collections with larger than with smaller convex hull (e.g., Clayton & Gilmore, 2015; Gilmore et al., 2016), or on collections of dots that occupy a larger area than on collections displayed with a smaller area (e.g., Gebuis & Reynvoet, 2012).

Moreover, given the potential influence of visual features, many studies manipulated congruency between numerosity and visual features (e.g., congruency and incongruency between numerosity and surface area). These studies found that dot comparison tasks involve general cognitive processes, such as executive control processes (i.e., cognitive flexibility, updating, and monitoring of working memory and inhibition processes; Miyake et al., 2000). The inhibition processes have been empirically evidenced in "congruency effects" that reflect better performance on congruent (i.e., when numerosities and visual features match like when smaller numerosities are displayed with smaller surface areas) than on incongruent items (i.e., when numerosities and visual features mismatch such as when smaller numerosities are displayed with larger surface areas). Congruency effects have been found in domain-general tasks (e.g., Stroop task; MacLeod, 1991, for a review) and in domain-specific tasks, like the dot comparison task tested here (e.g., Cappelletti et al., 2014; Clayton & Gilmore, 2015; Fush & McNeil, 2013; Gebuis & Reynvoet, 2012; Gilmore et al., 2015; Halberda et al., 2008; Nys & Content, 2012). In the dot comparison task, inhibitory processes are required when numerical and visual features of dot collections suggest different responses (i.e., numerical and visual information mismatch). For instance, when convex hull and numerosity are incongruent (i.e., a larger convex hull for a smaller collection of dots), participants have to ignore and inhibit the irrelevant visual dimension (i.e., convex hull information) and to focus on the relevant numerical dimension (i.e., numerosity) on incongruent items, whereas both dimensions converge to the same response on congruent items (i.e., a larger convex hull for a larger collection of dots).

Age-related differences in congruency effects have been found during adulthood in two studies (Cappelletti et al., 2014; Norris et al., 2015). For instance, Cappelletti et al. (2014) found congruency effects in older but not in young adults when participants were asked to compare collections of 5–16 dots. HOA were specifically impaired on incongruent items, those items for which it is necessary to inhibit the irrelevant stimulus dimension. Similarly, Norris et al. (2015) showed participants sets of yellow and blue dots and asked them to judge which colored set is more numerous. As in Cappelletti et al.'s (2014) study, congruency effects were only observed in HOA. In both Norris et al.'s and Cappelletti et al.'s studies, the authors accounted for age-related declines on incongruent items by assuming declined efficiency with age of inhibition processes.

Overview of the present study

We had two main goals. The first was to compare probable AD patients and healthy older adults' performance in numerosity estimation/comparison. The second was to determine sources of AD patients' deficits in numerosity abilities. To achieve these ends, we carried out two experiments. In Experiment 1, we assessed comparison and estimation abilities with two tasks, dot comparison and number-line tasks. First, in the dot comparison task, we asked participants to compare briefly presented collections of dots and to decide as quickly as possible which collection includes the largest number of dots. Collections of dots were easier (i.e., large-ratio collections) or harder (i.e., small-ratio collections) so that effects of difficulty were compared in HOA and AD patients. Second, we tested participants in another task, also often used to assess estimation skills, namely a number-line task. Participants had to indicate the position of a number on a line 0 to 100 or on a line 0 to 1,000. Observing AD deficits in both a dot comparison and number-line tasks was expected to provide converging evidence for how Alzheimer's disease impairs participants' estimation skills in different tasks requiring numerical estimations.

The hypothesis that probable AD patients have difficulties in numerical estimation makes the following predictions. In the dot comparison task, effects of ratio (performance on harder, small-ratio items – performance on easier, large-ratio items) should be larger in probable AD patients than in HOA. In the number-line task, above and beyond less accurate performance in probable AD, larger differences between large and smaller numbers on participants' accuracy were expected in probable AD patients as compared to HOA. Alternatively, comparable ratio effects in the dot comparison task and effects of number size in the number-line task in probable AD and HOA would suggest that AD patients have spared numerosity estimation.

We used the number-line tasks commonly used in previous studies to assess children's and adults' numerical estimation and the representations that give rise to their estimates (e.g., Log-Linear model; Booth & Siegler, 2006; Siegler & Opfer, 2003). Previous studies found that younger children show logarithmic representations of numbers, whereas older children and adults produce linear representations (e.g., Siegler & Opfer, 2003). This pattern is usually interpreted as evidence for a shift from logarithmic to linear mental representations of numbers. In addition to determining whether HOA show linear representations, like young adults, we wanted to test the possibility that AD patients show less precise representations of numbers. Such a possibility follows previous findings that probable AD patients are impaired when they estimate larger numbers or numerosities (e.g., Boone et al., 2002; Gandini et al., 2009; Maylor et al., 2005; Seron et al., 1991) and would be consistent with degraded number representations in AD patients.

Furthermore, following previous studies showing that numerosity comparison performance involves inhibition, we aimed at determining whether inhibition processes are impaired in probable AD when they compare numerosities. In Experiment 1, we created congruent and incongruent items based on the cumulative surface area of the dots and numerosity (i.e., the more numerous collections contained a larger cumulative surface area for congruent items, or a smaller cumulative surface area for incongruent items). We predicted larger differences between congruent and incongruent items in AD patients than HOA. This Group x Congruency on current items interaction should occur if inhibitory processes in AD patients are impaired compared to HOA, leading them to more slowly detect and resolve the conflict between numerosity (the relevant dimension) and cumulative surface area information (the irrelevant dimension).

In Experiment 2, we tested another visual feature, namely the convex hull information, or the smallest contour around the collection of dots, as previous studies found this feature to crucially influence participants' performance in numerosity comparison (Clayton et al., 2015; Dietrich et al., 2015; Gilmore et al., 2015; Inglis & Gilmore, 2014; Norris et al., 2019; Smets et al., 2015). This feature was tested to determine whether both HOA and AD patients are influenced by this visual feature and to further test group differences in congruency effects. Finding group differences in congruency effects for two visual features (cumulative surface area and convex hull) was expected to provide stronger and converging evidence for the conclusion that AD patients have difficulties in inhibiting irrelevant dimensions in stimulus when comparing numerosities.

A final goal of this project was to determine whether processing sequential modulations of congruency effects change with Alzheimer's disease. The sequential modulations of congruency effects are seen when congruency effects on current items are modulated by congruency of immediately preceding items. Thus, congruency effects on current items are smaller after incongruent items than after congruent items (i.e., Botvinick et al., 2001; Gratton et al., 1992; Egner et al., 2007; Kerns et al., 2004; Stürmer et al., 2002; Ullsperger et al., 2005; see Duthoo et al., 2014, for a review). The hypothesis that processes used to sequentially modulate congruency effects is impaired in AD patients predicts a Group x Congruency on Previous Items x Congruency on Current Items interaction. This interaction would be seen if congruency effects on current items are of the same magnitude when current items follow congruent and incongruent items in probable AD patients (who would not sequentially modulate congruency effects) in contrast to sequential modulations of congruency effects in HOA. This scenario is possible if, given decreased executive processes during Alzheimer's disease, probable AD patients process each item independently and do not prepare themselves to process interference on current items following incongruent items.

Experiment 1

The main goal of Experiment 1 was to test AD patients' and HOA's performance in numerosity estimation and comparison, so as to determine whether numerosity estimation, a core cognitive skill, is impaired in AD patients. In this context, each individual accomplished two tasks, a panamath version of the dot comparison and a number-line tasks, both known to assess estimation/comparison skills.

Method

Participants

Two groups of participants were selected tested, 23 HOA (17 women, age range = 65–91 years) and 25 individuals diagnosed with probable Alzheimer's disease (14 women, age range = 65–101 years). HOA were recruited from the community of Marseille (France). All participants were screened for global cognitive functioning using the Mini-Mental State Examination (MMSE; Folstein et al., 1975). All HOA obtained the minimum score of 27/30 to be included in the study.

