ARTICLE IN PRESS

Cognition xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Rapid parallel semantic processing of numbers without awareness

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ARTICLE INFO

Article history:
Received 21 May 2010
Revised 10 March 2011
Accepted 25 March 2011
Available online xxxx

Keywords:
Summary statistics
Ensemble coding
Subliminal priming
Numerical cognition

ABSTRACT

In this study, we investigate whether multiple digits can be processed at a semantic level without awareness, either serially or in parallel. In two experiments, we presented participants with two successive sets of four simultaneous Arabic digits. The first set was masked and served as a subliminal prime for the second, visible target set. According to the instructions, participants had to extract from the target set either the mean or the sum of the digits, and to compare it with a reference value. Results showed that participants applied the requested instruction to the entire set of digits that was presented below the threshold of conscious perception, because their magnitudes jointly affected the participant's decision. Indeed, response decision could be accurately modeled as a sigmoid logistic function that pooled together the evidence provided by the four targets and, with lower weights, the four primes. In less than 800 ms, participants successfully approximated the addition and mean tasks, although they tended to overweight the large numbers, particularly in the sum task. These findings extend previous observations on ensemble coding by showing that set statistics can be extracted from abstract symbolic stimuli rather than low-level perceptual stimuli, and that an ensemble code can be represented without awareness.

1. Introduction

Given the huge amount of sensory information arising from visual perception, a question of great interest concerns how the human brain manages to selectively extract the relevant pieces of information and encode the "gist" of the scene. The visual system appears to be organized as a massive parallel system which processes many elements non-consciously at the same time. Only late in the process do one or very few objects or parameters gain access to conscious processing and slow serial scrutiny.

In particular, the visual system appears to possess cognitive mechanisms capable of representing a set of similar stimuli by means of coding only their overall statistical properties (summary or set statistic, also referred to as "ensemble coding"). For example, when participants are presented a set of spots with different sizes, they can accurately categorize the mean size of the set as smaller or larger than a test spot (Ariely, 2001). Similarly, discriminating the speed of dot stimuli which contain many different speeds is done by integrating the different speeds, producing an average global speed (Watamaniuk & Duchon, 1992).

Besides representing the average size (e.g., Ariely, 2001; Chong & Treisman, 2003), or speed (Watamaniuk & Duchon, 1992), the visual system can also represent other statistics like the average position of dots (Alvarez & Oliva, 2008), or the mean spatial frequency and orientation of stimuli (e.g., Alvarez & Oliva, 2009; Dakin & Watt, 1997). Furthermore, in a series of studies, Haberman and colleagues recently suggested that ensemble coding is not limited to low-level visual parameters. In their experiments

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doi:10.1016/j.cognition.2011.03.005

participants automatically extracted the average emotion or gender from a set of faces (Haberman & Whitney, 2007, 2009; Haberman, Harp, & Whitney, 2009).

Obviously, for ensemble coding to be beneficial for processing visual information it needs to be highly efficient and automatic. In a recent study, attention to a set of stimuli was reduced by presenting them as a background, irrelevant for the experimental task. While participants were following the trajectory of dots on the screen, Gabor patches with different orientations on the background formed a spatial pattern. In a subsequent test phase, participants were able to match the spatial layout of the unattended background to a test stimulus indicating that the ensemble code of the spatial frequency and orientation was represented in the visual system (Alvarez & Oliva, 2009). In another study, the automatic extraction of ensemble coding was demonstrated using a priming paradigm. Here, the presentation of a set of spots on the screen increased the visibility of a single test spot if the mean size of the set of spots corresponded to the size of the test spot (Marchant & de Fockert, 2009). The representation of ensemble codes thus appears to be computed automatically and in parallel at a preattentive stage (Chong & Treisman, 2005).

In sum, statistical information can be extracted from a visual scene, and this can be done with reduced attention (for an alternative view see Myczek & Simons, 2008). The scope of these findings remains, however, largely unexplored. For example, to what extent can summary statistics be represented for more complex stimuli? Although low-level cues were distorted when participants were averaging faces (e.g., Haberman & Whitney, 2007) in this experiment, the potential contribution of feature-based information to the mean extraction might have been underestimated. Indeed, it is unclear how the recognition of gender or emotional expressions can occur without low-level cues.

In the present work, we investigate the possibility of ensemble coding for abstract yet highly familiar symbolic stimuli: Arabic numbers. The relation between the perceptual features of an Arabic digit and its magnitude is completely arbitrary. There have been many demonstrations of fast, subliminal encoding of the magnitude of a single Arabic digit (e.g., Dehaene et al., 1998; Van Opstal, Reynvoet, & Verguts, 2005). Demonstrating the representation of a set statistic for Arabic numerals would definitely prove that statistics extraction goes beyond the mere extraction of early visual parameters.

