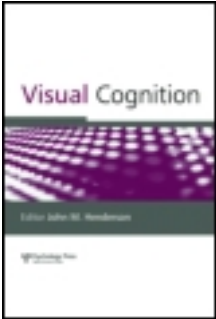


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Publisher: Psychology Press
Informa Ltd Registered in England and Wales Registered Number: 1072954
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UK



Visual Cognition

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/pvis20>

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Available online: 29 May 2012

To cite this article: Andreas Wutz, Alfonso Caramazza & David Melcher (2012): Rapid enumeration within a fraction of a single glance: The role of visible persistence in object individuation capacity, *Visual Cognition*, DOI:10.1080/13506285.2012.686460

To link to this article: <http://dx.doi.org/10.1080/13506285.2012.686460>



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Rapid enumeration within a fraction of a single glance: The role of visible persistence in object individuation capacity

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The number of items that can be individuated at a single glance is limited. Here, we investigate object individuation at a higher temporal resolution, in fractions of a single glance. In two experiments involving object individuation we manipulated the duration of visual persistence of the target items with a forward masking procedure. The number of items as well as their stimulus–onset asynchrony (SOA) to the mask was varied independently. The results showed main effects of numerosity and SOA, as well as an interaction. These effects were not caused by a generic reduction of item visibility by the mask. Instead, the SOA manipulation appeared to fractionate the time to access the sensory image. These findings suggest that the capacity limit of 3–4 items found in object individuation is, at least partially, the consequence of the temporal window of access to sensory information.

Keywords: Capacity; Object individuation; Sensory memory; Subitizing; Visible persistence.

As noted by Spelke, “the organization of the perceived world into units may be a central task of human systems of thought” (1988, p. 229). Extracting objects from sensory input is called object individuation and involves selecting features from a crowded scene, binding them into a unitary representation and individuating this spatiotemporal unit from other individuals in the image

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The research was supported in part by the Italian Ministry of Universities and Research (MIUR) project PRIN 2009 and by the Fondazione Cassa di Risparmio di Trento e Rovereto.

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<http://www.psypress.com/viscog> <http://dx.doi.org/10.1080/13506285.2012.686460>

(Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, 1989; Treisman & Gelade, 1980; Xu & Chun, 2009). It has long been noted that individuation is limited in capacity: We can quickly and effortlessly perceive that there are exactly three items but not that there are exactly 30 items (Jevons, 1871). Whereas enumeration of five or more items has to rely on serial and time-consuming counting or imprecise estimation, smaller numerosities are presumably simultaneously apprehended by a qualitatively distinct mechanism known as “subitizing” (Kaufmann, Lord, Reese, & Volkman, 1949). There are a number of competing theories for why subitizing, and individuation in general, is limited to sets of only about three or four (for review, see Piazza, Fumarola, Chinello, & Melcher, 2011), but it is widely assumed that this limit arises from a uniform process in one instant.

Here we examine what happens at a smaller time scale, *within* a single glance, to critically evaluate the assumption that subitizing is indeed instantaneous. Previous theories of subitizing have attempted to account for spatial or numerical limits (Pylyshyn, 1989; Pylyshyn & Storm, 1988). We consider an alternative hypothesis based on time, in which the effective duration of the stimulus limits the time available to individuate items. A briefly presented visual display has a limited perceptual persistence during which time it may be processed and categorized (Loftus, Duncan, & Gehrig, 1992; Sperling, 1960; Wundt, 1899). Object individuation within a single glance can be viewed, then, as a race for items to be individuated before this window closes. If individuation is time-limited, then a single glance might be too long to reveal the processes underlying rapid enumeration. We test whether the “magic number” is actually a “magic time period” for the individuation of items being held in a rapidly decaying sensory memory. Our experimental goal was to fractionate time into smaller units to watch the unfolding of the object individuation process.

In order to vary the effective duration of the items on the screen, we used a special form of visual masking. Masking can occur when two successive visual stimuli are presented within 100–150 ms from each other, effectively being integrated into a single percept (Di Lollo, 1980; Loftus & Irwin, 1998). Ongoing neural processes still active from the first stimulus can dramatically reduce the visible persistence of the second stimulus, a phenomenon called masking by integration of contours (Di Lollo, 1980). This forward masking manipulation makes it possible to quantitatively change the duration of visual persistence (and iconic memory access) by varying the onset asynchrony between the first and second display. This experimental manipulation provides a means to obtain more fine-grained temporal information about object individuation mechanisms.

To measure object individuation within a fraction of a single glance, we conducted two experiments in which we independently varied stimulus–onset asynchrony (SOA) between the forward mask and the target items, as well as the

number of items. The target items were presented superposed upon the mask and the time course of their visible persistence was altered by the onset asynchrony to the mask display. The first experiment investigated enumeration within and beyond the subitizing range, and the second experiment required participants to identify whether a previously viewed target shape was present among a variable number of shapes. Both experiments shared the selection and individuation of discrete entities from a crowded scene, differing only in later processing stages. As the same masking procedure was used in both experiments, any similarities in the results between the experiments can be ascribed to the effects of this manipulation on object individuation in isolation from additional mechanisms.

