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Aging and Numerosity estimation

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Abstract

In two experiments, young and older participants were asked to find the approximate number of dots in collections including 40—460 dots. Experiment 1 showed that both age groups had comparable performance and no age-related differences in the power-function exponents for numerosity. Experiment 2 found that these age-related similarities were not due to speed-accuracy trade-offs or to older adults compensating for potential age-related decline in numerosity estimation processes. Also, both young and older participants used physical features of stimuli only for numerosities that are poorly represented in long-term memory. Implications of these findings for further understanding how participants accomplish numerosity estimation tasks and effects of aging in this domain are discussed.

Age-related differences in numerosity estimation

How do we estimate numerosities of large sets of items? The present two experiments document numerosity estimation (i.e., finding the approximate number of elements in sets of items) in young and older adults. It determined whether participants use physical features (e.g., size of items or filled area of items) to find estimates for all numerosities, as suggested by many previous results or whether use of physical attributes varies with numerosities. Moreover, this study examined effects of aging in numerosity estimation. Before outlining the logic of the present experiments, we review previous findings on numerosity estimation.

Estimating numerosities of large sets of items has been studied in tasks where participants are presented collections of dots on a computer screen and are asked to provide a quick estimate of the number of dots for each collection (e.g., Beran, Taglialatela, Flemming, James, & Washburn, 2006). This skill can also be investigated by asking participants to compare two collections of dots and to decide which is the largest (e.g., Thomas, Fowlkes, Vickery, 1980) or by asking participants to reproduce (via finger tapping for example) a target numerosity (e.g., Cordes, Gelman, Gallistel, & Whalen, 2001). Note that participants are not asked (or do not have time) to find the exact number of dots. Numerosity estimation is investigated in a wide variety of populations, ranging from nonhuman animals (e.g., Beran, 2001), infants (e.g., Xue & Spelke, 2000), children (e.g., Huntley-Fenner, & Cannon, 2000), or adults (e.g., Boisvert, Abroms, & Roberts, 2003). Several findings from previous works are relevant to the present research. First, participants' estimates correlate with actual numerosity, such that they provide larger estimates with increasing numerosities. In fact, their estimates are a direct power function of the number of items presented. Indeed, estimates are reliably predicted with a power function of actual numerosity of the form $E = kN^b$, where E is the estimated numerosity, N is the correct numerosity, b is the power-function exponent, and k is a constant. The power-function exponents found in diverse studies are in the .70-90 range

(e.g., Bevan, Helson, & Maier, 1963; Dehaene, 1997; Krueger, 1972, 1982, 1984). A power function exponent smaller than 1 indicates that participants tend to underestimate (i.e., estimates are smaller than correct numerosities), and this underestimation increases with increasing numerosities (e.g., Krueger, 1972, 1982, 1984; Whalen, Gallistel, & Gelman, 1999). As discussed by several authors, this is consistent with the hypothesis that memory representations for numerosities are becoming less precise and harder to discriminate with increasing numerosities (e.g., Dehaene, 1997; Siegler & Opfer, 2003; Siegler & Booth, 2004).

The second important findings from previous research on numerosity estimation concern the influence of physical features (e.g., size or arrangement of items, of stimulus display, of filled area) on participants' estimates. For example, when dots are arranged in regular patterns (e.g., as a circle or a rectangle), participants tend to provide larger estimates than when dots are randomly displayed (e.g., Frith & Frith, 1972; Ginsburg, 1978, 1980; Ginsburg & Goldstein, 1987; Ginsburg & Pringle, 1988; Massaro, 1976). Also, participants provide larger estimates for one large cluster of dots than for several small clusters (e.g., Ginsburg, 1991; Vos, van Oeffelen, Tibosch, & Allik, 1988) or when items are spread out than when they are bunched together (e.g., Bevan, Maier, & Helson, 1963; Clearfield & Mix, 1999, 2001; Dixon, 1978; Ginsburg & Nicholls, 1988; Krueger, 1972; Mix, Huttenlocher, & Levine, 1996; Mix, Levine, & Huttenlocher, 1997). Participant's judgment of approximate numerosity is also highly influenced by density and texture patterns of large visual arrays (e.g., Compton & Logan, 1993; Durgin, 1995). These findings led researchers to propose that people use physical features to find estimates for all numerosities, such as the area of the stimulus field apparently occupied by a collection of dots (e.g., Allik & Tuulmets, 1991; Vos, van Oeffelen, Tibosch, & Allik, 1988).