A second point that deserves further investigation is the relation between ensemble coding and conscious perception. Previous results demonstrating that ensemble coding can proceed with reduced or little attention lead us to formulate the hypothesis that awareness might be an unnecessary condition for ensemble coding. One way to clarify this is to study the effect of the ensemble code indirectly, and to present the set of stimuli subliminally, i.e. below the threshold of conscious perception. If the statistic of an ensemble that is subliminally presented affects a subsequent decision this would unequivocally demonstrate that ensemble coding can occur entirely outside of conscious intention.

The use of subliminally presented symbolic stimuli further allows us to investigate the relation between consciousness and parallel and serial processing. Earlier work found that information coming from an unattended stimulus can build up in parallel with information from an attended stimulus (Posner & Snyder, 1975). In a dichotic listening task, for example, a word presented on the unattended ear can elicit a galvanic skin response the same size as when it is presented in the attended ear (Von Wright, Anderson, & Stenman, 1975). The unattended word is processed in parallel with the attended word without the participants' awareness. On the other hand, the processing of a target stimulus that is presented during a rapid serial visual presentation impairs the processing of a subsequent stimulus, and makes it inaccessible for conscious awareness (the attentional blink; Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). Dual-stage models of conscious access (e.g., Chun and Potter, 1995; Sergent, Baillet, & Dehaene, 2005) propose that this is caused because of a capacity limitation of central processing. According to the theory of the global neuronal workspace (Baars, 1988, 2002; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Dehaene, Kerzberg, & Changeux, 1998), multiple parallel processors can operate non-consciously, but the serial execution of multiple cognitive operations requires conscious access. This hypothesis was recently tested in a study where two successive operations had to be performed on a subliminal or supraliminal number. When the input number was subliminal, it was shown that participants could perform each individual operation better than chance, but were unable to perform the two operations serially in close succession without conscious access (Sackur & Dehaene, 2009). Translated to the present context, this would mean that the integration of multiple items into a serial computation should be impossible for subliminally presented stimuli. Only ensemble statistics that can rely on the parallel extraction of information should be extracted subliminally.

In the present case, we investigate the possibility that addition and averaging dissociate with respect to subliminal priming. Addition of several Arabic numbers, at least when performed in an exact, arithmetically rigorous manner, seems to be a typically serial and controlled process where one number is added to another number, and the next number is then added to this sum, etc. Approximate averaging, on the other hand, essentially amounts to finding the typical value of a set, and could be accomplished by a parallel process where all magnitudes are simultaneously weighted and their votes used to converge to a single attractor value on the internal number line, representing the entire set. Indeed, the above examples of ensemble coding with non-symbolic stimuli indicate that finding the mean of some parameter in a set can be done in a fast parallel manner.

Several factors might however mitigate the proposed dissociation between serial addition and parallel averaging. Summing and averaging are similar operations, and in the experiments below, they amount to performing exactly the same task, with the sole difference lying in the instructions given to subjects. Furthermore, human participants appear to have a capacity for fast approximate calculation, including addition, which may bypass serial symbolic processing (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; El Yagoubi, Lemaire, & Besson, 2003). When participants are trained in approximate calculation, performance generalizes without cost to neighboring addition problems and to problems present in a second language (Dehaene et al., 1999; Spelke & Tsivkin, 2001). These results could indicate that approximate addition might rely on intuitive parallel computations, and indeed there is evidence for subliminal addition of just two digits (Lefevre, Bisanz, & Mrkonjic, 1988; Sackur & Dehaene, 2009). From a computational point of view, it has been proposed that a neuron's activity is determined by the weighted sum of different parallel input signals (McCullough & Pitts, 1943) suggesting that the neuronal architecture of the brain permits parallel addition. Conversely, it could be argued that averaging is composed of two serial calculation steps, summing and dividing – in which case we would expect averaging to be impossible under subliminal conditions. Given these uncertainties about the computational processes underlying addition and averaging, the present experiments were exploratory in nature and merely examined if these tasks would dissociate under subliminal conditions.