Patients with a diagnosis of probable AD were recruited in the Department of Geriatric Neurology, Sainte Marguerite Hospital (Marseille, France), using consensus criteria published by McKhann et al. (2011). Exclusion criteria for patients included evidence of a second neurological condition such as other neurodegenerative diseases than AD (e.g., vascular disease, head trauma, a primary psychiatric disorder, visuo-spatial disorders, or an untreated medical condition affecting cognition). Probable AD patients had poorer MMSE scores than controls (22.0 ± 4.8 *v.s* 29.0 ± 0.9, respectively; $t(46) = 6.91$, $p < 0.001$).

The sample size used in this experiment was based on an *a-priori* power analysis conducted in G*Power 3.1 (Faul et al., 2007). Experiment 1 tested ratio effects, congruency effects, and group-related differences in these effects. Concerning ratio effects, we assumed an effect size of Cohen's $f = 0.61$ (derived from relevant previous studies; e.g., Barth et al., 2008) and an alpha of.05. A total sample size of 38 participants ($N = 19$ per group) provides 96% power to detect effects. In order to exceed this criterion and achieve 96% power, we recruited 48 participants ($N = 25$ AD and 23 HOA). Furthermore, we assumed an effect size of Cohen's $f = 0.65$ for congruency effects (derived from relevant previous studies; e.g., Tse et al., 2010) and an alpha of .05. A total sample size of 34 participants ($N = 17$ per group) provides 96% power to detect effects. Again, to exceed this criterion and achieve 96% power, we recruited 48 participants ($N = 25$ AD and 23 HOA). Concerning Group x Congruency interaction effect, we assumed an effect size of Cohen's $f = 0.79$ (derived from Bélanger et al., 2010) and an alpha of .05. We determined that a total sample size of 24 participants ($N = 12$ per group) would provide 96% power to detect effects. To exceed this criterion and achieve 96% power, we recruited 48 participants ($N = 25$ AD and 23 HOA). Finally, regarding group effects, we assumed an effect size of Cohen's $f = 0.48$ (also derived from Tse et al., 2010) and an alpha of .05. We determined that a total sample size of 48 participants ($N = 24$ per group) would provide 90% power to detect effects. To exceed this criterion and achieve 90% power, we recruited 48 participants ($N = 25$ AD and 23 HOA).

Panamath version of the dot comparison task

Stimuli. Stimuli were downloaded from the Panamath website (http://www.panamath.org; Halberda et al., 2008). On each trial, participants had to select the more numerous of two dot collections using left and right keys marked on the keyboard. The two collections consisted of blue or yellow dots displayed on a gray background and were presented simultaneously, side-by-side on a 15″ laptop screen. Participants saw eight practice trials followed by 80 experimental trials. To vary the difficulty of the task, the ratio between the blue and yellow dots was manipulated. Ratios varied from an large-ratio of 2.35 (21:9 dots; see Figure 1(c)) to a small-ratio of 1.07 (13:14 dots; See Figure 1(d)), such that item difficulty varied, with large-ratio known to be easier and small-ratio is known to be harder (e.g., Clayton et al., 2015; Halberda & Feigenson, 2008; Halberda et al., 2008; Libertus et al., 2011). The full set of ratios used here was 2.35, 2.21, 1.32, 1.24, 1.21, 1.14, and 1.07. For convenience of data analyses and presentation, these ratios were grouped into small-ratio conditions (i.e., ratios 1.07 to 1.24) and large-ratio conditions (i.e., ratios 1.25 to 2.4). Panamath stimuli

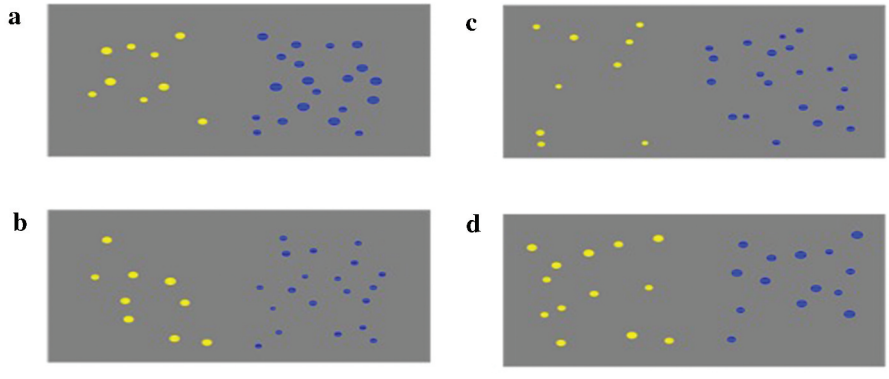

Figure 1. Examples of (a) a congruent item in which cumulative surface area and numerosity matched (i.e., left collection contained 9 dots displayed with a smaller cumulative surface area, and right collection included 20 dots displayed with a larger cumulative surface area); (b) an incongruent item in which cumulative surface area and numerosity mismatched (i.e., left collection contained 9 dots displayed with a larger cumulative surface area, and right collection included 20 dots displayed with a smaller cumulative surface area); (c) an easy item (i.e., the ratio was 2.35 with the left collection containing 9 dots vs. 21 dots in the right collection); (d) a difficult item (i.e., the ratio was 1.07 with the left collection containing 13 dots vs. 14 dots in the right collection).

can be classified as "congruent" and "incongruent" based on the cumulative surface area of the dots and numerosity (see Figure 1(a,b), for examples). Congruent items included pairs of collections where the more numerous collection occupied a larger cumulative surface area. Incongruent items included pairs where the more numerous collection occupied a smaller cumulative surface area. Four types of trials (20 items for each type) were tested depending on congruency and ratio effects: congruent/large-ratio trials, congruent/small-ratio trials, incongruent/large-ratio trials, and incongruent/small-ratio trials.

Procedure. Each item began with a warning signal ("+") displayed in the center of the computer screen. Then, each item was displayed for 600-ms (see Figure 2). Participants were asked to indicate, as quickly and accurately as possible, which collection of dots included the largest number of dots by pressing the appropriate response key on a computer keyboard. The participants could answer within 600-ms before stimulus disappears. If participants answered within 600-ms, a blank screen followed until the experimenter press the space bar for the next trial to start.

Number-line task

Stimuli. This task was adapted from Siegler and Opfer (2003). Participants were presented 20 sheets of paper, each with an identical 23-cm line, with the left end labeled "0" and the right end labeled "100" or "1,000." The number to be estimated appeared at the top left of the scale (see Figure 3, for example). Participants were asked to put a single mark on each line to indicate the location of a number. Following Siegler and Opfer (2003), for the 0–1,000 scale, the numbers included the values 2, 4, 6, 18, 25, 71, 86, 230, 390, and 810. For the 0–100 scale, the numbers included 2, 3, 4, 6, 18, 25, 42, 67, 71, and 86. These numbers were chosen to maximize the discriminability of logarithmic and linear functions and to minimize the influence of specific knowledge, such that 50 is halfway between 0 and 100 (e.g., Booth & Siegler, 2006; Siegler & Opfer, 2003). Moreover, many studies used 0–100 and 0–1,000 number-line for assessing the numerosity representations in children, young adults (e.g., Booth & Siegler, 2006; Kim & Opfer, 2017;

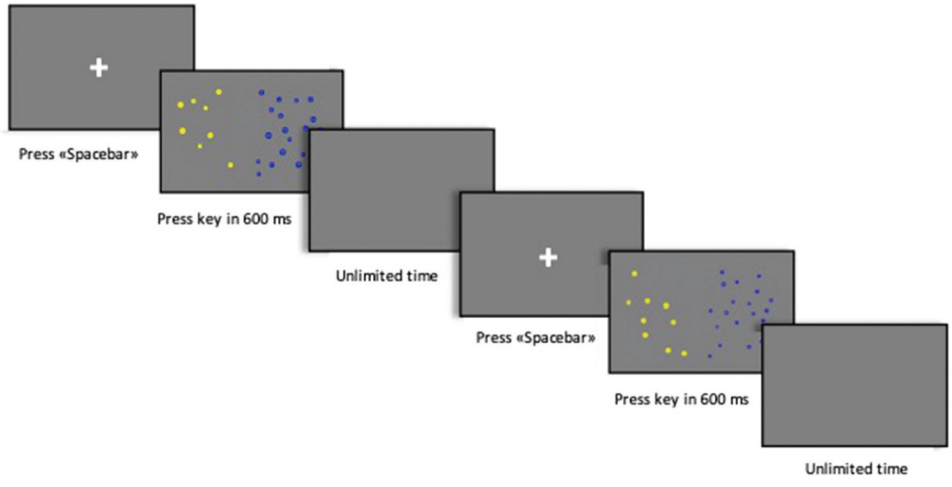

Figure 2. Sequence of events in a trial in the dot comparison task.