Previous studies had two limits that are addressed in the present two experiments. First, no studies examined directly the interaction between numerosities and physical properties of

stimuli. Such an interaction would be observed if, for example, the same number of dots distributed differently in an array or the same number of dots with different sizes appear to contain different numbers of elements. Observing such interactions (e.g., Ginsburg & Nicholls, 1988; Krueger, 1972; Taves, 1941) would be crucial for theories of numerosity estimation as it would no longer be possible to assume that we use physical features on all numerosities when we accomplish numerosity estimation tasks. Rather, this would suggest that we use physical properties of stimulus for some numerosities only. Here, we tested the hypothesis that we use physical properties of stimuli when their numerosities is not well represented in memory.

Although no studies directly tested the interaction between physical properties of stimulus and numerosities, closely looking at existing data sets suggests that this is a true possibility. For example, in Ginsburg and Nicholls' (1988) data, effects of size of dots seemed larger for large than for small numerosities. Differences in accuracy of estimates for small- and large-dot collections were larger for large numerosities than for small numerosities (see also Ginsburg, 1978, for larger regular-random differences when participants estimated small numerosities, compared to large numerosities). One goal of the present study was to directly test this Numerosity x Physical attributes of stimuli on participants' estimates. We predicted that effects of stimulus attributes would be larger for large than for small numerosities.

The second limit of previous findings is that all studies tested only young adults. Therefore, we do not know whether numerosity estimation skills decline with age and, if so, why. Given general cognitive declines with age (see Craik & Salthouse, 2000, for an overview), we tested the possibility that older adults would provide less accurate estimates than young adults. Alternatively, consistent with some data showing that numerical cognition is one of these cognitive areas where aging effects are mixed (with some domains, such as age complex arithmetic, showing age-related decrease and others, like counting, showing age-

invariance; see Duverne & Lemaire, 2005, for an overview), we tested the possibility that young and older adults obtains comparable numerosity estimation performance. Experiment 1 compared accuracy of estimates as well as memory representations for large numerosities in young and older adults, and Experiment 2 collected accuracy of estimates, as well as solution latencies and eye movements.

Experiment 1

Experiment 1 had two goals. First, we asked whether young and older adults have different performance in numerosity estimation tasks. Second, we aimed at determining whether memory representations for numerosities vary with age in adults. Young and older adults were asked to provide estimates of collections of dots varying in numerosities from 40 to 460 without enumerating them. The hypothesis that cognitive aging leads to decreased skills with age in numerosity estimation predicts less accurate estimates in older than in young adults. Moreover, we expected that predicting estimates as a function of correct numerosities should yield different functions in young and older adults, or similar functions with different parameters. From previous works, young adults are expected to show a power function. The hypothesis that aging is associated with different memory representations for numerosities predicts that older adults show either a different power-function exponent for numerosity or a different function.

Method

Participants. Participants were 96 individuals: 48 young adults (25 females) with a mean age of 26.0 years (range: 24-32 y.o.) and 27 older adults (27 females) with a mean age of 73.7 years (range: 67-81 y.o.). Young adults were undergraduate students from the University of Provence (Aix-en-Provence, France) who received course credit for their participation; older adults were recruited from the community who received a book on cognitive aging (Lemaire

& Bherer, 2005) for their participation. All older adults had scores larger than 27 (mean: 29.1) in the Mini Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975); therefore, none were excluded. At the end of the experiment, participants completed both the addition and the subtraction-multiplication subtests of the French Kit (French, Ekstrom, & Price, 1963), which provided assessment of participants' arithmetic fluency with an independent, paper-and-pencil test. Each subtest consisted of two pages of problems. All participants were given two minutes per page and were instructed to solve the problems as fast and accurately as possible. Number of correct answers on each of the addition and the subtraction-multiplication tests were summed to yield a total arithmetic score. Next, participants completed the French version of the Mill-Hill Vocabulary Scale (MHVS; Deltour, 1993; Raven, 1951) so as to test their verbal ability. MHVS consists of 33 items distributed across three pages. Each item was a target word followed by six proposed words, and the task consisted in identifying which of the proposed words had the same meaning as the target word. The number of correct items represented the level of verbal ability. Participants' characteristics are summarized in Table 1.