Since enumeration performance is affected by item visibility, with a uniform effect within the subitizing range (Palomares & Egeth, 2010; Palomares, Smith, Pitts, & Carter, 2011), we also ran a control condition in order to disentangle the effects of the mask on temporal processing from its more generic effect on item visibility. We report that reducing the effective persistence of the items, unlike other methods that simply reduce item visibility in general, leads to a specific effect within the subitizing range that is consistent with our hypothesis that capacity limits are caused, at least in part, by temporal limits on the individuation process.

METHOD

Subjects

Fourteen observers participated in the enumeration (13 female, mean age $M = 22.5$ years, $SD = 3.9$ years) and the identification experiment on visible persistence (nine female, $M = 23.9$ years, $SD = 9.1$ years). There were eight participants in the control experiment on item visibility (three female, $M = 29.1$ years, $SD = 2.0$ years). All participants provided informed consent, as approved by the institutional ethics committee, took part in exchange for course credits, and had normal or corrected-to-normal vision.

Stimuli and apparatus

The experiments were run on a HP Intel Quad core computer using MATLAB 7.9 (MathWorks, Natick, MA) and Psychophysics Toolbox Version 3 (Brainard, 1997; Pelli, 1997). Participants were seated in a dimly lit room, approximately 50 cm from a 19-inch Mitsubishi monitor (1600 × 1200 resolution) running at 85 Hz. On each trial a different pattern of 200 randomly oriented, partially crossing black lines (luminance: 0.07 cd/m²; mean line length = 1.2° visual angle, $SD = 0.24^\circ$; mean line width = 0.12°, $SD = 0.04^\circ$; mean size of whole pattern = 18° vertically × 10° horizontally) was presented centred on a white background (luminance:

99.93 cd/m²; Figure 1). This pattern remained on the screen and then after a variable onset delay a variable number of items (1–4 or 6) appeared which were linearly superposed upon the random line pattern by use of the image processing technique “alpha blending”. In the experimental trials the random line pattern was always presented with the same alpha-blending values as the target display and with full contrast. There was no contrast difference between mask and target displays; therefore, the target display

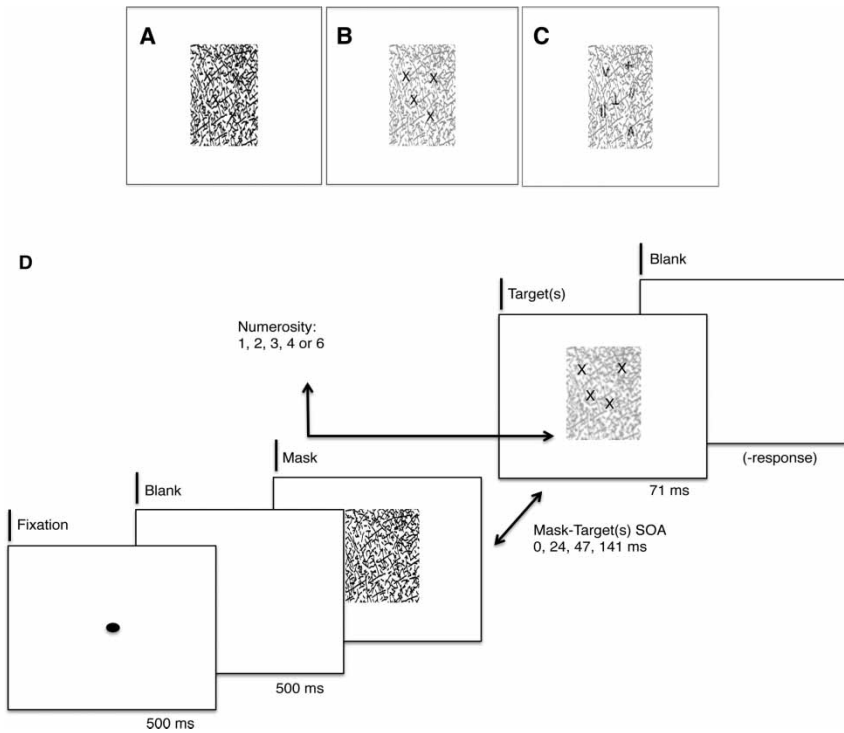


Figure 1. Illustration of the mask and target stimuli used in the experiments (Panels A–C) and of one trial in the enumeration experiment with the manipulation of SOA (Panel D). (A) Display with random line pattern and target letters “X” superposed upon it. Note that the target items are virtually invisible when presented simultaneously with the random line pattern. (B) The same display shown in the left panel but with the random line pattern shown 60% transparent for illustrative reasons. (C) Example of the two-line drawings used as targets, superimposed on the random line patterns shown here at 60% transparency. In the experiments on visible persistence, the random line patterns were always shown at full contrast, as shown in Panel A. Mask contrast was an independently varied factor in the control experiment on item visibility. (D) Illustration of one trial in the enumeration experiment with the manipulation of SOA. Throughout the trials, the two independent factors target numerosity (1, 2, 3, 4, or 6) and mask–target(s) SOA (0, 24, 47, or 141 ms) were varied. The targets superposed upon the masking pattern (here shown 60% transparent for illustrative reasons) were always presented for 71 ms, followed by a blank screen until the subject’s response.

