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Brief Report

Effects of Distraction on Visual Enumeration in Children and Adults

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Abstract

Speeded enumeration of visual stimuli typically produces a bilinear function, with a shallow subitizing rate (<100 ms/item) up to 3-4 items (subitizing span) and a steeper counting rate (~300 ms/item) thereafter. FINST theory (Trick & Pylyshyn, 1993, 1994) suggests that subitizing of targets is possible in the presence of distractors if attention is not required for target detection, but this has not been tested in children. The present study explored enumeration without distractors (Os alone) and with distractors (Os among Xs) in 35 children aged 6-11 years and 17 adults. Subitizing span increased significantly from childhood to adulthood, and counting rate increased significantly with age. Bilinear functions were significantly better than linear fits to the data for most children and adults both without distractors (97% and 100%, respectively) and with distractors (89% and 94%), consistent with their efficient visual search for a single O among multiple Xs. These findings are discussed in comparison with those from new modeling of earlier enumeration data from young and older adults, revealing striking asymmetries in subitizing with distractors between development and aging.

Keywords: subitizing, counting, development, visual search, distraction, aging

Effects of Distraction on Visual Enumeration in Children and Adults

On encountering several objects, how do people determine their exact number, and do the processes involved change over the course of development? In particular, are these processes differentially affected at various ages by the additional presence of distracting (nontarget) items? The study of visual enumeration in young adults has a long history, dating back at least a century (see Trick & Pylyshyn, 1994, for a summary). This has consistently shown that the time required to enumerate items in the absence of distractors increases monotonically, but not linearly, as the number of items increases. In fact, a bilinear function usually emerges from a plot of response times (RTs) as a function of numerosity, with a discontinuity or flex point at approximately 3-4 items. Before the flex point, RTs increase rather shallowly (typically <100 ms/item) and errors are rare; beyond it, RTs increase steeply with each additional item (~300 ms/item) and errors begin to occur (e.g., Trick & Pylyshyn, 1993). *Subitizing* is the term commonly used to refer to the fast and accurate enumeration of small numbers of items, while *counting* refers to the slower and less accurate enumeration of larger numbers of items (see Kaufman, Lord, Reese, & Volkman, 1949; Mandler & Shebo, 1982; Sagi & Julesz, 1984; Trick & Pylyshyn, 1993, 1994). The flex point or ‘elbow’ of a bilinear function fit to the data can be used to indicate the *subitizing span* (e.g., Watson, Maylor, Allen, & Bruce, 2007).

A number of explanations have been proposed to account for subitization, which include the involvement of a preverbal counting system that is accurate and reliable only for small numbers of items (Gallistel & Gelman, 1992), the use of pattern information as a cue to numerosity (Mandler & Shebo, 1982), and limits of working memory capacity (Klahr, 1973). However, the currently most comprehensive account is that of Trick and Pylyshyn (1993, 1994) who suggested that subitization occurs as a result of the visual system being able to simultaneously tag up to approximately four items that are individuated at a preattentive level of processing (Pylyshyn, 1989). These tags are called FINSTs (for FINgers of INSTantiation) and, according to FINST theory, subitization arises because small numbers of items can be enumerated by assigning FINSTs to them in parallel and then associating the number of bound FINSTs directly with number names. When the number of objects exceeds the number of FINSTs (~4), enumeration then proceeds via a serial process of disengaging and reassigning FINSTs to the remaining items, maintaining a running total, marking items as having been enumerated, and so on. These additional relatively complex operations result in a substantial and linear increase in RTs as numerosity increases. In addition to accounting for subitization (and other findings), there are several reasons why an efficient visual system requires the ability to tag multiple items simultaneously. Examples include the efficient relocation of attention around multiple identical stimuli, the computation of spatial relationships, and the integration of information across saccades (Pylyshyn, 1989, 1998, 2001).

Trick and Pylyshyn (1993) also examined enumeration of targets in the presence of distractors (e.g., enumerate letter Os but ignore other letters). Evidence of subitization was only found when the targets differed from the distractors by the possession of a unique feature (e.g., Os among Xs). When targets required attention for their detection (e.g., Os among Qs), subitization did not occur and enumeration slopes were substantial and linear even for small numbers of targets (see also Watson, Maylor, & Bruce, 2005). This is consistent with the FINST mechanism being located between a preattentive and serial attentive level of processing (Pylyshyn, 1989). Thus FINSTs can only be assigned in parallel to items that are represented and individuated preattentively. According to Trick and Pylyshyn (1994), the ability of the FINST theory to account for such attentional selection effects in enumeration distinguishes it from other accounts of enumeration such as pattern-based theories (e.g., Logan & Zbrodoff, 2003; Mandler & Shebo, 1982).