Insert here Table 1

Stimuli. Each participant solved 84 numerosity estimation problems. Each stimulus was made of black dots randomly displayed on a white screen. Each stimulus was made of black dots randomly displayed on a white screen. Numerosities ranged from 40 to 460, increasing in steps of 5 (i.e., 45, 50, 55...460). Within a collection of dots, all dots had the same size. However, to control as much as possible for parameters such as contour or surface occupied by dots, individual dots varied in sizes of 6, 8, 10, or 12 pixels.

Procedure. Participants were tested individually in one session that lasted approximately 30—40 minutes . They first performed the numerosity estimation task, and then the paper-and-pencil tasks (i.e., MHVS, Arithmetic fluency). At the end of the session, healthy older adults also completed the MMSE.

The experiment was controlled by the E-Prime software, and stimuli were displayed on a 14-inch computer (SONY G-FX201 PC) screen. The program generated the displays and recorded latencies to the nearest millisecond. The display resolution was 800 x 600 pixels. Each trial was preceded by a blank screen (1000 ms) and a fixation point (“*”) in the centre of the screen for 750 ms. The dot patterns were then displayed in the center of the screen until participants responded (and for a maximum duration of 4 seconds). Participants were instructed to try to find the approximate number of dots in each stimulus and to report this estimate orally as soon as possible after they found an estimate. The experimenter typed in participants’ estimates. Presentation of the stimuli was random for each participant in two blocks of 42 items each, with a few minutes break between blocks. A timer was started when collections of dots appeared on the screen and ended when the experimenter pressed on the space bar of the computer keyboard, which happened as soon as possible after participants provided their response orally. This procedure was used because pilot testing showed that when response time was recorded from participants’ first vocalization, they frequently changed their answer or were still estimating during production of the response. Experimenter timing of responses also minimized response demands on participants and potential loss of trials due to voice key artefacts.

Results

The first analysis examined age-related differences in accuracy of estimates. Following previous works on estimation, to measure estimation accuracy, for each problem, we calculated each participant's percent absolute error:

$$\left| \frac{\text{Estimated Numerosity} - \text{Correct Numerosity}}{\text{Correct Numerosity}} \right| \times 100$$

To illustrate, suppose a participant gave 129 as an estimate for 138 dots. That participant would be 6.5% $([(129-138)/139]*100)$ away from the exact numerosity. An analysis of variance (ANOVA) on each participant's mean percent absolute error indicate no effect of age on accuracy: Means were 31% and 33%, $F(1,94)=0.69$, for young and older adults, respectively.

The next analysis examined age-related differences in the power-function exponent for numerosity. First, the mean estimate for each numerosity generated by participants in each age group was calculated (Figure 1). Then, each group's estimate was predicted with a power function of actual numerosity, $E=kN^b$, where E is the estimated numerosity, N the correct numerosity, b is the power-function exponent, and k is a constant. The power functions were comparable in young (Estimate= $2.45N^{.80}$) and older (Estimate= $2.81N^{.77}$) adults. Consistent with previous research, power function exponents smaller than 1 resulted from both young and older participants underestimating numerosities. To test for group differences in the power-function parameters, we ran individual regression analyses predicting each participant's estimate from correct numerosity. One-way ANOVAs showed no age-related differences in the power function exponents or intercepts. Mean exponents were .90 and .93, $F(1,94)=.70$, ns., in young and older adults respectively; corresponding mean intercepts were .31 and .27, $F(1,94)=.36$, ns.

Insert Figure 1 about here

In sum, these results showed that (a) numerosity estimation performance does not decline in older adults, and (b) long-term memory representations remain stable with age. Before accepting these two conclusions, it is necessary to consider the possibility that numerosity estimation skills are not age-invariant. According to this hypothesis, comparable performance in young and older adults may be the results of some types of compensatory mechanisms. Among those is the possibility that older adults did not accomplish our task the same way as young adults (i.e., they used different estimation processes). Also, they may take more time to find estimates. The present experiments did not collect solution latencies, although stimuli were displayed for a maximum duration of 4 seconds, and both young and older adults provided their estimates before this deadline. Experiment 2 tested the possibility that older adults obtained equally good performance compared to young adults, because they used some types of cognitive compensations.

Experiment 2

Experiment 2 had two goals. First, we wanted to determine if participants use physical features (i.e., size of dots) to provide estimates for all numerosities or only for a subset of numerosities. Second, we wanted to further understand age-related similarities in numerosity estimation found in Experiment 1. To achieve these ends, we analyzed accuracy of estimates, solution times, and eye movements in young and older adults who were asked to find an approximate numerosity for small versus large collections of dots. We also manipulated size of dots with half collections including dots of small size and the other half including large dots.