Figure 3. Example of 0–1000 scale in the number-line task.

Opfer & Thompson, 2008; Siegler & Opfer, 2003 for example, of children's studies; see Opfer & Martens, 2012, 2003; Sullivan et al., 2011; Van der Weijden et al., 2018, for examples of adults' studies). Based on these previous studies, we used the 0–100 and 0–1,000 ranges to compare numerosity representations of HOA and AD with existing findings in children and young adults.

Procedure. All participants started with the 0–1,000 scale, then the panamath version of the dot comparison task, and finally the 0–100 scale. For each scale, the experimenter began by saying "*We are going to do task with number lines. I want you to show me where on the number line some numbers are. When you decide where the number goes, I want you to make a line through the number line like this (making a vertical hatch mark).*" Before each item, the experimenter said, "*This number line goes from 0 at this end to 100 (or 1,000) at this end. Where would you put the number specified*?".

Results

Panamath version of the dot comparison task

Participants' performance was measured by percentages of errors, RTs, and *w* (i.e., Weber fraction; Halberda et al., 2008). First, there was no significant difference in *w* between HOA and probable AD patients (0.28 and 0.23, respectively; $t(46) = 1.20$, $d = 0.35$), reflecting similar discrimination between numerosities in HOA and probable AD patients. Second, mean response times and percentages of errors on each item (see Table 1) were analyzed using 2 (Group: HOA, probable AD patients) x 2 (Items: Congruent, Incongruent) x 2 (Ratio: High, Small) mixed-design ANOVAs, with group as the only between-participants factor. To correct for multiple comparisons, Sidak corrections were applied.

Table 1. HOA and probable AD patients' mean response times (in ms) and percentages of errors in the dot comparison task for current congruent or incongruent items, and for small- and large-ratio items (Expt. 1).

	HOA			Probable AD patients		
Items	Large ratio	Small ratio	*RE*	Large ratio	Small ratio	*RE*
			Mean response times (in ms)			
Congruent	965	1134	169*	1324	1672	348**
Incongruent	1002	1121	119*	1519	1614	95
Means	984	1128	144**	1421	1643	222**
CE	37	−13		195*	−58	
			Mean percentages of errors			
Congruent	12	29	17***	11	37	26***
Incongruent	14	31	17***	12	36	24***
Means	13	30	23***	12	37	25***
CE	2	3		1	−1	

CE: Congruency effects (Incongruent items – Congruent items).
RE: Ratio effects (Small ratio – Large ratio). *p <.05, **p <.01 ***p <.001.

Response times. HOA were 477-ms faster than probable AD patients ($F(1,46) = 5.95$, *MSe* = 477,154, $n2p = .12$), and participants were 183-ms faster on large-ratio items than on small-ratio items ($F(1,46) = 18.32$, *MSe* = 87,532, $n2p = .29$). The Ratio x Congruency interaction ($F(1,46) = 7.19$, *MSe* = 37,976, $n2p = .14$) resulted from significant 116-ms congruency effects on large-ratio items ($F(1,46) = 6.82$, *MSe* = 37,976, $n2p = .13$) but non-significant −35-ms congruency effects on small-ratio items ($F < 1.0$). Interestingly, the Group x Ratio x Congruency interaction was marginally significant ($F(1,46) = 3.26$, *MSe* = 37,976, $n2p = .07$, $p = .07$). Probable AD patients showed significant congruency effects on large-ratio items (195 ms) but non-significant congruency effects on small-ratio items (−58 ms; $F(1,24) = 7.22$, *MSe* = 55,314, $n2p = .23$). HOA showed no congruency effects for either ratio (i.e., congruency effects were 37 ms and −13 ms, Fs<1.0, for large and small-ratio items, respectively).

Error rates. Analyses of errors revealed a significant main effect of ratio ($F(1,46) = 209.38$, *MSe* = 103, $n2p = .82$), as participants made more errors on small-ratio items (33%) than on large-ratio items (12%). Most interestingly, the Group x Ratio interaction ($F(1,46) = 7.85$, *MSe* = 103, $n2p = .15$) showed that probable AD patients made more errors than HOA only on small-ratio items (37% *vs.* 30%; $F(1,46) = 6.0$, *MSe* = 3701, $n2p = .12$), and both groups made comparable number of errors on large-ratio items (11% *vs.* 13%; $F < 1.0$). No other effects came out significant either on latencies or on error rates.

Number-line task

Error rates. First, to measure changes in estimation accuracy, we calculated for each item percent absolute error as followed:

$$|(Estimate - Estimated\ Quantity)|/Scales\ of\ Estimate \times 100.$$

For example, if a participant was asked to estimate the location of 15 on a 0–100 number line and placed the mark at the location that corresponded to 35, the percent absolute error would be 20% ($|(15–35)/100|\times 100$). Mean percent absolute errors were analyzed using 2 (Group: HOA, probable AD patients) x 2 (Number-Line: 0–100, 0–1,000) mixed-design ANOVA, with group as the only between-participants factor. HOA were more accurate than probable AD patients (6.9% and 11.0%, respectively; $F(1,46) = 3.97$, *MSe* = 0.231, $n2p = .08$).

Regressions. Second, following Siegler and Opfer (2003), we examined participants' numerical estimation

and the representations that gave rise to their estimates. In this way, we calculated the median estimate for each number generated by individuals in each group. Then, differences between that number and the number predicted by the best-fitting logarithmic and linear functions were compared.

As shown in Figure 4 on the 0–100 number lines, HOA's number line estimates were better fit by a linear function (R^2_{lin} = .99) than by a logarithmic function (R^2_{log} = .85; $t(9)$ = 5.31, d = 1.68, p = .001). Interestingly, this was also the case for probable AD patients (R^2_{lin} = .99 *vs.* $R^2_{log=}$.83; $t(9)$ = 4.36, d = 1.38, p = .002). Similar results were observed in the 0–1,000 number line. HOA's number line estimates were better fit by a linear function (R^2_{lin} = .99) than by a logarithmic function (R^2_{log} = .65; $t(9)$ = 3.41, d = 1.08, p = .01). Again, this was also the case for probable AD patients (R^2_{lin} = .95 *vs.* $R^2_{log=}$.68; $t(9)$ = 3.03, d = 0.96, p = .01).

On the 0–100 number line, paired-sample t tests indicated that the fit of the linear function to individuals' estimates was better than the fit of the logarithmic function for both HOA (mean R^2_{log} = .76, SE = .13, *vs.* mean R^2_{lin} = .92, SE = .21; $t(24)$ = 6.26, d = 1.30, p < .001) and probable AD patients (mean R^2_{log} = .72,