Enumeration in Children

Young (preverbal) infants appear to be sensitive to numerosity for small (<4) numbers of items but not larger numbers (Starkey & Cooper, 1980, 1995; van Loosbroek & Smitsman, 1990). Early observational studies of children carrying out enumeration tasks (e.g., Beckmann, 1923, as cited and replicated by Bocéréan, Fisher, & Flieller, 2003) described shifts from “counting” to “direct apprehension” with increasing age, suggesting developmental increases in subitizing span. However, the first study to formally measure enumeration RTs in children was by Chi and Klahr (1975) who compared 5-6 year-olds with adults in quantifying random dots. Their children were much slower, with an enumeration slope for 1-3 items of 195 ms/item and for 4-7 items of 1049 ms/item, compared with 46 ms/item and 307 ms/item, respectively, for adults. Similar results were obtained by Svenson and Sjöberg (1978) who tested 7-8 year-olds with 1-9 black dots arranged in a horizontal row. Discontinuities were again noted in the RT-numerosity functions, with a slope for 1-3 items of around 100 ms/item and for 5-7 items of around 1 s/item, both considerably steeper than those produced by adults in earlier investigations.

In a subsequent study (Svenson & Sjöberg, 1983), 7-15 year-old children were tested together with a group of adults. The enumeration slope for 1-3 items decreased monotonically from 7-year-olds to adults from 100 to 30 ms/item and over 5-7 items fell from 1030 to 290 ms/item. The authors used various criteria to estimate subitizing span and concluded that this increased from approximately 3 to 4 items from the youngest children to the adults. Finally, Trick, Enns and Brodeur (1996) used a 2-alternative forced-choice procedure (1 vs. 2, 3 vs. 4, and so on) to examine enumeration in 6-, 8-, 10-, and 22-year-olds. Enumeration slopes for 1-4 items fell monotonically from 185 to 68 ms/item with increasing age, and for 6-9 items fell from 892 to 301 ms/item (see Trick, Audet, & Dales, 2003, for similar findings). In general, developmental studies of enumeration have shown bilinear RT-numerosity functions even in the youngest children. Enumeration slopes within the range of 1-3 or 1-4 items are much steeper in children than in adults, as too are slopes for larger numbers of items.

However, developmental studies of enumeration have tended not to apply formal methods for determining subitizing spans. It is therefore not clear whether children's apparently slower subitizing rates are actually a consequence of reduced subitizing spans. That is, calculating their enumeration rates over *adult* subitizing ranges is not appropriate if the subitizing spans of children and adults differ. Instead, subitizing and counting rates should be determined for each participant based on their individual subitizing spans, which would then allow enumeration rates to be compared across different age groups (see Basak & Verhaeghen, 2003, for similar arguments in the aging literature). This was the first aim of the present study. A second aim was to examine, for the first time to our knowledge, enumeration with and without distractors in children. In addition to the enumeration of Os alone and Os among Xs, there was also a visual search task (search for a single O among multiple Xs). According to FINST theory (Trick & Pylyshyn, 1993, 1994), if target detection is efficient, as indicated by a relatively flat search function, then subitizing should occur both with and without distractors.

Method

Participants

Forty-one children (13 boys; 28 girls) aged 6-11 years and 20 adults (7 males; 13 females) aged 20-23 years participated in the experiment. Two children, one aged 9 and the other aged 11, failed to complete the full set of enumeration trials and the data from a further four children and three adults were lost because of technical issues. The remaining 35 children and 17 adults were divided into four age groups: 6-7 years (*n* = 12; 4 aged 6 and 8 aged 7), 9 years (*n* = 13), 10-11 years (*n* = 10; 6 aged 10 and 4 aged 11), and adults (*n* = 17; *M* = 21.0 years, *SD* = 0.9).

The children were recruited (with no exclusion criteria) from a state primary school in the Greater Manchester area in the UK. Written consent was first obtained from the parents of the children, and verbal consent was obtained from each child once the full procedure and their rights had been explained to them individually. Children were tested in a quiet corridor outside of the classroom and they received a sticker for taking part in the study and a sweet treat of their choice after completing each of the three tasks. The adult volunteers – undergraduate students at the University of Warwick – were also tested individually in quiet areas free from distractions. They provided informed written consent and were fully debriefed after taking part in the experiment (most children declined the offer of debriefing). Ethical approval for the study was obtained from the Department of Psychology's ethics committee.

Apparatus and Stimuli

The experiment was conducted on a Sony Vaio laptop computer with a 1.73-GHz Pentium-M processor and a 17-in. (43.2-cm) widescreen display with a resolution of 1,440 x 900 pixels. The laptop was placed so that the screen was approximately 60 cm away from the participant and 10 cm below eye level. The participant sat directly in front of the screen whereas the experimenter (the third author) sat to one side so that she could not see the displays. Participants' verbal responses were entered into the laptop computer by the experimenter via an external numeric keypad.

The stimuli were black letters (line width of 1 mm) on a white background. Targets (Os) were 8 mm diameter (0.76°) and distractors (Xs) were 7 mm x 6 mm (0.67° x 0.57°). Displays were generated by placing the stimuli randomly into the cells of an invisible 6 x 6 grid (105 x 105 mm, 10° x 10°) with an interelement spacing of 82 pixels (2°). Each item was displaced by ±1-10 pixels both horizontally and vertically to disrupt any perception of a regular grid structure (see Figure 1 for a typical display in one of the enumeration tasks). A black central fixation cross (“+”) of 4 mm x 4 mm (0.38° x 0.38°) preceded each display.