To address these points empirically, a numerical subliminal priming experiment was designed in which participants were presented with a target display consisting of four Arabic digits (the target set). Different groups of participants were explicitly asked to extract either the mean or the sum of the digits and to compare it to a reference value (five for the mean task, and 20 for the sum task; note that with four target digits, these tasks are formally identical). Unbeknownst to the participants, a prime display, sandwiched between two mask displays, presented four additional digit primes unrelated to the targets, shortly before the target display (the prime set). The automatic extraction of an ensemble code for symbolic stimuli could thus be investigated by looking at the influence of the four-digit prime display on the responses to the four-digit target display.

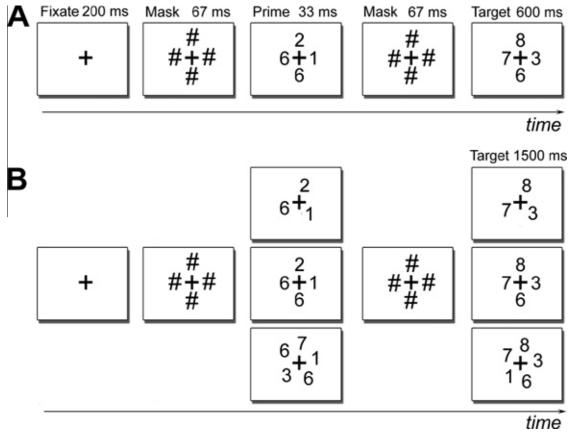

Fig. 1. Design of the experiments. In Experiment 1 (A), the prime and target set always consisted of four digits. In Experiment 2 (B), only 60% of the trials had a prime and target set of four digits. The remaining 40% were equally divided in trials with a prime and target set of three or five stimuli. The number of stimuli in the prime and target set were always the same.

2. Experiment 1

2.1. Method

2.1.1. Participants

22 university students (one male, aged between 18–21) took part in the experiment for course credits. None of the participants was aware of the purpose of the experiment.

2.1.2. Apparatus and stimuli

A 60 Hz monitor was used with stimulus presentation synchronized to the refresh rate (16.7 ms). Key presses were registered with a response box. Each trial was announced by a fixation cross (500 ms) followed by the presentation of a premask (67 ms), a prime display (33 ms), a postmask (67 ms), and a target display. The target display remained on the screen for 600 ms during which the subjects had to respond (see Fig. 1A). This response deadline was imposed in order to motivate the participants to perform very fast calculations, and therefore to prevent the possible decay of an effect of the prime before a response was given. If participants responded too slowly (i.e., after 600 ms) a feedback display (1500 ms) was presented, instructing them to respond faster. The intertrial interval was 200 ms. As in Haberman and Whitney (2007) the set comprised four stimuli. Prime and target displays thus consisted of four numbers randomly selected from the range 1–9 (except number 5). The randomization was constrained so that the mean of the numbers of the target or prime set was smaller than four or larger than six. Primes and targets were presented around a fixation cross (above, below, left from, and right from fixation). All characters were presented in black on a white background in Courier New font. Each digit had a height of 8 mm (0.75 visual degrees), and a width of 6 mm (0.57 visual degrees). The distance from the center of fixation cross to the center of every digit was 1.05 visual degrees.

2.1.3. Procedure

Participants were assigned either to the sum task or to the mean task Both tasks were strictly equivalent formally, and only differed in the instructions. In the sum task, participants were instructed to classify the sum of the target set as larger or smaller than 20. In the mean task, participants had to classify the mean of the target set as smaller or larger than five. The experiment started with a short training session of eight trials. After the training session, participants were presented with six blocks with the possibility of a short break after every block. Each block contained 120 experimental trials. Mapping of response hands was counterbalanced within each participant: After the third block, a new instruction screen appeared in which they were instructed to change response hand mappings. When the response mapping was changed, a new training session was presented to habituate to the new instructions. The order of response hand mapping was counterbalanced within each task. Twelve subjects were assigned to the sum task, 10 to the mean task. The main experiment was followed by a forced choice reaction task to evaluate prime visibility. The procedure of this task was identical to the main experiment, except that the response was to the prime rather than to the target set.