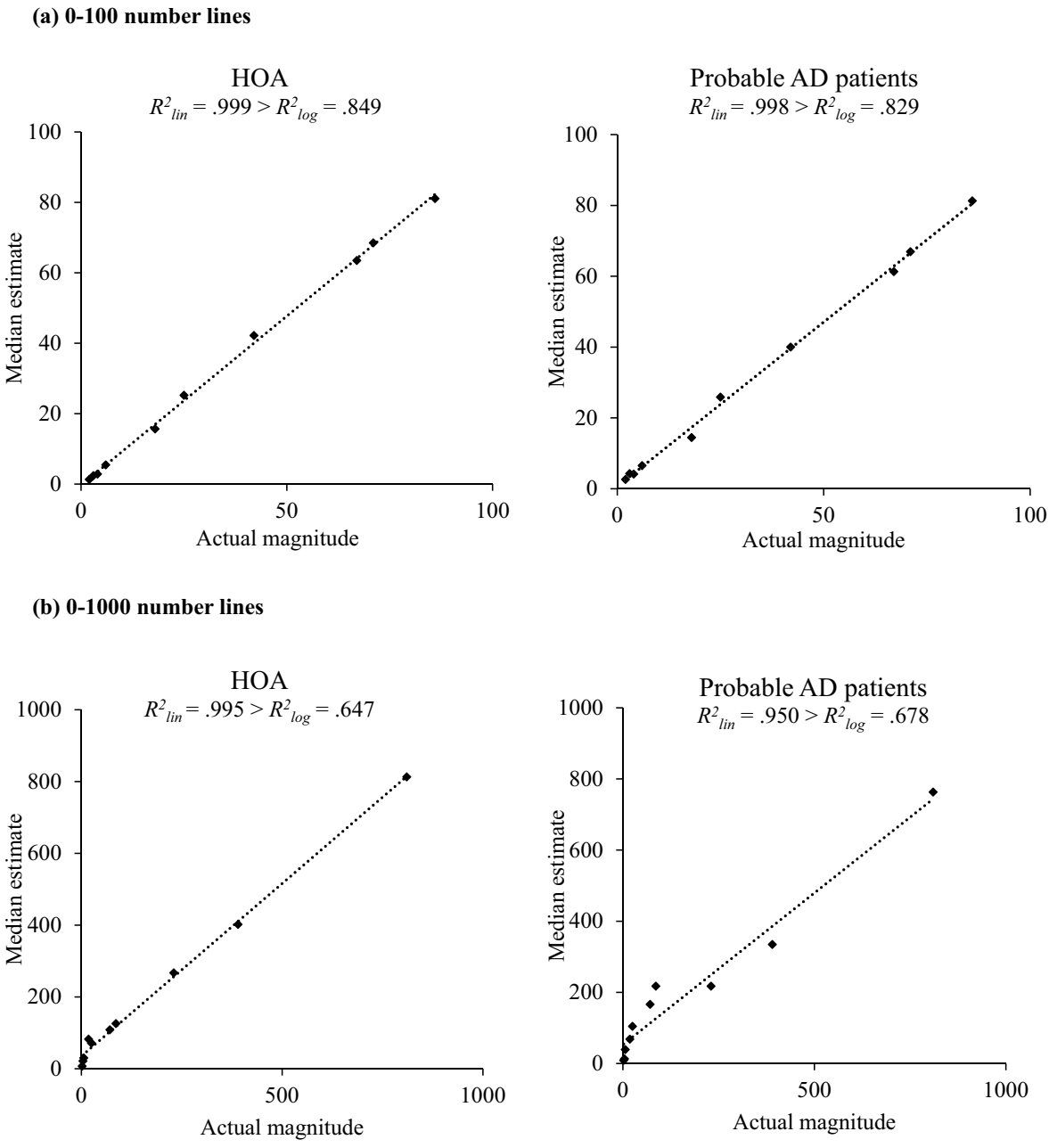

Figure 4. Best-fitting equations for median estimates (a) 0–100 number line and (b) 0–1000 number line estimates for HOA and probable AD patients. Lin = Linear; Log = Logarithmic.

SE = .16, *vs.* mean R^2_{lin} = .82, *SE* = .27; *t*(24) = 3.31, *d* = 0.66, *p* = .003). Similarly, the fit of the linear function was better than the fit of the logarithmic function for the 0–1,000 number line in both HOA (mean R^2_{log} = .52, *SE* = .16, *vs.* mean R^2_{lin} = .88, *SE* = .18; *t*(24) = 12.58, *d* = 2.62, *p* < .001) and probable AD patients (mean R^2_{log} = .33, *SE* = .24, *vs.* mean R^2_{lin} = .62, *SE* = .37; *t* (24) = 7.79, *d* = 1.58, *p* < .001).

Next, we compared the mean fit of the linear function in HOA and probable AD patients. Results showed that linear fits were significantly larger in HOA than in probable AD patients for the 0–1,000 scales (mean R^2_{lin}HOA = .88, *SE* = .18 *vs.* mean R^2_{lin} AD = .62, *SE* = .37; *t*(46) = 2.97, *d* = 0.86, *p* = .005), but equally good in both groups for the 0–100 scales (mean R^2_{lin} HOA = .92, *SE* = .21 *vs.* mean R^2_{lin} AD = .82, *SE* = .27; *t* (46) = 1.44, *d* = 0.41, *n.s*).

Relations between performance in dot comparison and number-line tasks

The main goal here was to examine the relation between number line estimation and dot comparison abilities. We calculated the correlations between ratio effects in the dot comparison task and the mean fit of the linear function for the 0–100 and 0–1,000 scales in probable AD patients and HOA. We found a significant correlation only in probably AD patients between the mean R^2_{lin} for the 0–1,000 scales with response times on small-ratio (*r* = −.43; *p* < .05), suggesting that more precise representations of numerosities between 0 and 1,000 were significantly correlated with better performance to compare numerosities on small-ratio items.

Discussion

Results of Experiment 1 showed that AD patients had difficulties when asked to compare collections of dots, especially harder, small-ratio collections. Poorer dot comparison performance for harder collections correlated with poorer performance on the number-line task for larger numerosities, suggesting that deficits in numerosity comparison might be associated with poorer representations of numerosities. Moreover, Experiment 1 revealed that AD patients showed congruency effects, while HOA showed no congruency effects. This result suggests that AD patients were influenced by irrelevant information from the dot area and had to take extra-time to inhibit this irrelevant information. Our HOA were not influenced by this visual feature, which is consistent with previous results reported by Gilmore et al. (2016) who also found that adults' performance was not most influenced by dot area information.

The design of Experiment 1 did not enable us to determine whether group differences in congruency effects came from HOA being more able than AD to focus on numerosity information, without being distracted by irrelevant surface area, or from both groups being equally distracted by irrelevant information, but HOA being more efficient at inhibiting it. Indeed, in order to test potential group differences, testing visual features that previous studies showed to influence HOAs' performance, such as the convex hull information, might be a more sensitive test. The dot comparison task proposed by Halberda et al. (2008) tested here, did not manipulate the convex hull information (see Norris et al., 2019, for a discussion). Recently, Norris et al. (2019) investigated the manipulation of convex hull by the panamath version of the dot comparison task (Halberda et al., 2008), and its effect on ANS acuity in young and older adults. In this perspective, the authors manipulated the visual features (e.g., cumulative surface area, average dot size) and the numerosity (i.e., four ratios; 1.1 to 1.19, 1.19 to 1.28, 1.32 to 1.43, and 2.28 to 2.47). They calculated convex hull size and convex hull congruency with post hoc tests for each item. Results showed positive correlations between convex hull and numerosity ratios, suggesting a confound between convex hull and numerosity information. Results also showed similar ANS acuity between young and older adults, and that older adults were less accurate than young adults on convex hull incongruent items. The authors argue that the panamath version produces stimuli that do not adequately control for the influence of convex hull on numerosity estimation/comparison. Following Norris and colleagues' analyses (see also, Gilmore et al., 2016), we manipulated convex hull in Experiment 2 to compare congruency effects in HOA and probable AD. Finally, we aimed at testing group differences in how participants sequentially modulate congruency effects from one trial to the next.

Experiment 2

In Experiment 2, like in Experiment 1, HOA and AD participants accomplished a dot comparison task (i.e., they compare arrays of dots and indicated which arrays included the largest number of dots). We manipulated another visual feature, namely convex hull (or smallest contour around the collection of dots). We manipulated convex hull because recent studies found this feature to be one salient physical feature that interferes most with healthy participants' performance while comparing collections of dots (Clayton et al., 2015; Dietrich et al., 2015; Gilmore et al., 2015; Inglis & Gilmore, 2014; Smets et al., 2014). This feature was

manipulated to more strongly test group differences in congruency effects and in sequential modulations of congruency effects. If congruency effects found in AD patients in Experiment 1 come from patients' difficulties to inhibit irrelevant dimensions in dots collections, AD patients should show larger congruency effects than HOA participants. Moreover, we tested group differences in sequential modulations of congruency effects (i.e., smaller congruency effects after incongruent items than after congruent items). Poorer sequential modulations of congruency effects in AD patients than in HOA would imply impairment of executive control mechanisms responsible for these modulations in AD. Finally, we collected measures of executive control mechanisms (both inhibition and its sequential modulations) independent of numerosity estimation with a general conflict task (Simon task), widely used to assess domain-general executive control (see Egner et al., 2007, for a review). These measures were collected to determine whether deficits in AD patients' executive control mechanisms in numerosity estimation correlate with corresponding deficits in general, domain-independent executive control mechanisms.