Procedure

After consent was obtained, the tasks were carried out in the following order: enumeration without distractors, enumeration with distractors, and visual search. Participants were instructed to respond as quickly as possible but without sacrificing accuracy. For all three tasks, a response procedure was used that has proved successful with children (Jarrold & Russell, 1999; Svenson & Sjöberg, 1978, 1983), neuropsychological patients (Watson & Humphreys, 1999), and older adults, particularly those with dementia (Maylor, Sheehan, Watson, & Henderson, 2008). This required participants to respond verbally while the experimenter simultaneously pressed the ‘+’ key on the external numeric keypad, which registered their response time (RT).[1] The experimenter then entered the participant’s actual response, again using the keypad. Although the experimenter’s reaction time would add a small delay to participants’ RTs, this would not be expected to vary systematically as a function of numerosity, distractor presence or age group, which were the main factors of interest.

The children’s data were collected prior to the adult data but the children were tested in a random order as far as their ages were concerned. Regression analyses were therefore conducted on RTs to examine the possibility that the experimenter may have speeded up with practice over the course of testing. There was a highly significant contribution to the regression equation from the children’s age but no effect whatsoever from the participant number (the testing order). A similar regression was conducted on the adult data and again there was no contribution at all from the order in which participants were tested. Thus there was no evidence that the experimenter sped up while testing the children, or while testing the adults.

Enumeration Tasks

For enumeration without distractors, each trial comprised a blank screen (500 ms), the central fixation cross (1,000 ms), and finally the display of between 1 and 8 Os,[2] which remained on the screen until the participant responded (see above) by saying aloud how many Os were presented. The next trial began after the experimenter had entered the numeric response.

After an explanation and demonstration of the displays and task requirements, participants completed a practice block of 16 trials (2 for each numerosity), followed by two experimental blocks each of 40 trials (5 for each numerosity), producing 10 replications of each numerosity. Trials within each block were presented in a unique random order. Between blocks of trials, participants could take short rest breaks and then continue when ready.

The enumeration task with distractors was similar except that in addition to 1-8 target Os there were also 19-12 (respectively) X distractors (see Figure 1), making a total of 20 items on every trial. Participants were required to say aloud how many Os were present and to ignore the Xs. Again, there was a 16-trial practice block followed by two 40-trial experimental blocks.

Visual Search Task

The procedure was similar to the enumeration tasks except that participants were required to search displays of 5, 10 or 20 items and to indicate the presence or absence of a single target O among X distractors. The target was present on half of the trials. Participants responded by saying aloud ‘yes’ (target present) or ‘no’ (target absent), which coincided with the experimenter pressing the ‘+’ key on the external keypad followed by the numeral

‘1’ or ‘0’, respectively. There was one practice block of 12 trials (2 for each combination of target present/absent and display size), followed by two experimental blocks each of 36 trials (6 for each combination), providing 12 replications of the six trial types. Trial order within a block was randomized.

Results

In all statistical analyses and modeling of the enumeration data, we followed the usual procedure of excluding the largest numerosity (i.e., 8) to avoid possible contamination by end effects (see Mandler & Shebo, 1982; Trick & Pylyshyn, 1994).[3] For each participant, the percentage error rate and the mean correct RT were calculated separately for each condition in each task. In all analyses of variance (ANOVAs) with a repeated measure, where there was evidence of departure from the sphericity assumption, we report Greenhouse-Geisser corrections.

Enumeration Tasks: Error Rates

An ANOVA was conducted on the percentages of errors with age group (4 levels: 6-7, 9, 10-11, and adults) as a between-subjects factor and distractors (2 levels: no distractors vs. distractors) and numerosity (7 levels: 1-7) as within-subjects factors. There was a significant effect of numerosity, $F(4.0, 193.3) = 12.14$, $MSE = 47.7$, $p < .001$, with overall error rates for numerosities 1-7 of 0.5%, 1.2%, 1.8%, 1.7%, 4.1%, 4.7%, and 5.6%, respectively. On the basis of nonoverlapping 95% confidence intervals (CIs), the error rates for numerosities 1-4 were significantly lower than for 5-7. Overall error rates were similar without (2.9%) and with (2.7%) distractors, $F < 1$, and similar across age groups at 3.3% (6-7), 2.4% (9), 2.1% (10-11), and 3.4% (adults), $F(3, 48) = 1.28$, $MSE = 56.4$, $p = .29$. No interaction approached significance, all F’s < 1.28. In sum, error rates were generally low but did show the expected increase from the subitizing to the counting range of numerosities.