2.2. Results

Trials with reaction times below 200 ms were discarded from further analyses. The upper limit for reaction times was 600 ms (i.e. the response deadline). In a first analysis, the effect of prime-target congruency in the different tasks and the presence of a distance effect were investigated. To this end, we grouped trials according to the distance of the mean target numbers to the number they had to be compared to (i.e. number 5, henceforth called 'the standard'), which could fall into three categories (a) 1 to <2; (b) 2 to <3 and (c) 3 to <4. A 2 (Congruency) $\times$ 2 (Task: Mean or Sum) $\times$ 3 (Distance: 1, 2, or 3) ANOVA with Task as a between participants factor to the mean reaction times of the correct trials, revealed a main effect of distance, $F(2, 40) = 19.14$, $p < .0001$, $MSE = 386$: Reaction times were slower for small distances (470, 457, and 444 ms for distances 1–3 respectively). There was also a main effect of congruency, $F(1, 20) = 86.47$, $p < .0001$, $MSE = 275$, with faster reaction times on congruent (443 ms) compared to incongruent trials (470 ms). There was also a significant interaction between task and congruency, $F(1, 20) = 4.81$, $MSE = 275$, $p = .04$. Planned comparisons revealed a significant congruency effect in both the sum and mean task (both p's < .0001), with a larger effect in the sum task (440 versus 473 ms for congruent and incongruent trials respectively in the sum task, a 33 ms effect; and 446 versus 467 ms for congruent and incongruent trials in the mean task, a 21 ms effect). The same analysis on the error rates revealed a main effect of distance, $F(2, 40) = 156.78$, $MSE = 13.30$, $p < .0001$ (24%, 14%, and 10% for distances 1–3 respectively), and a main effect of congruency, $F(1, 20) = 27.08$, $MSE = 30.33$, $p < .0001$ (22.4% versus 18.0% errors for the incongruent and congruent trials respectively).

For a finer analysis of how the participants' decision varied with the size of the prime and target numbers, we modeled responses using a logistic regression with response (larger = 1, smaller = 0) as the dependent variable (y), and distance of the mean target numbers to five as predictor (x). For this analysis, trials were binned according to distance to the standard, ranging from -3.75 to -1.25 and from 1.25 to 3.75 in steps of .25 (because of the small number of trials with distance 4 and -4 they were excluded from further analysis). The logistic equation is

$$y = 1/(1 + e^{-z}), \quad \text{with} \quad z = (\beta_0 + \beta_1 x) \qquad (1)$$

In this equation, β_0 defines the location of the intercept of the sigmoid, i.e. the amount of bias for one response over the other, while β_1 reflects the size of the effect of target distance on responses.

As seen in Fig. 2, participants' performance closely tracked the mean value of the target numbers. Thus, the logistic equation provided an excellent fit to the responses overall (mean McFadden's pseudo-R^2 = .33) as well as within each group of subjects (.33 and .32 for the mean and sum task respectively). We then investigated the influence of the mean size of the prime set on the logistic shape of responses to the visible targets. Thus, we ran the logistic regression separately for trials with a small prime set (mean of the primes <5) and trials with a large prime set. As can be seen in Fig. 2, the regression curve was shifted to the left for the trials with a large prime set, indicating that an increasing proportion of "large" responses are given when the target is preceded by a large prime set compared to when it is preceded by a small prime set. In other words, with small primes, there are more 'smaller than' responses compared to large primes; with large primes, there are more "larger than" responses compared to small primes. The prime is thus influencing the response in the direction of its magnitude. In the graph (Fig. 2) this priming effect is reflected in a rightward shift of the sigmoid response curve for small versus large primes. In the regression model, this shift is determined by the value of the fitted parameter β_0. By comparing the value of this parameter for small primes and large primes we can thus investigate the effect of the prime on the response. Results from our regression analysis showed that this leftward shift in curves induced a significant difference between the β_0 for small and large prime sets, $F(1, 20) = 26.63$, $p < .001$, $MSE = .033$. No main effect or interaction with task was found. No difference was observed for β_1, $F(1, 20) = 1.70$, $p = .22$, $MSE = .017$, indicating that targets were equally weighted on congruent and incongruent trials. Finally, no effects of task were found. Overall, these results indicate that the subliminal priming induced a pure additive bias to the logistic regression, and was not associated with a change in sensitivity to target distance.

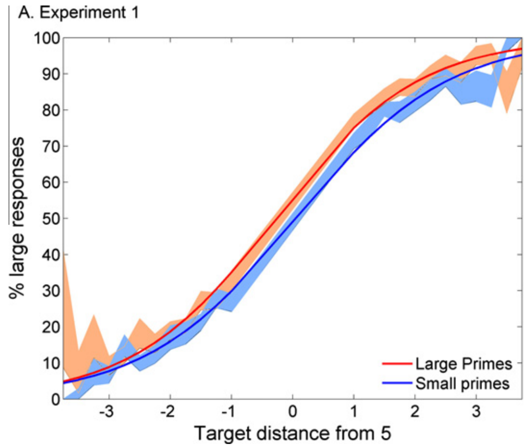

Fig. 2. Observed data from Experiment 1 and fit by the logistic model. A significant leftward shift can be observed for trials with large primes (red line), indicating more 'larger than' responses in these trials compared to trials with small primes (blue line). The shaded areas denote the observed data (mean ± squared error of the mean). The solid sigmoid curves are the fitted data using Eq. (1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In a second step, we investigated the influence of each individual prime and target number on the response. We therefore first studied the effect of the position of the primes and targets on the screen. Again, betas were obtained by performing a logistic regression on the exper-