Method

Participants

Participants were 50 individuals who did not participate in Experiment 1: 25 HOA (18 women; mean age = 76 years; age range = 65–94 years) and 25 individuals diagnosed with probable AD (14 women; mean age = 78 years; age range = 65–92 years). As in Experiment 1, HOA were recruited from the community of Marseille (France), and patients with a diagnosis of probable AD were recruited in the Department of Geriatric Neurology, Sainte Marguerite Hospital (Marseille, France). Probable AD patients (21.4 ± 3.8) had poorer MMSE scores than HOA (28.4 ± 1.6, t (48) = 8.60, $p < .001$). All participants completed the dot comparison and Simon tasks. None of our patients had visual acuity deficits, as suggested by normal performance in Rey Figure. Written informed consent was obtained from healthy older adults and AD patients after a presentation of the experiment.

To test group-related differences in sequential modulations of congruency effects, the sample size used in Experiment 2 was based on an *a-priori* power analysis conducted in G*Power 3.1 (Faul et al., 2007). Concerning sequential modulations of congruency effects, we assumed an effect size of Cohen's f = 0.20 (derived from relevant previous studies; e.g., Lemaire & Hinault, 2014) and an alpha of .05. We determined that a total sample size of 36 participants (N = 18 per group) provides 81% power to detect effects. In order to exceed this criterion and achieve larger than 81% power, we tested 50 participants (N = 25 per group). Second, regarding group effects, we assumed an effect size of Cohen's f = 0.27 (also derived from Lemaire & Hinault, 2014), an alpha of .05. We determined that a total sample size of 20 participants (N = 10 per group) would provide 81% power to detect effects. In order to exceed this criterion and achieve 81% power, we recruited 50 participants (N = 25 per group).

Stimuli

The dot comparison task included collections of black dots (i.e., dot size was 0.5-cm or 20 pixels in diameter; dot size represented 0.45 degree of visual angle; adapted from Gebuis & Gevers, 2011; Gebuis & Reynvoet, 2012) presented on a white background. Each item consisted of two collections of dots displayed side by side on a 15 ´´ laptop screen. For each collection, convex hull was smaller (i.e., 7.9-cm or 300 pixels in diameter) or larger (i.e., 10.6-cm or 400 pixels in diameter). Moreover, dots were randomly distributed and were at least 0.6-cm (or 25 pixels) away from each other to avoid dots overlap. In addition, all collections of dots had similar configurations (i.e., rounding shape). We created a set of stimuli including a total of 288 experimental items divided into two matched blocks of 144 items each. In each item, one dot collection always displayed 24 dots, and the other 18, 20, 22, 26, 28, or 30 dots. This resulted in three ratios for three levels of difficulty (i.e., calculated by dividing the larger number of dots by the smaller one). A third of the collections each instantiated easy (i.e., large-ratio; ratio 1.3 with 24:18 or 24:30 dots), medium (i.e., medium-ratio; ratio 1.2 with 24:20 or 24:28 dots), or difficult items (i.e., small-ratio; ratio 1.1 with 24:22 or 24:26 dots).

There were two types of items (see Figure 5(a,b), for examples): Convex hull and numerosity matched in congruent items (i.e., collections with the larger number of dots were displayed with a larger convex hull, and collections with the smaller number of dots appeared with a smaller convex hull) and mismatched in incongruent items (i.e., collections with the smaller number of dots were displayed with a larger convex hull, and collections with the larger number of dots were presented with a smaller convex hull).

Following previous studies (e.g., Hinault et al., 2017, 2014, 2014, 2016a, 2016b; Roquet et al., 2018), to assess sequential modulations of congruency effects on current trials, we compared participants' performance on current congruent and incongruent items as a function of congruency of the immediately preceding items. Thus, four types of trials were tested depending on whether

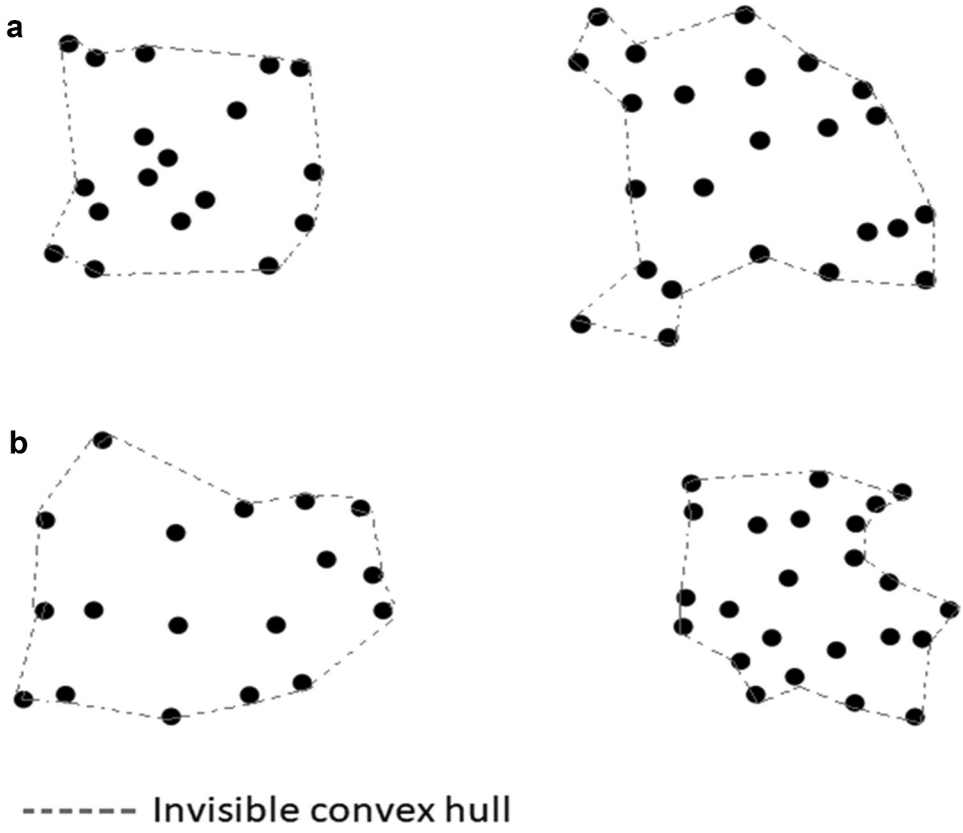

Figure 5. Examples of (a) a congruent item in which convex hull and numerosity matched (i.e., left collection contained 18 dots displayed with a smaller convex hull, and right collection included 24 dots displayed with a larger convex hull); (b) an incongruent item in which convex hull and numerosity mismatched (i.e., left collection contained 18 dots displayed with a larger convex hull, and right collection included 24 dots displayed with a smaller convex hull).

convex hull and numerosity matched on current and previous items: congruent – congruent trials (i.e., numerosity and convex hull matched on both current and previous items), congruent – incongruent trials (i.e., numerosity and convex hull matched on previous items and mismatched on current items), incongruent – congruent trials (i.e., numerosity and convex hull mismatched on previous items and matched on current items), and incongruent – incongruent trials (i.e., numerosity and convex hull mismatched on both current and previous items).

Procedure

Participants were individually tested first on a dot comparison task. The presentation of stimuli was controlled by the E-Prime Software. Each item began with a 500-ms blank screen, followed by a warning signal ("*") displayed for 400-ms in the center of the screen. Then, each item was displayed for 2000-ms (see Figure 6). Participants were asked to indicate, as quickly and accurately as possible, which collection of dots included the largest number of dots by pressing on the appropriate response key (i.e., S or L on an AZERTY keyboard) with the right or the left index finger. Participants were asked to respond within 2000-ms before stimulus disappears. If no response was given within 2000-ms, a blank screen appeared, and participants had to press any key on the keyboard to move to the next items.