intensity was relatively low. As also the presentation time was quite brief (71 ms), afterimages may have played a negligible role for these kinds of visual stimuli (Di Lollo, 1980). In the enumeration experiment and its control the letter “X” was used as targets (Figure 1A and 1B). In the identification experiment a variable number of 12 possible two-line drawings (i.e., cross, two parallel lines) was presented, of which one was previously defined as the to-be-identified shape (Figure 1C). All items were coloured in black, were 1.6° of visual angle in height and 1.28° in width, and were placed randomly on one of 16 possible locations within an invisible, central rectangle of 8.8° vertical and 7.52° horizontal eccentricity with a minimum buffer of 0.8° between the locations.

Procedure

Enumeration with variable mask–item(s) SOA. All subjects received verbal and written instructions about the task and completed 15 practice trials, in which the random line pattern was made 80% transparent by multiplying its alpha channels by a factor of 0.8. Each trial began with a central fixation dot (black, 0.4°) on a white background for 500 ms, followed by a white blank screen for another 500 ms. Then the random line pattern was presented for one of four durations, in order to control the SOA between the onset of the mask and the item(s). There were four different SOAs: 0 ms (common onset), 24, 47, or 141 ms. The target display, in which the item(s) to be enumerated were superposed upon the masking pattern, was always presented for the same brief duration of 71 ms. This target display was immediately followed by a white screen until the participant’s response, which was recorded by pressing the corresponding number on a keyboard (Figure 1D). Although reaction time was recorded, the analyses focused on the proportion of correct trials to avoid any potential effects of participants searching for the correct number key. Our approach is consistent with previous studies, which have measured correct performance while directly manipulating the presentation time of the stimulus, rather than depending on reaction time in order to avoid potential confounds at the response level (McElree & Carrasco, 1999; Reed, 1973). The participants were instructed that one to eight items could be presented, whereas only one to four or six items were actually shown. This manipulation was required in order to prevent a response bias to always report the highest possible numerosity when in doubt, as might have been expected given that the mask contained a large number of elements. Both the behavioural data and an explicit question after the experiment verified that none of the subjects was aware that there had been no displays with five, seven, or eight items. The experiment consisted of eight blocks of 60 trials. Each of the 20 possible combinations of

mask–item(s) SOA and target numerosity was shown three times per block in random order. The experiment lasted approximately 45 min.

Enumeration with variable mask contrast. A control experiment was conducted to disentangle the impact of the temporal duration of visible persistence from the masking effect on item visibility in general. Instead of varying stimulus onset of the mask relative to the target display, both were presented simultaneously for 71 ms with varying mask contrast. Prior to calculating the contrast values as different proportions along the RGB range, the monitor's luminance in the given settings had been calibrated and gamma corrected. In order to arrive at comparable performance levels between the experiments, the contrast values of the mask were chosen based on pilot studies to be 100%, 40%, 30%, and 0% contrast. The condition with 0 ms SOA in the first experiment was identical to the condition with 100% mask contrast in the control experiment. Given the five different numerosity levels, there were 20 possible factorial combinations presented within a block. Eight blocks of 60 trials were run. The control experiment lasted around 40 min.

Identification with variable mask–item(s) SOA. The procedure for the identification task was the same as in the enumeration experiment except for the following changes. First, a target shape was shown centrally at the beginning of the trial for 500 ms, followed by a 500 ms white blank screen. The task on each trial was to state whether or not the target shape was one of the items presented in the subsequent display. The target shape was present on 50% of the trials. Participants responded by pressing a key corresponding to target absent or present. Based on the results of the enumeration experiment, and taking account of the additional requirement of identification in this task, the mask–item(s) SOAs were slightly changed with respect to the first experiment to be fit within the range of 24 to 200 ms. Within one block every combination of the three factors—SOA (24, 47, 71, 200 ms), set size (1–4 or 6), and target presence (present/absent)—was shown three times and in random order. Experiment 2 comprised eight blocks of 120 trials and lasted approximately 90 min.

Data analysis

As the study was designed to investigate object individuation within the subitizing range, data for numerosities from one to four items were fed into a two-way (Masking level \times Number) within-subject analysis of variance (ANOVA) for all reported experiments. The residuals of all reported variables were normally distributed as shown by a Kolmogorov-Smirnov test. In case sphericity for the given factor was not tenable, F -ratios have been adjusted

with a Greenhouse-Geisser correction. To further investigate interactions between the two factors, post hoc *t*-tests between performance at each numerosity (1–4) and a baseline condition (see later) were conducted (*p*-values Bonferroni-corrected). Due to technical difficulties, reaction time data for the enumeration experiment with variable mask–item(s) SOA were available for only 12 of the 14 subjects.