The hypothesis that participants use physical features of dots on all items predicts that size of dots should influence participant's estimates whatever the size of numerosities.

Alternatively, the hypothesis that physical features influence only numerosities that are hardest to estimate predicts that size of dots should influence large numerosities only (and not small numerosities). That is, we tested a Numerosity x Size of dots interaction on participants' estimates. Such an interaction is possible if participants can retrieve numerosities for small collections of items better than for large collections. This would result from more clear and distinguishable memory representations for small than for large numerosities.

The hypothesis that comparable young and older adults' performance in numerosity estimation stems from older adults compensating for age-related declines in cognitive resources makes predictions on patterns of solution latencies and eye movements. First, older participants may take more time to provide their estimates, and even more for large numerosities (i.e., Age x Numerosity). Second, young and older adults may have different patterns of eye movements. For example, older may make more and shorter eye fixations so as to fixate distinctive portions of stimulus and, thereby, to maximize information gain with each fixation. Such possibility would result from older adults' reduced useful field of view (UFOV; Ball, Beard, Roenker, Miller, & Griggs, 1988; Scialfa, Kline, & Lyman, 1987; Sekuler, Bennet, & Mamelak, 2000; Watson et al., 2005). More importantly, the Age x Numerosity on eye movements should show different effects of numerosities on young and older adults mean number and duration of fixations, amplitude of saccades, and dispersions of regard (or breadth of visual scanning of stimuli). Like for the corresponding Age x Numerosity interaction on latencies, this can happen if memory representations for large numerosities are not as clear and distinguishable as those for small numerosities, and even more so in older adults. Finally, Experiment 2 offered the possibility to test the Age x Numerosity x Size of dots interaction. Such an interaction is possible if the Numerosity x Size of dots results from significant Numerosity x Size of dots interaction in young adults only.

Alternatively, similar Numerosity x Size of dots interactions in both age groups would be additional evidence of age-invariance in numerosity estimation.

Method

Participants. Participants were 54 individuals: 27 young adults (17 females) with a mean age of 25.6 years (range: 22-30 y.o.) and 27 older adults (20 females) with a mean age of 70.9 years (range: 65-88 y.o.). Young adults were undergraduate students from the University of Provence (Aix-en-Provence, France) who received course credit for their participation; older adults were recruited from the community who received a book on cognitive aging (Lemaire & Bherer, 2005) to thank them for their participation. Like in Experiment 1, participants' verbal and arithmetic fluency were assessed and all older adults took the MMSE. Participants' characteristics are summarized in Table 1.

Stimuli. Each participant solved 128 numerosity estimation problems. Each stimulus was made of black dots randomly displayed on a white screen. Two types of problem features were factorially manipulated, size of numerosity (i.e., small vs. large numerosity) and size of dots (i.e., small vs. large dots). Half the small-dot problems had dots with a ray of 2.25 pixels and the other half had dots with a ray of 2.5 pixels; half the large-dot problems had dots with a ray of 2.75 pixels and the other half had dots with a ray of 3.0 pixels. Moreover, half the small-numerosity problems included 49 dots and the other half included 78 dots; half the large-numerosity problems included 91 dots and the other half included 147 dots. To control for potential factors such as filled area or between-dot distances, all dots occupied a small area (100 cm²; 250 x 250 pixels) in the center of the computer screen for half the stimuli and a large area (296 cm²; 430 x 430 pixels) for the other stimuli. Within each stimulus, all dots had the same size and two adjacent dots were separated by at least one pixel so that no pixels from different dots overlapped.

Procedure. Procedure was the same as in Experiment 1, except that participants' eye

movements were recorded during the experiment with an iView® X Eyetracking Device (Senso-Motoric Instruments). Participants were asked not to make too much head or body movement and were helped with the rest chin of the iView® X system. Calibration was performed by requesting participants to view nine crosses on the screen. Recalibration was performed between each block if necessary. Eye position was sampled every 20 ms (sampling rate: 240 Hz) and analyzed offline using customized software. Participants were tested individually in one single session that lasted approximately 60 minutes.

Results and Discussion

Results are reported in two main parts. The first analyzes approximate quantification performance; the second looks at patterns of eye movements. In all results, unless otherwise noted, differences are significant to at least $p < .05$.

Approximate quantification performance

Mean solution times and percentages of deviation were analyzed with 2(Age: young, older adults) x 2 (Numerosity: small, large) x 2(Size of dots: small, large) ANOVA designs, with age as the only between-subjects factor (see Table 2).