Participants were then tested in the Simon task. The Simon task consisted of pressing the appropriate response key (i.e., green or red) as quickly and accurately as possible, with the right or the left index finger according to the figure displayed 7-cm either to the left or to the right of a central fixation point. Participants had to press on the red response key if a 2-cm x 3-cm blue rectangle was displayed or on the green response key if a 6-cm diameter blue circle was displayed (see Figure 7).

There were two types of items, 60 congruent items, and 60 incongruent items. In the congruent items, the spatial location of the stimulus corresponded to the task-relevant aspect of the stimulus (i.e., the circle was displayed on the left and the rectangle on the right sides of the screen). In the incongruent items, the spatial location of the stimulus did not match with the task-relevant aspect of the stimulus (i.e., the circle was

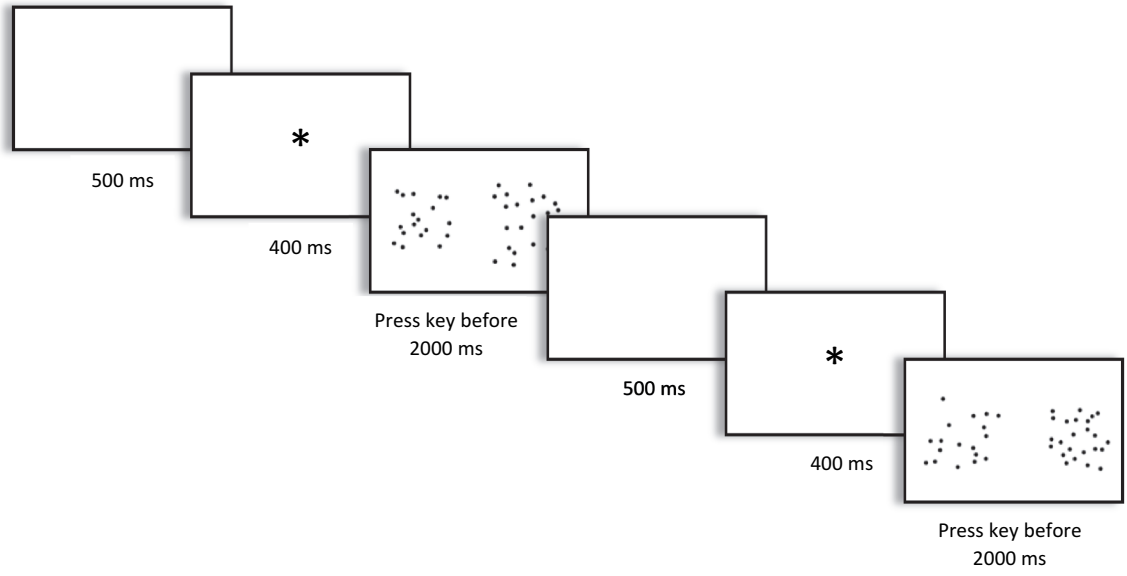

Figure 6. Sequence of events in a trial in the dot comparison task.

displayed on the right and the rectangle on the left sides of the screen). Each item began with the display of a cross in the center of the computer screen, corresponding to a fixation point. After 800 ms, the blue rectangle or the blue circle was presented, and participants had to respond. Participants practiced the Simon task on 20 items prior to the 120 experimental items. Four types of trials were tested depending on congruency on current and previous items: congruent – congruent trials, congruent – incongruent trials, incongruent – congruent trials, and incongruent – incongruent trials.

Results

Group-related changes in congruency effects and their sequential modulations in dot comparison task

Preliminary analyses were run with the block (1st *vs.* 2nd half of the experiment) and item difficulty (i.e., large-ratio, medium-ratio, and small-ratio items) factors. Except for significant main effects of block (i.e., participants were faster during the second block than during the first block) and of item difficulty (i.e., participants were faster on large-ratio than on medium-ratio

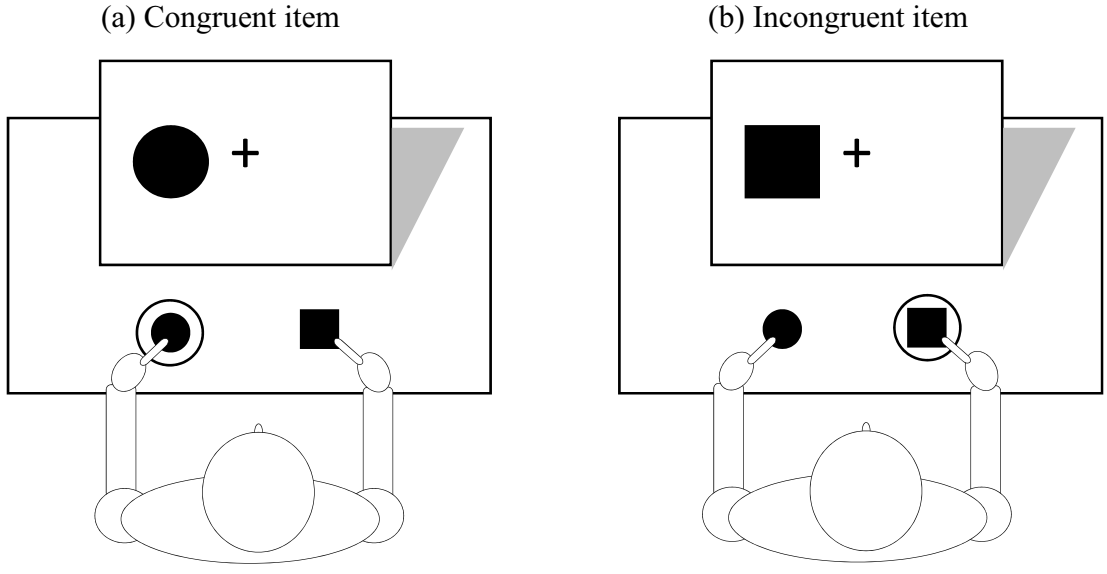

Figure 7. Examples of (A) a congruent item in which the required response (e.g., left keypress) is congruent with the location of the stimulus (e.g., left side of a fixation cross); (B) an incongruent item in which the required response (e.g., right keypress) is incongruent with the location of the stimulus (e.g., left side of a fixation cross).

or small-ratio items), and for a significant Group x Block interaction (i.e., HOA were 19-ms faster in Block 1 than in Block 2 compared to 141-ms for probable AD patients), no other main or interaction effects involving these two factors came out significant. Unless otherwise noted, differences are significant to at least $p < .05$. To correct for multiple comparisons, Sidak corrections were applied.

To examine congruency effects, sequential modulations of congruency effects, and group-related differences therein, mean response times and error rates were analyzed using 2 (Group: HOA, probable AD patients) x 2 (Congruency on the previous items: Congruent, Incongruent) x 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with group as the only between-participants factor (see means in Table 2).

Response times. HOA were 477-ms faster than probable AD patients ($F(1,46) = 53.97$, $MSe = 104{,}770$, $n2p = .53$), and participants were 66-ms faster on current congruent items than on current incongruent items ($F(1,48) = 27.79$, $MSe = 7930$; $n2p = .37$). Congruency effects were significant and of comparable magnitudes in HOA (80 ms; $F(1,24) = 29.71$, $MSe = 5479$; $n2p = .55$) and probable AD patients (52 ms; $F(1,24) = 6.53$, $MSe = 10{,}381$; $n2p = .21$), as seen in the non-significant Group x Congruency on the current items interaction ($F < 1.0$).

Moreover, participants sequentially modulated congruency effects, as shown by a significant interaction between congruency on the previous items and congruency on the current items ($F(1,48) = 12.21$, $MSe = 5166$, $n2p = .20$). This interaction was significant in both HOA ($F(1,24) = 9.79$, $MSe = 1849$, $n2p = .29$) and probable AD patients ($F(1,24) = 5.58$, $MSe = 8483$, $n2p = .19$). Sequential modulations of congruency effects (i.e., congruency effects after congruent items – congruency effects after incongruent items) were of comparable magnitudes in HOA (i.e., 54 ms) and probable AD patients (i.e., 87 ms), and there was no interaction with groups ($F < 1.0$).