Enumeration Tasks: RTs

Mean correct RTs are shown in Figure 2 for enumeration without distractors (top) and with distractors (bottom). In both cases, and across all age groups, there was the usual pattern of shallower increases in RT with each additional item for smaller numerosities than for larger numerosities. Also RTs decreased with increasing age from 6-7 year-olds to adults, and increased with distractors. In a 4 x 2 x 7 ANOVA (age group, distractors, and numerosity as between-, within- and within-subjects factors, respectively), there was a significant effect of age group, $F(3, 48) = 45.08$, $MSE = 1020827.9$, $p < .001$, with nonoverlapping 95% CIs revealing that 6-7 year-olds ($M = 2317$ ms) were slower than 9 year-olds ($M = 1958$ ms) and 10-11 year-olds ($M = 1809$ ms), who did not differ but were both slower than adults ($M = 1186$ ms). There were also significant effects of distractors, $F(1, 48) = 172.10$, $MSE = 37888.2$, $p < .001$, and numerosity, $F(1.6, 77.1) = 676.76$, $MSE = 374374.5$, $p < .001$, with interactions between age group and distractors, $F(3, 48) = 6.05$, $MSE = 37888.2$, $p < .002$, and between age group and numerosity, $F(4.8, 77.1) = 25.82$, $MSE = 374374.5$, $p < .001$. Thus the overall effect of distractors decreased from the youngest to the oldest children (274, 232, and 132 ms for 6-7, 9, and 10-11 year-olds, respectively; 133 ms for adults), and the difference between numerosities 1 and 7 decreased across age groups (2845, 2142, 1993, and 1135 ms for 6-7 year-olds to adults). There were no other significant interactions: Distractors x Numerosity, $F(3.5, 167.9) = 1.69$, $MSE = 41264.8$, $p = .16$, and Age x Distractors x Numerosity, $F(10.5, 167.9) = 1.51$, $MSE = 41264.8$, $p = .13$.

An unexpected feature of Figure 2 is the unusually slow responses to numerosity 5 in all three groups of children both with and without distractors. The reason for this is unclear (a similar trend appears to be evident in Svenson & Sjöberg’s, 1983, data). However, it can be noted that additional ANOVAs conducted over the traditional subitizing ranges of numerosities 1-3 and 1-4 both produced the same highly significant effects as the full ANOVA. In these cases, the Distractors x Numerosity interactions were also significant, *F*(1.5, 70.3) = 8.57, *MSE* = 7981.4, $p < .01$, and *F*(2.1, 100.7) = 5.38, *MSE* = 12529.1, $p < .01$, for numerosities 1-3 and 1-4, respectively, indicating an increase in the effect of distractors from numerosities 1-4 of 125, 177, 214, and 219 ms, respectively. Finally, an ANOVA over the traditional counting range of numerosities (5-7) produced exactly the same significant effects as the full ANOVA. In all cases, the three-way interaction remained nonsignificant.

Enumeration Tasks: Modeling

Each participant's correct RTs for numerosities 1-7 were subjected to both linear trend analysis and bilinear function fitting. In the latter case, an optimization procedure was employed that minimized the error between the model prediction and observed data by varying the model's 4 free parameters (2 slopes and 2 intercepts). Following optimization, the subitizing span was taken to be the x-axis value corresponding to the bilinear flex point (where the two linear functions meet), which represents the point at which the subitization process was replaced by the slower serial counting process. The slopes of the functions to the left and right of the flex point were taken as the subitizing and counting rates, respectively.

Both linear and bilinear models were found to be good fits to the data across all age groups (see Table 1) but bilinear fits were significantly better than linear fits on one-tailed tests[4] ($p < .1$) for the majority of participants in each age group, both with and without distractors. Without distractors, bilinear fits were significantly better for 11 out of 12 6-7 year-olds, 13 out of 13 9 year-olds, 10 out of 10 10-11 year-olds and 17 out of 17 adults; with distractors, the corresponding numbers were 12 out of 12, 11 out of 13, 8 out of 10 and 16 out of 17. Thus bilinear functions were preferable to linear functions for 97.1% of children and 100% of adults without distractors, and for 88.6% of children and 94.1% of adults with distractors.

Figure 3 displays subitizing spans and Figure 4 displays subitizing and counting rates for those participants whose bilinear fits were significantly better than their linear fits both with and without distractors.[5] ANOVAs were conducted on each of these parameters, with age group (4 levels) as the between-subjects factor and distractors (2 levels) as the within-subjects factor.

For subitizing span, there was a significant effect of age group, $F(3, 42) = 9.25$, $MSE = 0.36$, $p < .001$, with 95% CIs revealing that the three children's groups did not differ amongst themselves but all three differed from adults, with overall subitizing spans of 2.78 for children and 3.45 for adults. There was no effect of distractors, $F < 1$, and no interaction, $F(3, 42) = 1.91$, $MSE = 0.18$, $p = .14$.

For subitizing rate (see top panel of Figure 4), there was a significant overall slowing with distractors from 20 to 53 ms/item, $F(1, 42) = 4.31$, $MSE = 5425.7$, $p < .05$, but there was no effect of age group, $F(3, 42) = 1.56$, $MSE = 6930.9$, $p = .21$, and no interaction, $F < 1$. In contrast, for counting rate (Figure 4; bottom panel), there was a significant effect of age group, $F(3, 42) = 17.23$, $MSE = 36789.1$, $p < .001$, but no effect of distractors, $F < 1$, and no interaction, $F(3, 42) = 2.80$, $MSE = 3550.6$, $p > .05$. From 95% CIs, the counting rates of 9 and 10-11 year-olds did not differ but both age groups were significantly faster than 6-7 year-olds and significantly slower than adults.