Insert Table 2 about here

ANOVAs on mean percentages of deviations showed that participants were more accurate when estimating small than large numerosities (20.9% vs. 26.4%), $F(1,52)=12.93$, $MSe=123.56$. Young participants were as accurate as older adults (22.6% vs. 24.8%, $F(1,52)=2.60$ ns). Moreover, the interaction between numerosity and size of dots was significant, $F(1,52)=20.35$, $MSe=7.59$. When participants estimated small numerosities, they provided equally accurate estimates for small-dot and large-dot collections (21.6% vs. 20.4%, $F(1,52)=2.23$ ns, $MSe=17.20$). In contrast, participants provided more accurate estimates on

small-dot collections than on large-dot collections (25.2% vs. 27.5%, $F(1,52)=14.59$, $MSe=8.88$) while estimating large numerosities.

ANOVAs on solution latencies revealed significant main effects of numerosity, $F(1,52)=7.23$, $MSe=201439$, showing that participants were faster at estimating small numerosities (3832 ms) than large numerosities (3996 ms). Moreover, the Numerosity x Size interaction was significant, $F(1,52)=16.70$, $MSe=63573$. This interaction resulted from participants being faster with large dots (3733 ms) than with small dots (3931 ms) while estimating small numerosities, but equally fast with small- and large-dots collections (3955 ms and 4037 ms) when estimating large numerosities. The main effect of age was not significant ($F(1,52)=1.41$, ns, $MSe=28781676$, although young adults tended to be faster than older adults (3480 ms vs. 4348 ms). However, age interacted with size of dots, $F(1,52)=6.96$, $MSe=65145$. Young adults were not influenced by size of dots (means were 3463 ms and 3497 ms, $F<1$, for small and large dots, respectively), but older adults were (means were 4423 ms and 4273 ms, $F(1,52)=9.29$, for small and large dots, respectively). No other effects came out significant on solution times or percent deviations.

Eye movement data

Mean number and durations of fixations, mean amplitudes of saccades, and dispersion of regard (DOR) were analyzed with the following ANOVA designs: 2 (Age) x 2 (Numerosity: small, large) x 2 (Size of dots: small, large), with age as the only between-subjects factor.

Mean number, mean durations of fixations, and mean amplitudes of saccades. Age was the only factor that significantly influenced mean number and duration of fixations. Young adults made fewer fixations than older adults (7.7 vs. 9.1), $F(1,52)=4.20$, $MSe=54.96$. They also made longer fixations (420 ms vs. 343 ms; $F(1,52)=6.03$, $MSe=52502$). Analyses of mean amplitudes of saccades showed no significant main or interaction effects ($F_s<2.14$).

Young and older participants had equally large saccades (4.5° vs. 4.6°), and both age groups made saccades of comparable amplitudes on small- and large-dot collections (4.6° vs. 4.5°) or on small and large numerosities (4.3° vs. 4.7°).

Dispersion of regard (DOR). To investigate the spatial distribution of attention during each trial, we calculated the dispersion of regard (DOR) on the grid during approximation. This DOR was the mean of standard deviations of points of regard in the X and Y axis. Larger DOR means that participants visually scanned larger surface of stimulus, independently of saccade amplitudes. Older participants scanned larger surface of stimuli than young adults (52.9 vs. 55.8 ; $F(1,52)=4.65$, $MSe=929.81$). When participants scanned large numerosities, they scanned stimuli with large dots less broadly than stimuli with small dots (54.8 vs. 57.6 , $F(1,52)=18.99$), but scanned stimuli with large and small dots (56.1 vs. 56.7 , $F<1$) similarly while estimating small numerosities. No other effects came out significant on DOR.

General Discussion

We found the following phenomena that are important for understanding how young and older people find approximate numerosities of large sets of items. Participants' estimates were influenced by both the number of dots in a collection and the size of dots. There were no age-related differences. Finally, young adults made fewer and longer eye fixations than older adults and scanned stimuli less broadly. In this section, we discuss implications of these findings to further understand numerosity estimation and effects of aging in this activity.

The present results replicate and complement previous findings regarding effects of numerosities and physical features in numerosity estimation. First, participants' estimates could be predicted from actual numerosity with a power function. Power-function exponents in numerosity estimation were here, like in previous studies, in the .70-.90 range (e.g., Krueger 1984). Such smaller-than-one exponents indicate that participants underestimate the number of elements in large collections of items. This underestimation phenomenon was

generalized here to very large numerosities. Moreover, the present study replicated effects of size of dots, first found by Ginsburg and Nicholls (1988) for numerosities smaller than those tested here.