Error rates. Participants made fewer errors on current congruent (i.e., 16.3%) than on current incongruent items (i.e., 36.0%, $F(1,48) = 65.59$, $MSe = 295$, $n2p = .58$), and there was no Group x Congruency on current items interaction ($F < 1.0$). Also, the significant interaction between Congruency on the previous items x Congruency on the current items ($F(1,48) = 7.31$, $MSe = 52$, $n2p = .13$) revealed larger congruency effects on current items following congruent items (i.e., 22.5%; $F(1.48) = 76.81$, $n2p = .62$) than after incongruent items (i.e., 16.9%; $F(1,48) = 39$, $n2p = .45$). Most importantly, the Group x Congruency on the previous items x Congruency on the current items interaction was significant ($F(1,48) = 3.98$, $MSe = 53$, $n2p = .0.8$). Differences in congruency effects after congruent and after incongruent items were larger in probable AD patients (9.7%; $F(1,24) = 13.28$, $MSe = 44$, $n2p = .36$) than in HOA (1.5%; $F < 1.0$). This result showed that sequential modulations of congruency effects on error rates were found only in probable AD patients and not in HOA.

Group-related changes in congruency effects and their sequential modulations in the Simon task

Mean response times and percentages of errors on each item (see Table 3) were analyzed using 2 (Group: HOA, probable AD patients) x 2 (Congruency on the previous items: Congruent, Incongruent) x 2 (Congruency on the current items: Congruent, Incongruent) mixed-design ANOVAs, with group as the only between-participants factor.

Response times. HOA were 269-ms faster than probable AD patients ($F(1,48) = 36.87$, $MSe = 24{,}611$, $n2p = .43$), and participants were 84-ms faster on current congruent items than on current incongruent items ($F(1,48) = 86.05$, $MSe = 4120$, $n2p = .64$). Most

Table 2. HOA and probable AD patients' mean response times (in ms) and percentages of errors in the dot comparison tasks for current congruent and incongruent items following congruent or incongruent items in the dot comparison task (Expt. 2).

	HOA			Probable AD patients		
Congruency of current items	Congruent previous items	Incongruent previous items	*Means*	Congruent previous items	Incongruent previous items	*Means*
			Mean response times (in ms)			
Congruent	940	971	955	1284	1327	1305
Incongruent	1047	1023	1035	1379	1336	1357
CE	107***	52*	80***	95***	9	52***
			Mean percentages of errors			
Congruent	11.7	11.8	11.8	19.4	22.2	20.8
Incongruent	36.8	35.4	36.1	39.3	32.4	35.8
CE	25.1***	23.6***	24.3***	19.8***	10.1*	15.0***

CE: Congruency effects (Incongruent items – Congruent items). *p <.05, ***p <.001.

Table 3. HOA and probable AD patients' mean response times (in ms) and percentages of errors in the Simon task for current congruent or incongruent items following congruent or incongruent items (Expt. 2).

	HOA			Probable AD patients		
Congruency of current items	Congruent previous items	Incongruent previous items	*Means*	Congruent previous items	Incongruent previous items	*Means*
			Mean response times (in ms)			
Congruent	500	548	524	749	774	761
Incongruent	599	553	576	902	853	878
CE	99***	5	52***	153***	79***	117***
			Mean percentages of errors			
Congruent	6.9	8.1	7.5	9.6	9.1	9.4
Incongruent	15.2	10.0	12.6	18.3	13.8	16.0
CE	8.3***	1.9	5.1***	8.7***	4.7*	6.6***

CE: Congruency effects (Incongruent items – Congruent items). *p <.05. ***p <.001.

importantly, the Group x Congruency on the current items interaction (F(1,48) = 12.39, MSe = 4120, $n2p$ = .21) showed that congruency effects on current items were larger in probable AD patients (116 ms; F (1,24) = 55.27, MSe = 6103, $n2p$ = .70) than in HOA (52 ms; F(1,24) = 31.94, MSe = 2136, $n2p$ = .57).

Finally, the Congruency on the previous items x Congruency on the current items interaction (F (1,48) = 32.17, MSe = 2761, $n2p$ = .40) revealed larger congruency effects on current items when previous items were congruent items (i.e., 126 ms; F (1,48) = 99.66, $n2p$ = .68) than when previous items were incongruent (i.e., 42 ms; F(1,48) = 15.37, $n2p$ = 24). Most importantly, both HOA and probable AD patients sequentially modulated congruency effects to the same extent, as showed by a non-significant Group x Congruency on the previous items x Congruency on the current items (F < 1.0) interaction.

Error rates. Participants made fewer errors on current congruent (i.e., 8.5%) than on current incongruent items (i.e., 14.3%, F(1,48) = 28.89, MSe = 60, $n2p$ = .38). Also, the significant Congruency on the previous items x Congruency on the current items interaction (F(1,48) = 18.21, MSe = 19, $n2p$ = .28) revealed larger congruency effects on current items following congruent items (i.e., 8.5%; F(1,48) = 48.01, $n2p$ = .50) than after incongruent items (i.e., 3.5%; F (1,48) = 6.45, $n2p$ = .12). HOA and probable AD patients sequentially modulated congruency effects to the same extent, as showed by a non-significant Group x Congruency on the previous items x Congruency on the current items interaction (F < 1.0).

In sum, AD patients showed similar congruency effects than HOA in dot comparison task, but larger CE in Simon task. Interestingly, this suggests that declines in general inhibitory mechanisms found in the Simon task do not lead AD patients to be more impaired in the dot comparison task when they inhibit irrelevant information and focus on relevant information. Equally interesting, AD patients and HOA modulated inhibitory processes to the same extent, suggesting that sequential modulations of cognitive control processes seem to be preserved in Alzheimer's disease, both in the dot comparison and the Simon tasks.

Finally, additional analyses revealed that group differences found here in numerical comparisons or number-line performance (Experiments 1 and 2) were not contaminated by corresponding differences in speed-accuracy tradeoffs.[1]

General Discussion

This study makes important contributions to our understanding of how AD affects numerosity comparison, a core domain of numerical cognition. We found decreased comparison performance in AD patients relative to HOA. These group-related differences originated in how AD affects domain-specific and domain-general processes. Indeed, our results showed that decreased performance in AD patients reflected deficits in some specific and general processes, while other specific and general processes seem to be preserved in the early stage of AD. These findings have important implications to further our understanding of how AD impairs numerosity estimation and comparison. We discuss these implications.

First, we found that AD influences specific numerical processing mechanisms during comparison tasks. In Experiment 1, AD patients were impaired when asked to compare collections of dots that had close numerosities (i.e., small-ratio collections). Such impairment of numerosity estimation performance in AD is consistent with previous findings showing poorer performance in AD patients when estimating or comparing numerosities of dot collections (e.g., Boone et al., 2002; Fujimori et al., 2000; Gandini et al., 2009; Maylor et al., 2005; Seron et al., 1991). For example, Gandini et al. (2009) found that

AD patients had more difficulties than HOA to estimate numerosities of dot collections including 40–460 dots.

Moreover, we found that (a) both HOA and AD group's numerical estimates were better fit by linear than by logarithmic functions, and (b) the linear fits for the 0–1,000 scales were better for HOA than for AD patients. The linear fits here extend to HOA and AD patients with previous findings in children and young adults (e.g., Thompson & Opfer, 2010, 2016; Opfer et al., 2011; Siegler & Booth, 2004; Siegler & Opfer, 2003). The authors have commonly interpreted that linear fits were associated with better representation of numbers. Thus, a smaller linear fit could be interpreted as less precise representation of numbers in adults, as well as in children.

These previous results in children and young adults suggest that a decline in numerosity representations in AD found here, especially for large numbers, could be responsible for smaller linear fits in AD than HOA for 0–1,000 numbers. Moreover, that the linear fits for the 0–1,000 scales were larger in HOA than in AD patients is consistent with previous findings which suggest that patients are less accurate in processing large numbers (e.g., Boone et al., 2002; Gandini et al., 2009; Seron et al., 1991).