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imental trials of each subject separately with response (smaller/larger) as dependent variable, and the four primes (numbers x_1–x_4) and four targets (numbers x_5–x_8) ordered according to their position on the screen (above, left, right, below) as dependent variables.

$$y = 1/(1+e^{-z}), \quad \text{with} \quad z = (\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_8 x_8) \qquad (2)$$

The individual beta values for the primes and targets (β_1–β_8) were entered in a 2 (Task: Mean/Sum) × 2 (Stimulus: Prime/Target) × 4 (Position: Above, Left from, Right from, or Below fixation) repeated measures ANOVA with Task as a between-subjects factor and Stimulus and Position as within-subject factors. Results revealed a main effect of Stimulus, $F(1,20) = 74.31$, $p < .0001$, $MSE = .034$, and of Position, $F(3,60) = 41.40$, $p < .0001$, $MSE = .006$, and a significant interaction between Stimulus and Position, $F(3,60) = 32.56$, $p < .0001$, $MSE = .005$. There was no effect or interaction involving the factor Task. Post hoc comparisons revealed that the betas for the visible target stimuli were higher than those for the invisible primes (respectively 0.27 versus 0.03). The contribution was highest for the target presented on the left side of the fixation cross, followed by the target on the right side of the fixation cross, then those above and below fixation respectively (betas of 0.25, 0.16, 0.12, and 0.07 for the four positions respectively), suggesting an influence of Western reading direction (from left to right, from top to bottom). All the beta values for the primes differed from 0, except for the beta of the prime presented just below fixation ($p = .50$). Although the beta values for the prime stimuli were not significantly different from each other, a correlation analysis showed a significant correlation between the pattern of betas for the four target locations and the four prime locations ($r = .29$, $p = .048$), suggesting that the spatial pattern of the betas for the primes was similar to the pattern observed for the targets. All the beta values from this analysis are presented in Fig. 3A.

The above analysis demonstrates that the location of the primes on the screen plays an important role on the overall decision. Another factor that might influence the weight of the primes on the decision is the magnitude of the primes. It could be that primes only weigh on the decision when they have very small or very large numerical values like 1 or 9. To evaluate this possibility, we also studied the effect of the value of the primes and targets, irrespective of their position on the screen. We therefore rank ordered the primes and targets according to their numerical value for every trial. We then reapplied the logistic regression Eq. (2), where x_1 now corresponds to the smallest value of the four primes, x_2 the next larger one, and so on, with x_4 corresponding to the largest value of the four primes (and similarly for x_5 to x_8 in the target display). The beta values were entered in a 2 (Task: Mean/Sum) × 2 (Stimulus: Prime/Target) × 4 (Rank Order: 1(smallest), 2–4 (largest)) repeated measures ANOVA with Task as a between-subjects factor and Stimulus and Rank Order as within-subject factors. This revealed a main effect of stimulus, $F(1,20) = 64.51$, $p < .001$, $MSE = .039$, because of the smaller betas for the primes than for the targets. There was also a main effect of rank order, $F(3,60) = 6.49$, $p < .001$, $MSE = .018$: The beta for the largest value was larger than the betas for the other values, meaning that the largest target value was contributing the most to the response (betas were 0.14, 0.12, 0.10 and 0.22 for the smallest to the largest number in a trial with all betas significantly different from zero; all p's < .001). The three-way interaction was also significant, $F(3,60) = 3.13$, $p < .05$, $MSE = .022$ and is presented in Fig. 3B Further analyses of the betas revealed significant betas for all the targets in both the sum and mean task (all p's < .005). For the prime betas, only the largest prime in the mean task was reliably different from zero ($t(9) = 5.67$, $p < .005$).