Most originally, the present study is the first to find that the effect of size of dots is restricted to large numerosities. Size of dots exerted no effects on participants' estimates of small numerosities. Presumably, participants have better, clearer, and more easily distinguishable memory representations for small than for large numerosities. Such better memory representations led participants to use physical features to much lower extent than on the large, most poorly represented numerosities in memory. At a more general level, this suggests that physical features interact with internal representations of numerosities. Future studies may test whether such a conclusion holds to estimation activities other than numerosity estimation (Dixon, 1978). Estimating dimensions of stimuli such as weight, length, or distance are often influenced by another, irrelevant though sometimes correlated, dimension (e.g., Krueger, 1984). For example, participants are influenced by volume of objects when they estimate their weight, estimating heavy objects that have big volume (e.g., Nyssen & Bourdon, 1956).

One of the most interesting results in the present study concerns age-invariance in participants' performance. Both accuracy of estimates and solution latencies were comparable in young and older adults, and there were no age-related differences in the power-function exponents for numerosity. Most interesting was the fact that effects of size of dots interacted with numerosities in both young and older adults, consistent with the hypothesis that memory representations for numerosities do not degrade with age. Future studies will enable a deeper understanding of the specific characteristics of this numerosity estimation activity that make it immune to age deficits. At this stage of research, only speculations may be offered. Of these is the possibility that numerosity estimation relies on a phylogenetically old system of

numerical representations. This system rests greatly on the manipulation of mental magnitudes or nonverbal representations of approximate number and is often viewed as a prerequisite for symbolic mathematical processing (e.g., Dehaene, 1997, Gallistel & Gelman, 1992, 2000; Geary & Lin, 1998; Pica, Lemer, Izard, & Dehaene, 2004). Such pre-symbolic system might suffer less from age-related declines than other cognitive systems.

Before accepting the conclusion that aging does not influence numerosity estimation, it is important to consider two points. The present age-equivalence may be the results of cohort effects. Moreover, numerosity estimation skills may decline with age, but older adults did use compensatory mechanisms to circumvent deleterious effects of age.

It is impossible to discard the hypothesis that the present age-equivalence in numerosity estimation is a cohort effect. As found in other domains of cognition, like arithmetic (Geary, Salthouse, et al., 1996), it is possible that age-equivalence found in numerosity estimation stems from older adults' quantification skills having been well-developed at school or practiced during their adults' daily lives. Such practice and/or training effects would yield highly functional numerosity estimation processes in older adults. Using cross-sequential or cross-cultural (such as Geary, Salthouse, et al., 1996, for example) comparisons will enable to determine if this activity is truly age-invariant during adulthood.

The different patterns of eye movements across age groups (i.e., shorter and more numerous fixations together with larger visual scanning of stimuli in older adults) would be consistent with the hypothesis that older adults used different numerosity estimation strategies. Such strategies would enable older adults to compensate age-related declines in numerosity estimation. However, four points suggest that this might not be the case. First, differences in eye movements may result from older adults' reduced useful field of view (e.g., Ball et al., 1988; Scialfa et al., 1987; Sekuler et al., 2000; Watson et al., 2005). By doing more fixations and fixating more shortly than young adults, older adults may have tried to

maximize how much information they could encode in each gaze, a reasonable encoding strategy to adopt given a less efficient visual system. Second, the lack of Age x Numerosity x Size of dots and of Age x Numerosity interactions on eye movements suggest that this age-related difference in encoding strategies reflects more a less efficient visual system than degraded memory representations for numerosities. Indeed, the latter predicts that older adults would have greater difficulties than young adults to do numerosity estimation tasks, especially when quantifying large collections of dots. This was found here in none of our measures. Third, effects of size of dots on older adults' solution times, and lack thereof in young adults, is consistent with an encoding deficit account. Large dots helped older adults to more quickly encode stimuli. Finally, assessments of the specific strategies that young and older participants use on each problem are needed to directly assess the possibility of compensatory mechanisms in older adults.

To conclude, the present study showed that numerosity estimation performance results from participants' using both semantic (e.g., size of numerosities) and physical (e.g., size of dots) features of stimuli and that these two features interact to support people's performance. Moreover, we found no age-related declines in numerosity estimation, above and beyond peripheral encoding differences, suggesting that estimation skills may be one of these rare cognitive domains showing no age-related decline.