Before this study, no information was available on HOA's and AD patients' performance in number-line tasks. The present data helped to characterize the evolution of representations of numbers between 0 and 1,000 in the early stages of the AD. The next step involves testing the effects of normal and pathological aging on harder estimation to determine how larger numerosities change with age during healthy aging and whether they are spared or degraded in AD patients. Indeed, several studies investigated magnitude estimation in children and young adults when placing large numbers on a number line (e.g., Thompson & Opfer, 2010; Landy et al., 2017, 2013). For example, Landy et al. (2013) asked young adults to select a location for numbers presented on a number line with endpoints marked with the values 1 thousand and 1 billion. Results showed that linear fits were found for half the participants only, leaving up the possibility that performance in such large scales may stem from mental representations and/or other factors (e.g., strategies used to divide up the line, or difficulties in arithmetic). If numerosity representations for much larger numerosities are degraded in AD patients, we might observe smaller linear fits in AD than HOA for large numerical magnitudes.

Note that the interpretation of mental representations of numbers is debated in the literature, and alternative theoretical models have been proposed (e.g., Cyclical power model, Hollands & Dyre, 2000; Occupancy model; Allik & Tuulmets, 1991; Vos et al., 1988; Proportional-reasoning model; Barth & Paladino, 2011; Cohen et al., 2018; see Opfer et al., 2011,; Young & Opfer, 2011, for more in-depth discussions of these models). These alternative models propose that participants' response in a number-line task (and most likely in other numerosity estimation tasks) result from both mental representations of quantity and strategies that participants use to accomplish such tasks. This suggests that any group differences in participants' performance in number-line tasks thus may reflect contributions of both mental representations of magnitudes and strategies.

Our experimental design did not enable us to test strategic variations, which could be done in future studies. This could be achieved via collecting verbal protocols (after each trial, participants would say how they estimated) and/or measuring eye-movements (e.g., Sullivan et al., 2011). This would inform group differences not only in performance but also in other aspects of this performance, such as strategies and biases.

In addition to replicating, extending, and refining our knowledge on when AD patients are impaired in numerosity comparison, the present study helps to further understand sources of such impairment. Experiment 1 revealed that AD patients' poorer performance in numerosity comparison correlated with poorer representations of numbers as assessed in our number-line task. This finding suggests that (a) more precise, accurate, and distinctive representations of numerosities are a key component of numerosity estimation performance, and (b) AD degrades these representations, leading AD patients to have more difficulties in numerosity estimation. This is consistent with previous findings that have shown that AD patients were impaired in cognitive estimation performance (e.g., Brand et al., 2002; Della Sala et al., 2004; Goldstein et al., 1996; Kopelman, 1991), and more specifically in estimation of larger numbers or numerosities (e.g., Boone et al., 2002; Gandini et al., 2009; Maylor et al., 2005; Seron et al., 1991).

One additional original and interesting findings in Experiments 1 and 2 concern how domain-general, executive processes in numerosity comparison are affected or not in AD patients. We found that AD is associated with both impairment of some executive control processes and maintenance of other executive control processes in numerosity comparison.

First, we reported larger congruency effects in AD patients than HOA in a domain-general, Simon task. Such difficulties in processing congruency have been found in AD in previous studies using a Stroop task (e.g., Balota & Faust, 2001; Bélanger et al., 2010; Castel et

al., 2007; Duchek & Balota, 2005; Perry & Hodges, 1999; Spieler et al., 1996).

Second, pathological aging effects on inhibitory processes were more nuanced in the numerosity comparison tasks. The congruency effects and group-related differences depended on visual features manipulated in dot comparison tasks. Indeed, we found significant effects of both dot area and convex hull information on participants' performance, indicating that numerosity processing was influenced by these visual features. Importantly, the influence of dot area and convex hull information was dependent on the participants' group. Indeed, Experiment 1 showed that dot area information influenced AD patients, but not HOA. Convex hull information influenced both AD's and HOA's performance (Expt. 2). Previous studies reported that dot area information is easier to inhibit than convex hull information in young adults, and much less strongly influences HOA's numerosity comparison performance (e.g., Clayton & Gilmore, 2015; Gilmore et al., 2016; Norris et al., 2019). Although HOA can inhibit dot area information, AD patients, whose inhibitory processes are known to be less efficient (see Amieva et al., 2004; Guarino et al., 2019, for reviews), had difficulties inhibiting this visual feature.

One surprising result in our experiments is comparable sequential modulations of congruency effects in HOA and AD patients. This suggests that processes enabling participants to maintain active in working memory congruency processing and to prepare processing incongruency on subsequent items remain very efficient during the early stages of AD. Of interest for future studies is whether they remain efficient in later stages of AD or whether severe AD impairs these processes before or in parallel to deteriorating mechanisms processing congruency. That mechanisms processing congruency and enabling the cognitive system to sequentially modulate congruency processing are different mechanisms suggests different time courses of alteration of these mechanisms during the progression of AD.

An alternative explanation to both poorer numerosity comparison performance and congruency effects in AD patients and HOA concerns strategies used to accomplish dot comparison tasks. Indeed, previous studies reported that participants use several strategies to estimate numerosities and compare numerosities of collections of dots (Gandini et al., 2008, 2009; Roquet & Lemaire, 2019; Siegel et al., 1982). These strategies are based on visual features of the collections to compare. For example, Roquet and Lemaire (2019) found that both young and older adults used the same set of nine strategies, but each group used available strategies with different proportions. Older adults preferred strategies based on a single visual feature (e.g., total surface occupied by dots in a collection), while young adults used strategies combining several visual features (e.g., total surface occupied by dots in collections and distance by dots). Roquet and Lemaire (2019) also found group differences in the number of strategies used by individuals and in how good participants were at executing numerosity comparison strategies. Also, when they asked HOA and AD patients to estimate numerosities of large collections of dots, Gandini et al. (2009) found that AD patients and HOA used multiple strategies, and that AD patients used fewer strategies and executed strategies less efficiently than HOA. Following these findings, it would be fruitful to determine whether strategic variations may contribute to some or all of the present findings (group differences in numerosity performance and congruency effects, as well as group similarities in sequential modulations of congruency effects). Future studies may address these issues by running the same experiments and assess strategy use on each trial. Such a procedure is possible to adopt in AD patients, as previous studies did investigate strategic variations in AD patients (e.g., Arnaud et al., 2008).

To conclude, our results have important empirical and practical implications. Empirically, they further our understanding of how numerosity estimation and comparison performance are influenced by specific and general cognitive mechanisms. More specifically, we highlighted impairment in some specific (e.g., representations of large numerosities) and general (e.g., inhibition processes when dot area information was manipulated) processes, while other specific (e.g., representations of small numerosities) and general (e.g., inhibition processes when convex hull information was manipulated) estimation processes seem to be preserved in the early stage of AD. At the clinical level, the present findings suggest that (a) numerosity impairment exist and is important in AD patients, (b) such impairment results from decline in either general or specific processes (or both), and (c) patients may vary in the extent of impairment and which processes are impaired. Also, the present results highlight the importance for clinicians to test both domain-general and domain-specific processes when assessing numerosity estimation in patients to better understand sources of impairment in their patients. Note also that given usually reported impairment in clinical settings and in studies on AD patients while estimating in daily life (e.g., Guarino et al., 2019; Jekel et al., 2015; Marshall et al., 2012), the present findings suggest some important sources of such impairment, as numerosity and daily life estimations most likely rely on common estimation mechanisms.

Note

1. Item-based correlations between speed and accuracy in each group were significantly positive in HOA (r=.46 &.34, in Expts. 1 & 2, respectively), and non-significant in AD (r=.15 &.04, in Expts. 1 & 2). These correlations showed that increased RTs associated with increased percentages of errors were significant in HOA, and that speed and accuracy were not related in AD. This was also seen when examining means. For example, in Expt. 1, both HOA and AD patients were faster on large-ratio items than on small-ratio items and both groups were more accurate on large-ratio items than on small-ratio items; the ratio effects were larger in AD patients than in HOA on both speed and accuracy. As another example, in Expt. 2, poorer performance on incongruent relative to congruent items was found on both speed and accuracy in AD patients and in HOA.

Data availability

Data will be made publicly available on data sharing website (e.g., OSF), once this article is accepted for publication or during review process upon request.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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