RESULTS

Enumeration with variable mask–item(s) SOA

In contrast to previous studies showing good enumeration performance up to about four items, the masking manipulation used here led to a dramatic effect on proportion correct (Pc) and reaction times (RT) even within the subitizing range (Figure 2A and 2B; see also Figure S2 in the online Supplementary Material). This effect is confirmed by a within-subjects ANOVA on the accuracy and the reaction times, which revealed main effects of SOA [Pc: $F(3, 39) = 198.9$, $p < .001$, $\eta_p^2 = .939$; RT: $F(1.7, 18.7) = 33.7$, $p < .001$, $\eta_p^2 = .754$] and item numerosity [Pc: $F(3, 39) = 14.5$, $p < .001$, $\eta_p^2 = .526$; RT: $F(1.6, 17.9) = 29.9$, $p < .001$, $\eta_p^2 = .731$], as well as an ordinal interaction between these two factors [Pc: $F(9, 117) = 5.1$, $p < .001$, $\eta_p^2 = .283$; RT: $F(3, 33.5) = 7.4$, $p < .001$, $\eta_p^2 = .402$]. As expected, enumeration accuracy increased and reaction times generally decreased for smaller item numerosities and longer SOA. As subitizing capacity can vary between three and four items across participants, a similar ANOVA with a subitizing range of up to three items was calculated and comparable results were obtained (see Table S1 in the online Supplementary Material).

Visual inspection of Figure 2A and 2B confirms a qualitative difference in performance between small and large numerosities (Kaufman et al., 1949; Piazza et al., 2011). Accuracy meliorated less for six items (39.6% increase) compared to four (64.5%) and reaction times for six items increased with longer SOAs. However, the different SOA conditions affected enumeration differently even for small numerosities within the subitizing range. To better understand these differences, average performance for one to four items at each SOA was used as a baseline condition (BL) for subsequent paired comparisons. The mean proportion of correct trials across numerosities is the expected value given stochastic independence of the probability of a correct response and the specific number of items within the subitizing range (for a definition of stochastic independence, see Pearson, 1900). In other words, within the subitizing range the probability of a correct response should not depend upon the specific number of items shown on the screen—indeed, the equality of accuracy and RTs within the subitizing range has been the defining aspect of the concept of subitizing. Any deviations from this

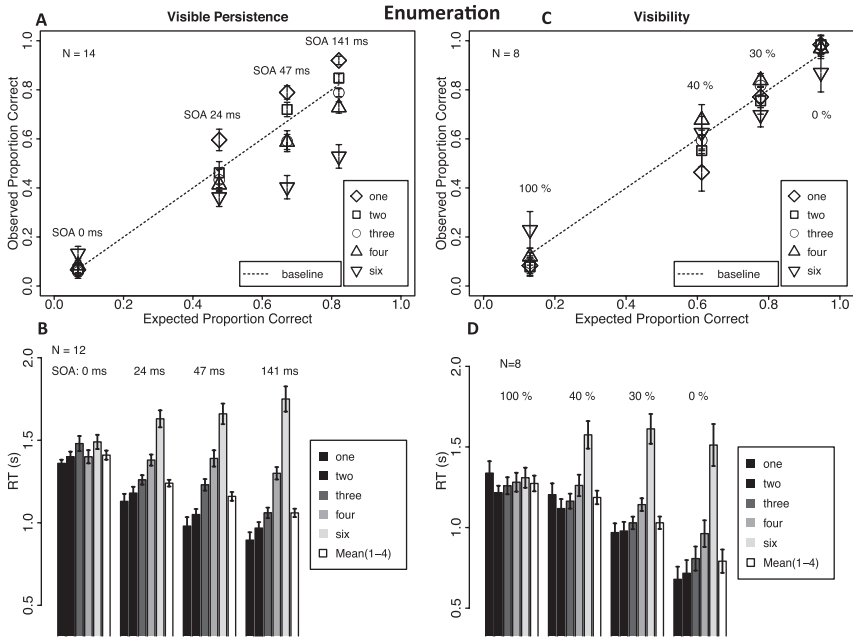


Figure 2. Results of the enumeration experiments with the manipulation of SOA (Panels A and B) and mask contrast (Panels C and D). (A) Observed proportion as a function of expected proportion of correct trials, given stochastic independence of the probability of a correct response and numerosity within the subitizing range at every level of mask–item(s) SOA for different item numerosities. (B) Reaction times at each mask–item(s) SOA for different item numerosities and for the average reaction time within numerosity one to four. (C) Observed proportion as a function of expected proportion of correct trials, given stochastic independence of the probability of a correct response and numerosity within the subitizing range at every level of mask contrast for different item numerosities. (D) Reaction times at each mask contrast for different item numerosities and for the average reaction time within numerosity one to four. Vertical deviations from the dashed lines indicate differences between observed and expected values. Error bars display 1 standard error of the mean for within-subject designs (Loftus & Masson, 1994).

value of stochastic independence between numerosity and response are indicative of an effect of SOA.

The forward mask was effective at limiting the effective duration of the target stimulus. In the case of 0 ms SOA, enumeration accuracy did not exceed expected performance at chance level (12.5% correct) for all item numerosities (min = 6%, max = 13% correct), one-tailed $t_s(13) < 0.3$, $d_s < 0.09$, and reaction times were generally quite high. Behavioural performance therefore indicates a high level of uncertainty within the observers, confirming the phenomenological experience that targets were virtually invisible when the mask and the item(s) were presented simultaneously.