Visual Search Task

Searching for a single O among Xs produced few errors (3.9%, 2.6%, 1.8%, and 2.6% of trials for 6-7 year-olds, 9 year-olds, 10-11 year-olds, and adults, respectively) and a 4 x 2 x 3 (age group x target absence/presence x display size) mixed ANOVA revealed no significant effects or interactions (all p's $> .2$).

Mean correct RTs for target absent and present trials as a function of display size are shown in Figure 5 for each of the four age groups. A 4 x 2 x 3 mixed ANOVA revealed a significant effect of age group, *F*(3, 48) = 37.57, *MSE* = 92141.3, $p < .001$, with nonoverlapping 95% CIs revealing that 6-7 year-olds (*M* = 1121 ms) were slower than 10-11 year-olds (*M* = 929 ms), who in turn were slower than adults (*M* = 683 ms); the 9 year-olds (*M* = 1069 ms) differed only from the adults. There were no other main effects or interactions (all *F*'s < 1). As Figure 5 shows, mean RTs in all cases were strikingly flat across increases in display size from 5-20 items, with no overall search slope exceeding 2 ms/item (note that slopes of less than 10 ms/item are typically taken to indicate spatially parallel search).

Discussion

To summarize, performance differences between age groups in the present study were confined to RTs – hence speed-accuracy trade-offs do not complicate interpretation of our main results. As expected, RTs decreased systematically with increasing age from the youngest children to the adults in all three tasks (Cerella & Hale, 1994), and the overall influence of distractors on enumeration RTs decreased with increasing age (cf. Plude, Enns, & Brodeur, 1994; Trick & Enns, 1998). The vast majority of participants in all age groups subitized small numerosities and counted larger numerosities, as evidenced by significantly better bilinear than linear fits to the data, regardless of whether distractors were absent or present. Subitizing span increased significantly from children (2.8 items) to young adults (3.5 items), confirming impressions from some earlier studies. Subitizing rate, however, did not vary with age, although it was significantly slowed by the presence of distractors. In contrast, counting rate improved considerably with increasing age, but was not impaired by distractors. Finally, visual search for a single O among Xs was highly efficient in all age groups.

It is important, first, to appreciate that different conclusions would have been drawn from applying traditional methods of analyzing developmental enumeration data to the present study. Previous studies concluded that both subitizing and counting rates are slower in children than in adults but ‘subitizing’ rates were derived from enumeration slopes over numerosities 1-4 or 1-3. Indeed, in the present study, enumeration slopes without distractors for numerosities 1-4 decreased significantly with increasing age from 230 ms/item (6-7 y), to 219 ms/item (9 y), to 142 ms/item (10-11 y), to 60 ms/item (adults), as did the corresponding slopes for numerosities 1-3 (92, 83, 67, and 24 ms/item). However, formal bilinear modeling revealed no developmental differences in subitizing rates as measured with respect to each individual’s subitizing span. Crucially, there was significant developmental improvement in subitizing span, which could be interpreted as evidence of an increase from children to adults in the number of FINSTs available. This would be consistent with recent data from a multiple-object tracking task (Trick, Jaspers-Fayer, & Sethi, 2005) in which there was an age-related increase in the number of moving objects that could be tracked simultaneously (2 objects for 6-8 year-olds; 3 objects for 10-12 year-olds; 4 objects for 19 year-olds).

The substantial improvement in counting rate from approximately 700 to 300 ms/item is presumably attributable to development and coordination of the complex set of operations involved in enumerating beyond the subitizing range (see Introduction). These are likely to include an increase in working memory capacity (Gathercole, Pickering, Ambridge, & Wearing, 2004; Tuholski, Engle, & Baylis, 2001).

In line with Trick and Pylyshyn’s (1993, 1994) claim that subitizing of targets remains possible in the presence of distractors if attention is not required for target detection (as indicated by efficient search), most children and adults showed significant bilinearity for both standard enumeration and enumeration with single-feature targets. Although subitizing spans and counting rates were not affected by distractors, subitizing rates were significantly slowed, and to the same extent in all age groups. Thus it seems that the presence of distractors can reduce the efficiency of FINST assignment such that, depending on the saliency of the target items, subitizing rate may nevertheless be influenced by distractors even when targets can be detected efficiently (see Watson et al., 2007, for related findings and further discussion).