2.3. Prime-awareness test

To measure subjective visibility of the primes, participants were asked to report what symbols they had seen on the screen before the presentation of the target during the experiment. None of the participants reported having

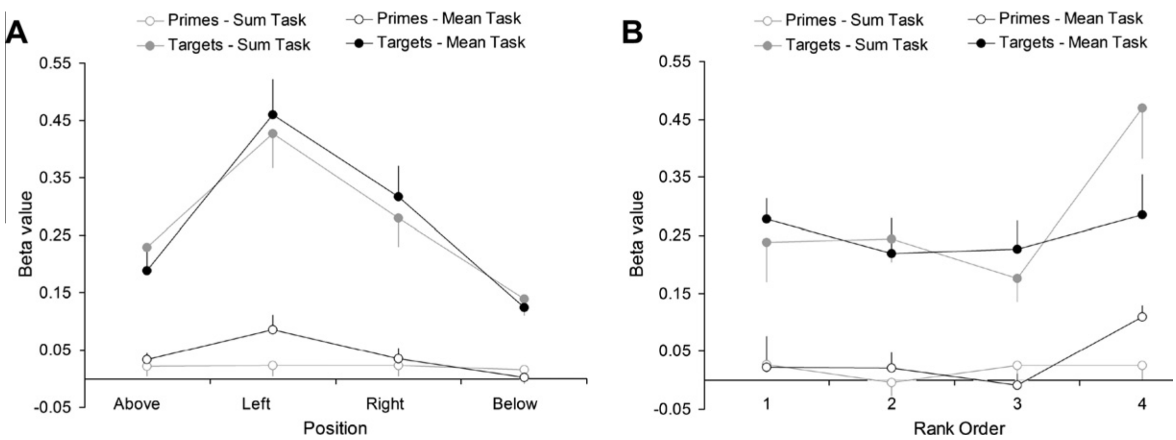

Fig. 3. Results from the logistic regression in Experiment 1 with (A) the position on the screen and (B) the rank order of the digits as independent variables. Vertical bars denote the standard error of the mean.

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seen any symbols other than the hash masks, before the presentation of the target. This finding suggests that participants had no subjective awareness of the primes. To measure objective prime visibility, all participants performed a forced-choice task on the prime set after they were fully informed about the experiment. The procedure was identical to the experiment, except that the response was to the prime rather than to the target set. The prime-awareness test consisted of 120 trials. Average d' was −.097 (48.3% correct), and differed not significantly from zero, $t(21) = .83$, $p = .41$. Regression analysis (Greenwald, Draine, & Abrams, 1996) showed that a large congruency priming effect was observed at zero d' (i.e., in the regression equation, $y = \beta_0 + \beta_1 x$, with y = the congruency effect size and $x = d'$, y is still significantly different from zero when $x = 0$). This classical analysis indicates a significant priming effect with no prime visibility (34 ms, $t(20) = 7.77$, $p < .001$). Furthermore, a positive congruency effect was present in all participants.

2.4. Discussion

Both the regression analysis and the analysis of the reaction times and error rates clearly demonstrate that participants performed the sum and mean tasks satisfactorily on the four target digits, but with a significant influence of the four subliminally presented digits, as indicated by a significant congruency effect. In other words, this experiment shows that ensemble statistics can be extracted from symbolic stimuli and that this process can proceed without awareness.

Closer inspection of the differential contribution of each prime and target stimulus to the decision revealed that the target digits were processed according to Western reading directions, i.e. the left digit was most important for the response decision, followed by the right digit, the digit above and below fixation. Although the result was less clear for the prime digits, correlational analyses suggested a similar pattern for prime processing. Besides the position on the screen, the size of the digits was another factor that influences the decision: Overall, the largest digit had a stronger contribution to the decision compared to the other digits.

Finally, essentially no difference was observed between the sum and mean tasks. One possible explanation for this is that participants were using the same strategy in both tasks. Formally, comparing the sum of four digits to 20 results in the same response as comparing the mean to five of the same four digits. In other words, although the instructions differed, participants in the sum task could have been performing the mean task, or vice versa. Furthermore, it is likely that participants were not calculating the exact sum or mean, but were using an approximation strategy based on the overall magnitude of the display. Given the time constraint that we put on the response (600 ms deadline), in order to maximize priming, exact addition was not really possible and approximation could indeed have been an efficient strategy to complete the task. At this point it is thus unclear if the absence of an effect of task is due to the use of a general approximation strategy in both tasks, or to the possibility of both serial and parallel non-conscious processing.