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Table 1: Participant's Characteristics

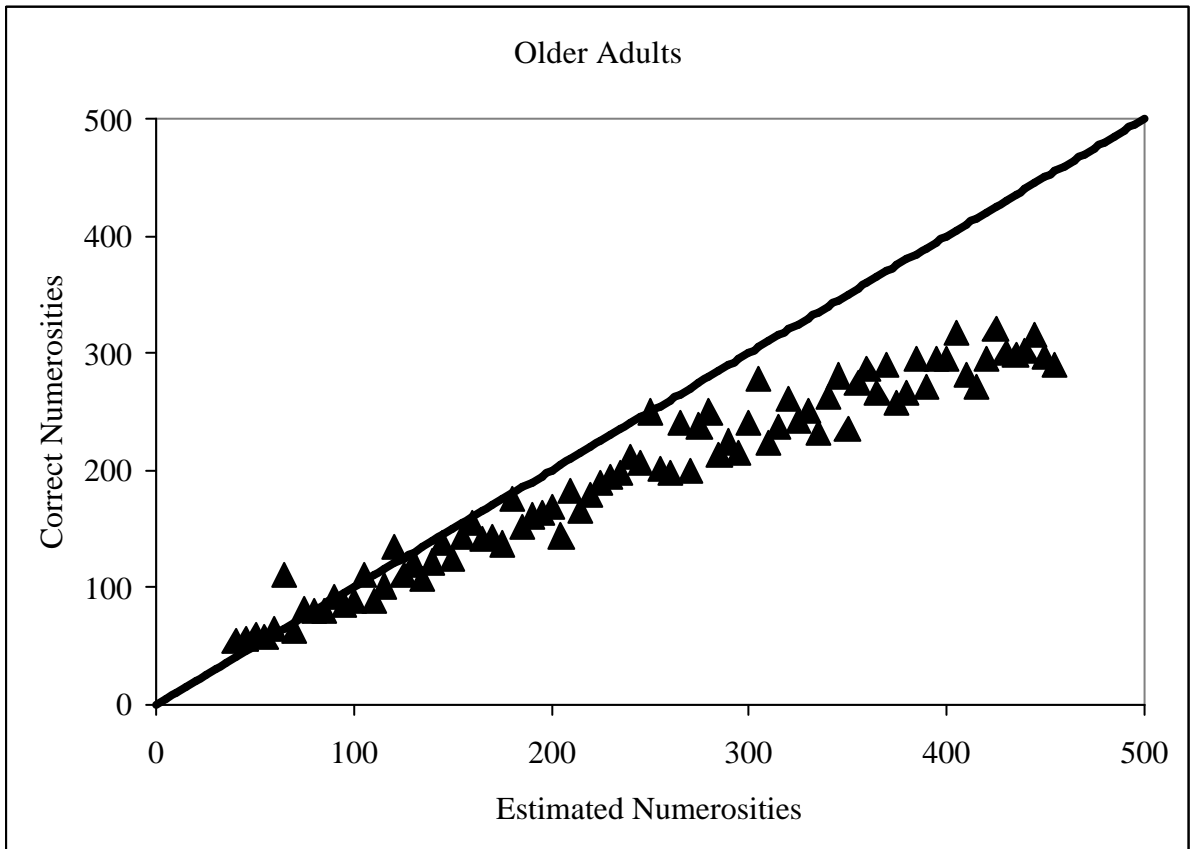
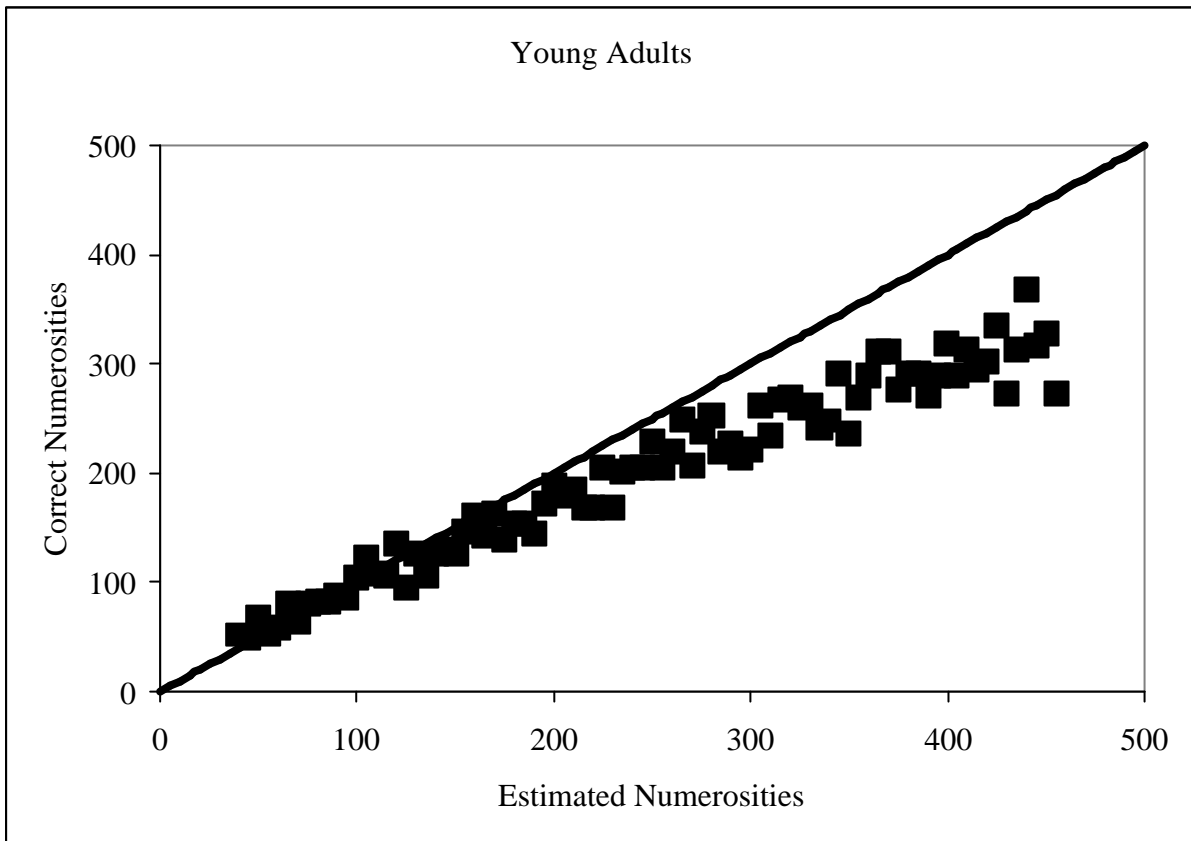
	Young adults	Older adults	<u>F</u>
	<u>Experiment 1</u>		
<u>N</u>	48	48	--
Age	26	73.7	--
Years of education	15	14	0.9
Mean score MHVS	24	26	111.1*
Arithmetic fluency	68	82	259.6*
Mean score MMSE	-	29.1	--
	<u>Experiment 2</u>		
<u>N</u>	27	27	--
Age	25.6	70.9	
Years of education	12.3	13.1	0.89 ns
Mean score MHVS	25.8	26.6	1.64 ns
Arithmetic fluency	72.2	78.1	1.56 ns
Mean score MMSE	--	28.9	--