Finally, it is interesting to compare the present findings with those from similar tasks in a study by Watson, Maylor, and Manson (2002) involving 30 young and 35 older adults (*M* = 21 and 72 years, respectively).[6] Their original analysis followed Trick and Pylyshyn's (1993) procedure to establish the presence or otherwise of subitization, namely, linear trend analysis on each participant's RTs to numerosities 1-8, with a significant deviation from linearity indicative of subitizing. However, it is possible that these deviations may not necessarily have been due to the existence of subitizing-counting bilinearity – indeed deviations from linearity could arise from many different patterns of data. Accordingly here we applied the present modeling methodology (see earlier) and found that bilinear fits were significantly better than linear fits in 97% of both young (29/30) and older (34/35) adults when enumerating Os alone, and in 87% (26/30) of young but only 40% (14/35) of older adults when enumerating Os among Xs, a highly significant difference, $\chi^2(1) = 14.86$, $p < .01$. This new modeling confirms Watson et al.'s original conclusion that older adults' subitizing is especially vulnerable when distractors are present, despite their ability in a visual search task to detect a single O among Xs as efficiently as young adults. Thus there is a clear asymmetry between development and aging in the fate of subitization with single-feature distractors – whereas the majority of both children and young adults continue to subitize at small numerosities, the majority of older adults fail to do so. The 'last in, first out' principle suggests that there are numerous parallels between the processes of child development and adult aging (e.g., Cerella & Hale, 1994; Hommel, Li, & Li, 2004; Plude et al., 1994; Li et al., 2004). However, there are also cases of processes specific to one or other end of the lifespan (e.g., Li, Hämmerer, Müller, Hommel, & Lindenberger, 2009), to which can now be added the present contrast between development and aging in vulnerability of subitizing to distraction.

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Footnotes

[1] Other studies have adopted different techniques. For example, some require participants themselves to press the response key corresponding to their decision (e.g., Sliwinski, 1997), and some require participants to press a single key as soon as they have reached a decision and then enter their choice when prompted (e.g., Maylor, Watson, & Muller, 2005; Watson, Maylor, & Manson, 2002). However, such techniques were considered too cognitively demanding for young children. An obvious alternative would be to employ voice keys (e.g., Nebes, Brady, & Reynolds, 1992) but these can sometimes trigger in response to background noises and fail to trigger in response to the participant's voice onset. Importantly, comparisons between the present adult data and the young adult data from Watson et al. (2002) confirmed that the different response methods produce statistically indistinguishable numerosity functions.

[2] The usual range of 1-9 items was reduced to 1-8 as a result of pilot tests, which indicated that blocks of trials needed to be shorter to maintain the youngest children's concentration.

[3] RTs for the largest numerosity can be artificially lower because participants know that there are no more remaining items to find as compared with the other numerosities. In fact, this may not have been true of all participants in the present experiment judging by occasional responses of ‘9’ and even ‘10’.

[4] Bilinear rather than linear functions were expected on the basis of previous literature, hence the use of one-tailed tests. Note that a qualitatively identical pattern of results emerged from applying two-tailed tests.

[5] The data patterns in Figures 3 and 4 were qualitatively similar when all participants were included.

[6] It should be noted that the present study differed in one potentially important respect from that of Watson et al. (2002), namely, the order of enumeration tasks (without vs. with distractors) was fixed here but was counterbalanced in the earlier study. However, similar aging data were obtained by Maylor et al. (2008, Experiment 2) who employed the same fixed order as the present study.

Table 1

Median R^2 Values for Linear and Bilinear Fits to Participants' Correct RTs (Numerosities 1-7) for Enumeration Without Distractors (Os Alone) and With Distractors (Os Among Xs)

	Os Alone		Os Among Xs	
Age Group	Linear	Bilinear	Linear	Bilinear
6-7 years	.758	.805	.767	.813
9 years	.769	.798	.801	.820
10-11 years	.748	.802	.713	.747
Adult	.701	.783	.674	.736

Figure 1. Example of a stimulus display in the enumeration task with distractors (1-8 randomly positioned Os among 19-12 Xs). (For enumeration without distractors, the 1-8 Os appeared alone.) The visual search display was the same except for the numbers of Os (0/1) and Xs (5/4, 10/9, and 20/19 for display sizes of 5, 10, and 20, respectively).

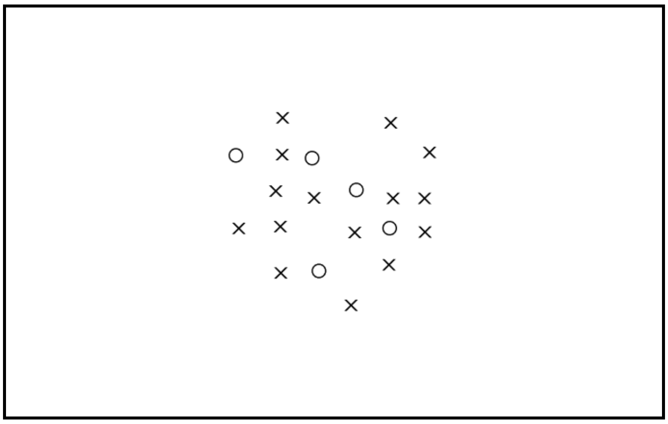

Figure 2. Mean correct response times (RTs) in ms for each age group as a function of numerosity for the enumeration of Os alone (top panel) and Os among Xs (bottom panel).