3. Experiment 2

To further investigate this issue, we designed another experiment in which we discouraged subjects from adopting similar strategies in the sum and mean task. We achieved this result by changing the number of stimuli presented on a trial. Each set now comprised 3, 4 or 5 digits. Because the sum or mean of the target set still had to be compared to 20 or 5 respectively, participants were now forced to use the instructed calculation (mean or sum) in order to respond correctly. For example, when the target set contained the three digits 4, 8, and 7, the sum was smaller than 20 (sum = 19) but the mean was larger than 5 (mean = 6.34). Similarly, in the case of five digits, the sum could be larger than 20 (e.g., digits 7, 6, 1, 3, 6, sum = 23), while their mean stayed smaller than five (in this instance, a mean of 4.75). The correct response was thus task-dependent, and participants could no longer use the same strategy in both tasks (though they could, in principle, still do so just on the four-digit trials). Note that participants could still perform the sum or mean tasks in an approximate manner. However, in an attempt to discourage an approximation strategy, we increased the response deadline to 1500 ms in this experiment.

3.1. Method

3.1.1. Participants

Twenty four university students (four male, aged between 18 and 20) took part in the experiment for course credits. None of the participants were aware of the purpose of the experiment or participated in the previous experiment.

3.1.2. Apparatus and Stimuli

A 60 Hz monitor was used with stimulus presentation synchronized to the refresh rate (16.7 ms). Key presses were registered with a response box. Each trial was announced by a fixation cross (500 ms) followed by the presentation of a premask (67 ms), a prime display (33 ms), a postmask (67 ms), and a target display. The target display remained on the screen for 1500 ms during which the subjects had to respond. If participants responded too slowly (i.e., after 1500 ms) a feedback display (1000 ms) was presented, instructing them to respond faster. Feedback was also presented if participants made an error. The intertrial interval was 200 ms. Prime and target sets consisted of three, four or five numbers randomly selected from the range of small number (i.e., numbers 1–9). The only constraint on the randomization procedure was that the mean could not be exactly equal to five and the sum could not be exactly equal to 20. The number of digits was always the same for the prime and target (i.e., if the prime set consisted of three digits, the target set also consisted of three digits). Primes and targets were presented on the same locations around fixation. These locations were identical for all trials with the same number of primes and targets (Fig. 1B). Because our analysis focused entirely on trials with four digits, these trials were presented more often than trials with three or five digits: 60% of the trials had four digits, against 20% trials with 3% and 20% trials with five digits. For trials with three and five digits, one third were trials in which both the sum and mean elicit the 'smaller than' response, one third were trials in which both tasks elicit the 'larger than' response, and one third were trials in which the mean task and the sum task elicited different responses. In the case of four digits, half of the trials were trials with a smaller than response, the other half with a larger than response. This was true for both the prime and target stimuli. The number of incongruent and congruent trials was matched (50% each). This means that 25% of the trials with four digits consisted of a small prime with a small target, 25% of a small prime with a small target, 25% of a large prime with a small target, and 25% of a large prime with a large target (21 trials per block for every combination).

Primes and targets were presented around a fixation cross (above, below, left from, and right from fixation). All characters were presented in black on a white background.

3.1.3. Procedure

Participants were assigned either to the sum task or to the mean task. The tasks were the same as in the first experiment: Participants were instructed to classify the sum of the target set as larger as or smaller than 20, or the mean of the target set as smaller as or larger than five. The experiment started with a short training session of 15 trials. After the training session, participants were presented with 6 blocks with the possibility of a short break after every block. Each block consisted of 138 experimental trials. Mapping of response hands was counterbalanced within each participant: After the third block, a new instruction screen appeared in which they were instructed to change response hand mappings. The order of response hand mapping was counterbalanced within each task. Twelve subjects were assigned to the sum task, 12 to the mean task. The main experiment was followed by a forced choice reaction task to measure prime visibility.

3.2. Results

Our first concern was to check if participants in this experiment adopted distinct strategies to solve the mean and sum tasks. This was investigated by looking at performance on the critical trials in which the target sets consisted of three or five stimuli and the mean and sum task elicit different responses. By design, if participants performed the same computation and therefore gave the same response to both, performance on those trials would be below 50% in one task and above 50% in the other (the two scores being related as p and 100-p). Conversely, if the error rates in these trials were below 50% in both groups, this would indicate that participants adapted their strategy to the required task. Simple t-test indeed showed that the error rates were significantly below 50% in both the sum ($t(23) = 9.16$, $p < .001$, average error rate = 29%), and the mean task ($t(23) = 3.69$, $p < .005$, average error rate = 37%). This result clearly shows that participants were comparing the sum of the targets in the sum task and the mean of the target in the mean task. Nevertheless, the error rate was higher on these critical trials than on the remaining three-digit and five-digit trials where the required responses were the same under the sum and mean tasks (error rates for three-digit trials were 14.8% and 29.2% for same and different responses respectively, $t(23) = 5.35$, $p < .001$; for five-digit trials error rates were 23.4% and 36.7% for same and different responses respectively, $t(23) = 3.23$, $p < .005$). This finding could be due to several factors: the trials differed in their distances to the comparison reference; the subjects could also have been aware that two computations were available to them (adding versus averaging) and become confused when the two gave distinct results; and the subjects might have performed worse on trials when they were forced to adopt a strategy rather than using their preferred one.