As SOA increased to 24 ms, accuracy improved for all item numerosities within the subitizing range ($M = 47.6\%$), but most strongly for one-item displays (59.6%). Only accuracy for one item was higher than the baseline, $t(13) = 4.2$, $p < .005$, $d = 1.1$, whereas the other numerosity levels (two, three, and four items) showed no significant difference, $\text{abs } t(13)s < 1.9$, $\text{abs } ds < 0.5$. Reaction times for one item were significantly lower than the baseline, $t(11) = -3.1$, $p < .05$, $d = -0.9$. Overall, these results show that the small increase in SOA affected object individuation most strongly for one-item displays. In other words, at the 24 ms SOA the assumption of stochastic independence of target set size, within the subitizing range, was violated.

For a mask-item(s) SOA of 47 ms, one-item and, marginally significant, two-item displays (showing a 26% increase compared to the 24 ms SOA) were more accurately enumerated than the baseline: Two vs. BL, $t(13) = 2.6$, $p < .095$, $d = 0.7$. Reaction time data revealed the same pattern of results: One and two items yielded faster reaction times compared to the baseline average, both $ts(11) < -4.3$, $p < .005$, both $ds < -1.2$. These results suggest that there was a particular benefit in enumeration for one- and two-item displays with the 47 ms SOA condition.

At the longest SOA tested, performance for three-item displays finally approached the baseline level. Accuracy and reaction times for four-item displays were still significantly worse than the baseline [Pc: $t(13) = -4.9$, $p < .001$, $d = -1.3$; RT: $t(11) = 5.5$, $p < .001$, $d = 1.6$]. Therefore, at the 141 ms SOA there was an additional improvement in performance for the three-item displays.

The role of temporal effects of masking versus a general reduction in visibility

As described earlier (see introduction and Methods), a control condition varying mask contrast was used to distinguish between time constraints on enumeration and a more general effect of reduced visibility. The pattern of results (Figure 2C and 2D; see also Figure S3 in the online Supplementary Material) shows that reducing item visibility per se had a quite different effect on enumeration compared to those reported above with variable mask-item(s) SOA. One particularly obvious difference between the two conditions is shown by greater accuracy for large numerosities (six items) in the contrast control task when the mask contrast was high. Good performance for six items reflects a bias towards reporting higher responses under this condition, perhaps due to confusing the mask with the target. This finding is interesting because it shows that better performance for small numerosities in the main experiment, described earlier, was not due to a

tendency to guess a small number when visibility was poor. When the mask was not presented at all (0% contrast), accuracy was equally high for all set sizes within the subitizing range. In addition, RTs showed a clear qualitative distinction between small and large numerosities, even though the slope was not completely flat within the subitizing range (Figure 2C and 2D). Therefore the observed enumeration performance with these stimuli in this unmasked condition fits well into the existing literature (see Folk, Egeth, & Kwak, 1988; Mandler & Shebo, 1982).

Reducing mask contrast from 100 to 30% led to an increase in enumeration accuracy, $F(1.2, 8.6) = 89.2, p < .001, \eta_p^2 = .927$, and decrease in reaction times, $F(2, 14) = 9.0, p < .005, \eta_p^2 = .564$, within the subitizing range (Figure 2C and 2D). Furthermore, for both accuracy and reaction times, a main effect of numerosity was observable [Pc: $F(3, 21) = 4.5, p < .02, \eta_p^2 = .393$; RT: $F(3, 21) = 4.3, p < .02, \eta_p^2 = .381$]. As the pattern of this effect, however, is quite the opposite for these two measures (Figure 2C and 2D), enumeration performance cannot really be distinguished within the subitizing range with respect to a possible speed–accuracy tradeoff. Most importantly, the two factors (mask contrast and item numerosity) within the subitizing range, did not interact [Pc: $F(6, 42) = 1.9, p > .1, \eta_p^2 = .210$; RT: $F(2.5, 17.3) = 1.4, p > .2, \eta_p^2 = .166$] (Figure 2C and D). Thus, the overall trend showing that manipulating item visibility in general had a uniform effect across small item numerosities was consistent with previous studies (Palomares & Egeth, 2010; Palomares et al., 2011). These results suggest that the effect of masking on enumeration observed in the first experiment is not simply due to alterations in item visibility in general but to constraints on the temporal aspects of visual processing, namely the time course of visible persistence of the to be enumerated items.

Identification

In the first experiment, object individuation was operationalized by enumeration. Of course, enumeration is a complex task. Therefore, it was useful to include a second task, which shared the first two stages of processing (selection and individuation) with Experiment 1 but differed in later stages. Thus, the second experiment isolated individuation from the “numerical cognition” aspects of enumeration and added an additional identification component.