* $p < .001$;

Table 2: Mean solution times (in ms), percent deviations, number and duration of fixations, dispersion of regard (DOR), and excentricity, in young and older adults as a function of size of dots and numerosity (Expt. 2).

Numerosity x Size of Dots	Solution Times	Percent deviation	Number of Fixations	Durations of Fixations	DOR
<u>Young Adults</u>					
<u>Small Numerosity</u>					
Small dots	3442	20.6	7.3	425	52.6
Large dots	3371	19.2	7.5	409	53.9
<u>Means</u>	3407	19.9	7.4	417	53.2
<u>Large Numerosity</u>					
Small dots	3484	24.0	7.4	421	53.9
Large dots	3623	26.4	7.4	425	51.3
<u>Means</u>	3554	25.2	7.4	423	52.6
<u>Older Adults</u>					
<u>Small Numerosity</u>					
Small dots	4420	22.5	9.1	345	59.5
Large dots	4095	21.5	8.9	342	59.6
<u>Means</u>	4257	22.0	9.0	343	59.6
<u>Large Numerosity</u>					
Small dots	4426	26.6	9.3	338	61.3
Large dots	4452	28.6	9.0	350	58.3
<u>Means</u>	4439	27.6	9.1	344	59.8

Figure 1: Mean estimated numerosities in young and older adults (Expt. 1).



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