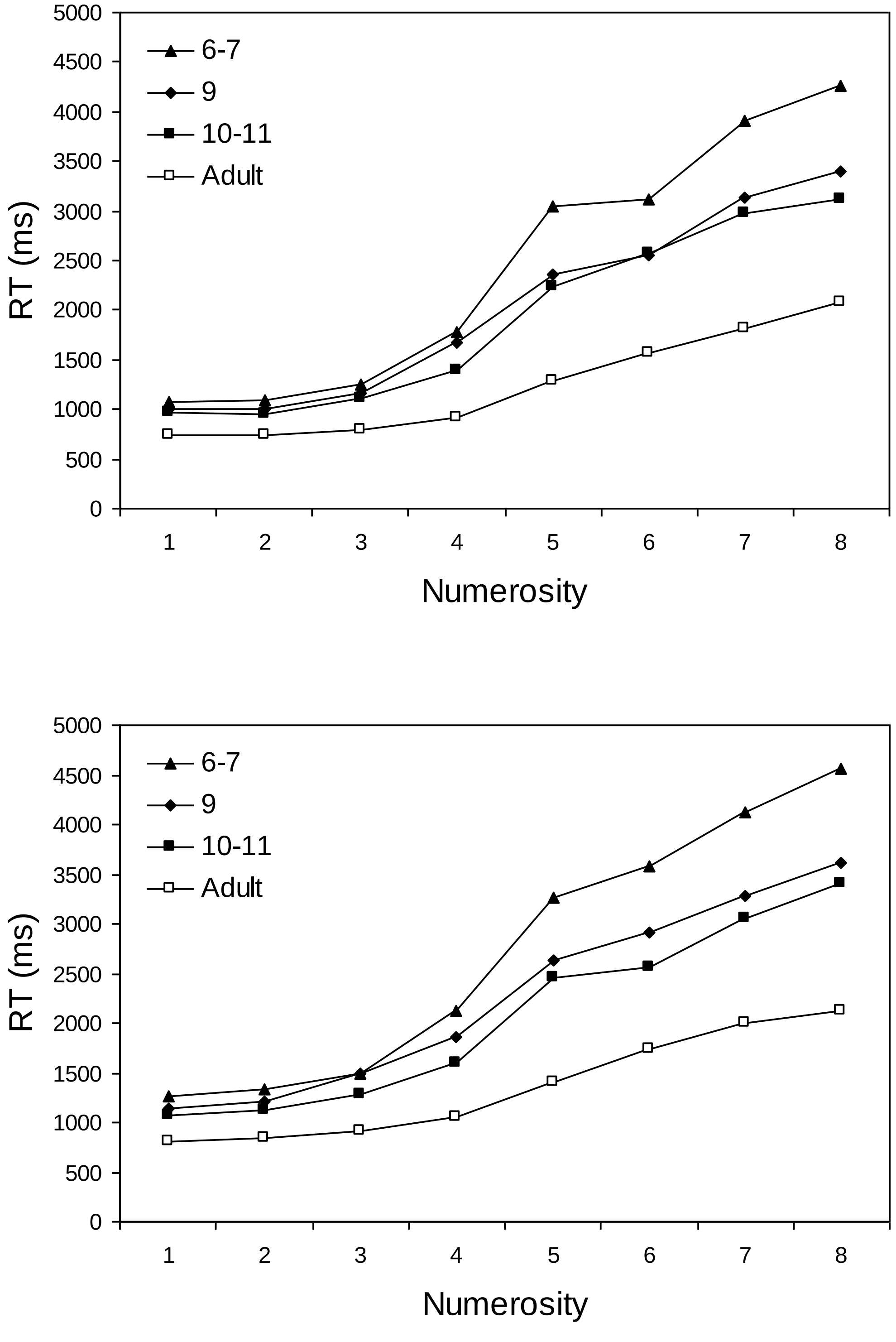

Figure 3. Mean subitizing spans (±1 *SE*) as a function of age group for the enumeration of Os alone and Os among Xs.