Despite the difference in tasks, the overall trend was remarkably similar. Both reaction times and the proportion of correct trials (which includes hits and correct rejections) were significantly altered by mask–item(s) SOA [Pc: $F(3, 39) = 47.7, p < .001, \eta_p^2 = .786$; RT: $F(1.6, 21.2) = 14.2, p < .001, \eta_p^2 = .521$] and set size [Pc: $F(3, 39) = 30.7, p < .001, \eta_p^2 = .702$; RT: $F(3, 39) = 29.0, p < .001, \eta_p^2 = .690$]. An interaction was found between

SOA and set size for the accuracy measure [Pc: $F(9, 117) = 3.6, p < .002, \eta_p^2 = .215$] (Figure 3). Again, post hoc t -tests between each numerosity from one to four and their mean at every level of SOA were conducted to highlight the pattern of interactions of the masking manipulation within the subitizing range (Figure 3; see also Figure S4 in the online Supplementary Material).

Accuracy for a single item was higher than baseline performance at the 24 ms SOA, $t(13) = 3.3, p < .025, d = 0.9$, but this was found only for the single item condition, $abs\ t(13)s < 1.9, abs\ ds < 0.5$. This confirms the particular benefit in the individuation of one item with a very short SOA found in the enumeration task (Experiment 1). With 47 ms and 71 ms SOA, accuracy for one- and two-item displays were significantly above the baseline average, all $ts(13) > 2.9, p < .05, all\ ds > 0.75$. Reaction times for one item were faster than the baseline for both SOAs, both $ts(13) < -3.8, p < .01, both\ ds < -1.0$. The striking difference in identification accuracy for two-item displays compared to baseline performance suggests that, as in the enumeration experiment, there was a shift in the number of items preferentially processed.

Accuracy and reaction times for three-item displays converged towards baseline performance only at the longest SOA (200 ms). Identification for four items remained less accurate (74.3%), $t(13) = -5.7, p < .001, d = -1.5$, and slower (0.87 s), $t(13) = 5.3, p < .001, d = 1.4$, than baseline. As the performance measures for larger set sizes (4 and 6) seem to saturate, this pattern of results suggests an increase in capacity as a function of SOA with a limit of around three items. It is important to note that the persistent one item benefit in

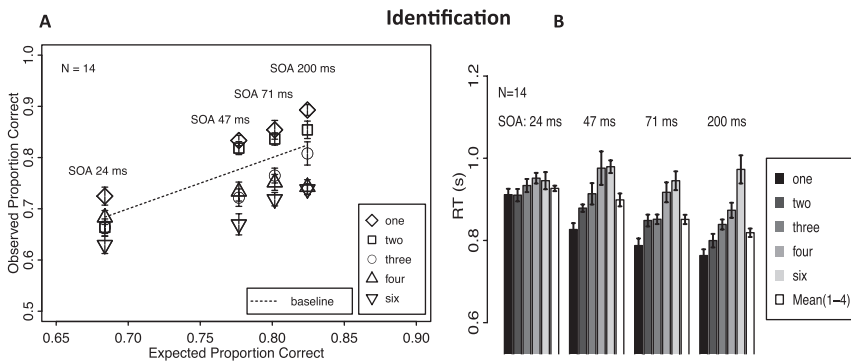


Figure 3. Results of the identification experiment with the manipulation of SOA. (A) Observed proportion as a function of expected proportion of correct trials, given stochastic independence of the probability of a correct response and set size within the subitizing range at every level of mask-item(s) SOA for different item set sizes. (B) Reaction times at each mask-item(s) SOA for different item set sizes and for the average reaction time within set sizes one to four. Vertical deviations from the dashed line indicate differences between observed and expected values. Error bars display one standard error of the mean for within-subject designs (Loftus & Masson, 1994).

enumeration was also found with a binary (present/absent) response. This finding strongly argues against the possibility that a tendency to report the ordinal extremes (one or eight items) completely explains the results of the first experiment (see also Figure S5 in the online Supplementary Material for response matrices at each SOA). Moreover, a table showing reaction times and accuracy for each experiment is included in the online supplementary materials (Tables S6–S8).

DISCUSSION

The main finding was that the masking procedure affected performance within the subitizing range. This effect was observable in two tasks that both required object individuation but differed in response selection. Thus, it is likely that masking interacted with the individuation of multiple objects and not with subsequent response-limited processes. Furthermore, this effect was not caused by generic alterations in item visibility, as shown by the control condition of the first experiment. Instead, the manipulation of the SOA appeared to temporally fractionate the effective persistence of the visual image and this limited the capacity of object individuation. Thus, theories that try to explain the “magical number four” by a limit in a simultaneous process may undersample its timescale. We suggest that a more thorough analysis of the temporal dynamics of individuation might help to explain capacity limitations.

It is important to note that the effect of mask–target(s) SOA cannot be explained by an improvement in the visual system’s readiness to process temporally trailing displays. Di Lollo (1980) showed that presenting a mask with a variable SOA, but also changing the mask configuration simultaneously with target display onset disrupted performance regardless of SOA. Based on that earlier result we can exclude attentional precueing as a major determinant of the current pattern of findings.