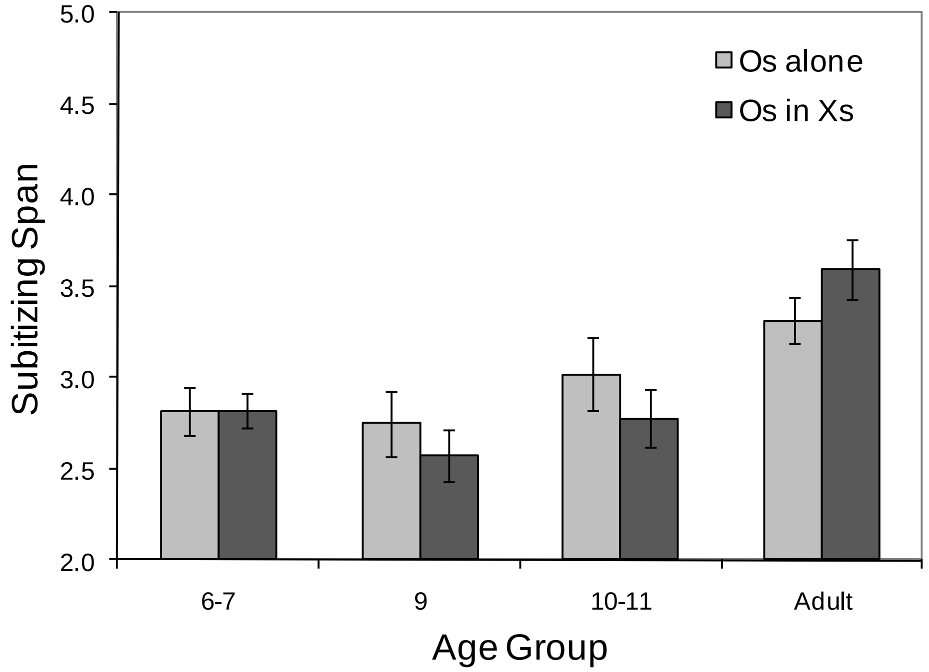

Figure 4. Mean rates (±1 *SE*) in ms/item for subitizing (top panel) and counting (bottom panel) as a function of age group for the enumeration of Os alone and Os among Xs.

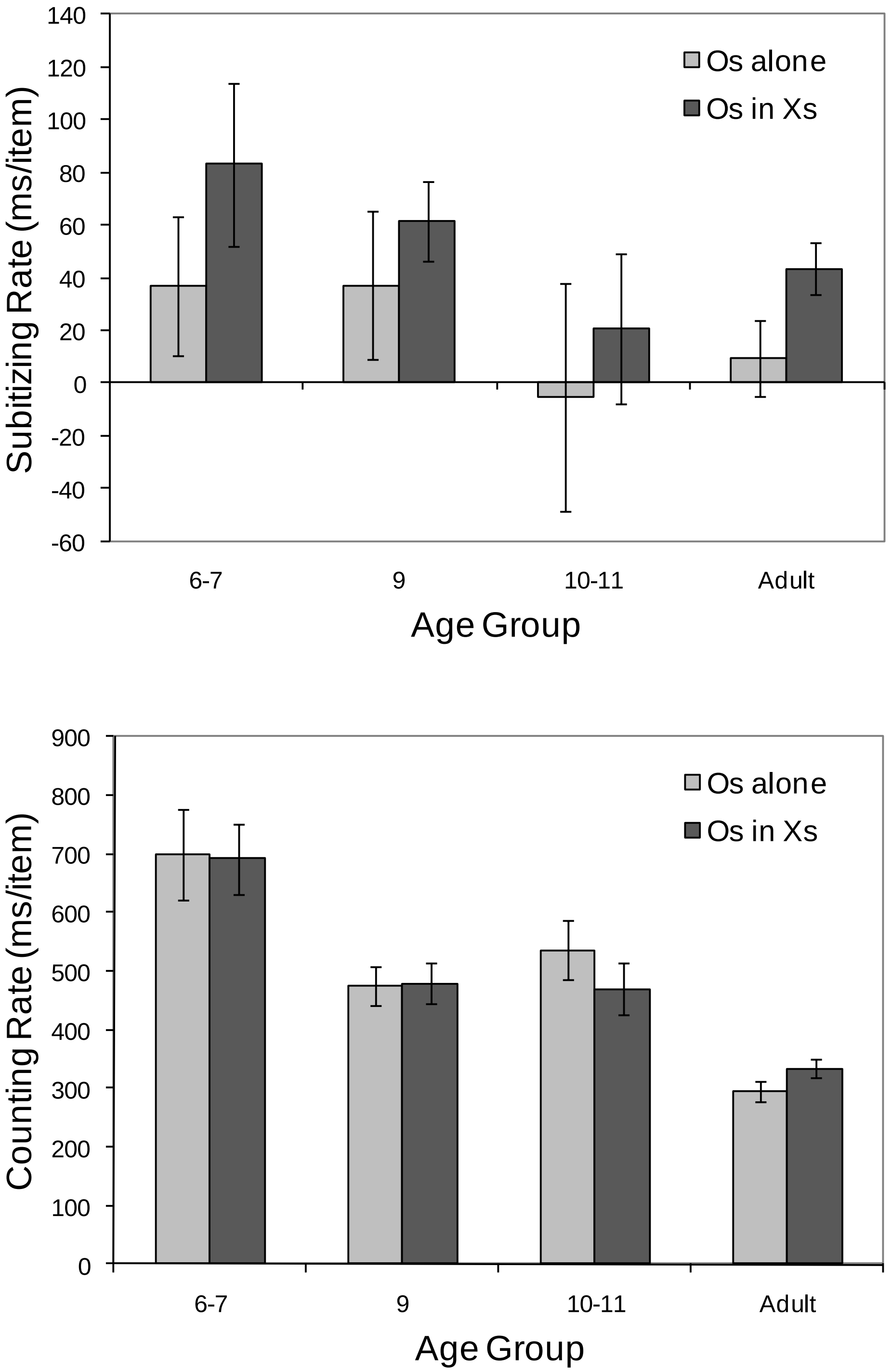

Figure 5. Mean correct response times (RTs) in ms for each age group as a function of display size for the visual search task. Dashed lines represent target absent trials; solid lines represent target present trials.