Although we focus here on rapid individuation, rather than memory, for objects, previous studies of visual working memory have also reported an effect of time (Gegenfurtner & Sperling, 1993; Vogel, Woodman, & Luck, 2006). In those earlier studies, a backward mask was used to limit the display duration of multiple items in a visual working memory paradigm. Our study differs in several ways. First, we focus on rapid individuation, rather than consolidation of already individuated items into memory. Our task does not require subjects to remember the identity of multiple items, only the numerosity of multiple items or the identity of a single item. Second, we examined the first tens of milliseconds of visual processing, whereas the earlier studies—which were interested in higher cognitive aspects of working memory—focused on mental processes happening after 100 ms. In other words, the earlier studies

investigated what happened after the glance, whereas we explored the unfolding of object individuation within the glance.

Here, we examined object individuation as a process in which multiple objects race to emerge from a complex scene as unique, individual objects, within a very short window of time. However, in interpreting a time-limited process it is important to acknowledge the mathematical complexity of determining whether unobservable processes are parallel or serial, based on input–output relationships or its statistics (Townsend, 1971). The finding that subitizing is not purely instantaneous, but *evolves within a single glance*, could be accounted for by either a serial or parallel mechanism. Vanishing access to sensory information could limit the time to serially repeat a number of actions. A theoretical implementation of such a serial mechanism to extract information from a visual scene was proposed by Ullman (1984). Elemental operations, like shifting the processing focus or indexing a salient item, are combined into sequences or *visual routines* to allow real-time execution of computationally complex tasks, like enumeration. The subitizing phenomenon therefore may reflect the cardinal number of such a *visual routine* applied upon the sensory image during the time of its persistence.

On the other hand, the duration of sensory memory could constrain a parallel process that converges into a correct percept above a specific intensity threshold: “[T]he greater the number of objects to which our consciousness is simultaneously extended, the smaller is the intensity with which it is able to consider each” (Hamilton, 1859, p. 164). It is therefore reasonable that the time required for a temporally evolving, parallel process to reach threshold depends on the number of items it processes. Processing intensity in visual neurons can be modulated by attention (Moran & Desimone, 1985). Given that subitizing has been demonstrated to require attention (Egeth, Leonard, & Palomares, 2008; Olivers & Watson, 2008), the computational speed of object individuation in parallel may be a function of the degree to which attentional resources have to be shared among multiple items. Increasing attentional load, e.g., by increasing target-distractor similarity (Watson, Maylor, Allen, & Bruce, 2007) or adding an attention demanding dual task (Olivers & Watson, 2008), might slow down the core individuation process to an extent that the read-out of information cannot be accomplished within the time in which the sensory input is available to the mechanism at work. In these situations, one might expect that the observers rely on counting or estimation mechanisms even for small numbers of items, instead of specialized subitizing, which is in general accordance with recent findings (Burr, Turi, & Anobile, 2010). Our results are consistent with, but go beyond, recent evidence for a role of attention in subitizing by providing testable hypotheses for how and when attention might limit subitizing performance.

In a similar way, competitive interactions between potential protoobjects in a type of saliency map could explain numerosity-dependent processing rates for a parallel mechanism. When there is only one salient object, the protoobject would emerge *in a fraction of a single glance*. Competition among multiple items may require more time to converge into a stable percept both at the stage of individuation and at the level of memory (Dempere-Marco, Melcher, & Deco, 2011). Subitizing, therefore, might be explained if the duration of the decay of sensory information was on average equal to the time necessary to process four items in parallel.

If sensory input is available indefinitely to the observer, e.g., under unlimited viewing conditions, a new cycle of read-out of information can be initiated after the initial glance, in order to refresh the initial sensory image. One example is “counting”, a process that is generally considered to require multiple perceptual steps and the use of saccadic eye movements (Kowler & Steinman, 1977). When the sensory image contains more informational units than those individuated during the “initial glance”, an increase in both reaction times and eye movement frequencies for item numerosities above the subitizing range would be expected (Watson, Maylor, & Bruce, 2007).

Independent of the processing mechanism—serial or parallel—the present results show that object individuation is not a temporally uniform process across the subitizing range. We suggest that capacity limits in individuation are caused, at least in part, by temporal constraints on the underlying mechanism. The rate of temporal processing for individuation would likely depend on the stimuli used and on the individual subject. The analysis of the temporal dynamics of object individuation evolving in *fractions of a single glance* might therefore lead to an explanation of subitizing as revealing a “magical time period”, rather than a “magical number”.

SUPPLEMENTARY MATERIAL

Supplementary material for this paper is available online at <http://dx.doi.org/10.1080/13506285.2012.686460>.

REFERENCES

- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.
- Burr, D. C., Turi, M., & Anobile, G. (2010). Subitizing but not estimation of numerosity requires attentional resources. *Journal of Vision*, *10*(6), 1–10. doi:10.1167/10.6.20
- Dempere-Marco, L., Melcher, D., & Deco, G. (2011). A computational study of visual working memory capacity in the presence of saliency effects. *BMC Neuroscience*, *12*(1), 64. doi:10.1186/1471-2202-12-S1-P64
- Di Lollo, V. (1980). Temporal integration in visual memory. *Journal of Experimental Psychology: General*, *109*, 75–97. doi:10.1037/0096-3445.109.1.75

- Egeth, H. E., Leonard, C. J., & Palomares, M. (2008). The role of attention in subitizing: Is the magical number 1? *Visual Cognition*, *16*(4), 463–473. doi:10.1080/13506280801937939
- Folk, C. L., Egeth, H., & Kwak, H. (1988). Subitizing: Direct apprehension or serial processing? *Perception and Psychophysics*, *44*, 313–320.
- Gegenfurtner, K. R., & Sperling, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance*, *19*(4), 845–866. doi:10.1037/0096-1523.19.4.845
- Hamilton, W. (1859). Lectures on metaphysics and logic. In H. L. Mansel & J. Veitch (Eds.), *Metaphysics* (Vol. 1). Boston, MA: Gould & Lincoln.
- Jevons, W. S. (1871). The power of numerical discrimination. *Nature*, *3*, 363–372. doi:10.1038/003281a0
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*, 174–219. doi:10.1016/0010-0285(92)90007-0
- Kaufman, E. L., Lord, M. W., Reese, T., & Volkman, J. (1949). The discrimination of visual number. *American Journal of Psychology*, *62*, 496–525. doi:10.2307/1418556
- Kowler, E., & Steinman, R. M. (1977). The role of small saccades in counting. *Vision Research*, *17*, 141–146.
- Loftus, G. R., Duncan, J., & Gehrig, P. (1992). On the time course of perceptual information that results from a brief visual presentation. *Journal of Experimental Psychology: Human Performance and Perception*, *18*, 530–549. doi:10.1037/0096-1523.18.2.530
- Loftus, G. R., & Irwin, D. E. (1998). On the relations among different measures of visible and informational persistence. *Cognitive Psychology*, *35*, 135–199. doi:10.1006/cogp.1998.0678
- Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin and Review*, *1*, 476–490.
- Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General*, *111*, 1–22. doi:10.1037/0096-3445.111.1.1
- McElree, B., & Carrasco, M. (1999). The temporal dynamics of visual search: Evidence for parallel processing in feature and conjunction searches. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1517–1539. doi:10.1037/0096-1523.25.6.1517
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, *229*, 782–784. doi:10.1126/science.4023713
- Olivers, C. N. L., & Watson, D. G. (2008). Subitizing requires attention. *Visual Cognition*, *16*(4), 439–462. doi:10.1080/13506280701825861
- Palomares, M., & Egeth, H. (2010). How element visibility affects visual enumeration. *Vision Research*, *50*(19), 2000–2007. doi:10.1016/j.visres.2010.07.011
- Palomares, M., Smith, P. R., Pitts, C. H., & Carter, B. M. (2011). The effect of viewing eccentricity on enumeration. *PLoS ONE*, *6*(6), e20779. doi:10.1371/journal.pone.0020779
- Pearson, K. (1900). On the criterion that a given system of derivations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *50*(5), 57–175.
- Pelli, D. G. (1997). The VideoToolbox software for visual psycho-physics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.
- Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition*, *121*(1), 147–153. doi:10.1016/j.cognition.2011.05.007
- Pylyshyn, Z. W. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial index model. *Cognition*, *32*, 65–97. doi:10.1016/0010-0277(89)90014-0
- Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, *3*, 179–197. doi:10.1163/156856888X00122

- Reed, A. V. (1973). Speed-accuracy trade-off in recognition Memory. *Science*, *181*(4099), 574–576. doi:10.1126/science.181.4099.574
- Spelke, E. (1988). Where perceiving ends and thinking begins: The apprehension of objects in infancy. In A. Yonas (Ed.), *Perceptual development in infancy* (pp. 197–234). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11), 1–29. doi:10.1037/h0093759
- Townsend, J. T. (1971). A note on the identifiability of parallel and serial processes. *Perception and Psychophysics*, *10*(3), 161–163. doi:10.3758/BF03205778
- Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97–136. doi:10.1016/0010-0285(80)90005-5
- Ullman, S. (1984). Visual routines. *Cognition*, *18*, 97–159. doi:10.1016/0010-0277(84)90023-4
- Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(6), 1436–1451. doi:10.1037/0096-1523.32.6.1436
- Watson, D. G., Maylor, E. A., Allen, G. E. J., & Bruce, L. A. M. (2007). Early visual tagging: Effects of target-distractor similarity and old age on search, subitization, and counting. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(3), 549–569. doi:10.1037/0096-1523.33.3.549
- Watson, D. G., Maylor, E. A., & Bruce, L. A. M. (2007). The role of eye movements in subitizing and counting. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(6), 1389–1399. doi:10.1037/0096-1523.33.6.1389
- Wundt, W. (1899). Zur Kritik tachistoskopischer Versuche. *Philosophische Studien*, *15*, 287–317.
- Xu, Y., & Chun, M. M. (2009). Selecting and perceiving multiple visual objects. *Trends in Cognitive Sciences*, *13*(4), 167–174. doi:10.1016/j.tics.2009.01.008

Manuscript received January 2012

Manuscript accepted April 2012

First published online May 2012