Indeed, compared to the previous experiment, the overall error rates were higher in experiment 2, ($t(44) = 1.21$, $p = .06$; the average error rate was 20.2% and 22.9% in Experiments 1 and 2 respectively). This increase in error rates between experiments may also indicate that participants were trying to do more exact calculation in Experiment 2, but might have failed to do so within the time limit. Overall 22.9% of the trials were errors (1.8% responses were too slow, i.e. above 1500 ms). For trials with four stimuli, the error rate was 24.2%. The analyses reported below focused on trials with four stimuli only.

Outliers were removed by discarding all trials with RTs outside an interval of two standard deviations relative to the mean (i.e., 1.2% of the trials). As a probe into how participants solved the tasks, we first performed an ANOVA on response times with number of target digits (3, 4, or 5) and task (sum or mean) as factors. If the sum task required serial processing of the Arabic digits, an effect of the number of targets would be expected: the more target numbers, the longer the RTs. In contrast, in the parallel mean task the number of digits should exert no, or little, effect on the RTs. The analyses indeed revealed a main effect of the number of digits, $F(2, 44) = 30.72$, $p < .001$, $MSE = 533$, and a significant interaction, $F(2, 44) = 6.70$, $p < .005$, $MSE = 533$. Planned comparisons revealed a significant difference in the mean task between 3 and 4 digits, $F(1, 22) = 77.09$, $p < .001$, $MSE = 274$, and between three and five digits, $F(1, 22) = 35.12$, $p < .001$, $MSE = 807$, but not between four and five digits, $F(1, 22) = 1.01$, $p = .33$, $MSE = 518$ (mean RTs of 686, 746, and 755 ms for 3–5 stimuli respectively). In the sum task only the difference between three and four digits was significantly different, $F(1, 22) = 24.44$, $p < .001$, $MSE = 274$. There was no reliable difference between three and five digits, $F(1, 22) = 2.97$, $p = .099$, $MSE = 807$, or between four and five digits, $F(1, 22) = 1.88$, $p = .184$, $MSE = 518$, in the sum task (mean Rts of 759, 791, and 779 ms for 3–5 stimuli respectively). Comparison of the reaction times between the sum and mean task only revealed a marginally significant difference when 3 stimuli were presented, $F(1, 22) = 3.87$, $p = .062$, $MSE = 8186$, with faster RTs in the sum compared to the mean task.

To investigate the priming effect, the same analyses as in Experiment 1 were performed. A 2 (Task: Mean/Sum) $\times$ 2 (Congruency) ANOVA on the mean, correct RTs revealed a significant congruency effect, $F(1, 22) = 5.48$,

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$p < .05$, $MSE = 161$: RTs for incongruent trials were on average 8 ms slower (781 ms) than on congruent trials (773 ms). Although no main effect or interaction with task was observed, the congruency effect in the sum task was close to significance (12 ms, $F(1, 11) = 3.39$, $p = .093$, $MSE = 260$), but not in the mean task (8 ms, $F(1, 11) = 2.29$, $p = .16$, $MSE = 171$). To investigate how our manipulations in Experiment 2 affected the priming effect in comparison with Experiment 1, we applied a factorial ANOVA on the effect size of the congruency effect ($RT_{incongruent} - RT_{congruent}$) with Experiment and Task as between participant factors. To control for differences in baseline RTs in both experiments, the size of the congruency effect was calculated as $(RT_{incongruent} - RT_{congruent})/RT_{congruent}$. This revealed a significant effect of Experiment, indicating that the priming effect was smaller in Experiment 2 compared to Experiment 1 (28 ms versus 8 ms for Experiments 1 and 2 respectively), possibly caused by a decay of the prime activation because of slower RTs in Experiment 2 compared to Experiment 1. No effect of task was observed, suggesting the priming effect or response times was similar in both the mean and the sum tasks.

Similar ANOVAs on overall error rates revealed no reliable priming or task effects in experiment 2. However, for a finer-grain analysis, a logistic regression similar to experiment 1 was done to study whether and how priming affected decision making. As in Experiment 1, participants' decision were well fitted by the logistic regression model, and showed a small but significant shift by the prime set, as attested by a priming effect on β_0 ($t(23) = 2.57$, $p < .05$). No effect was found for β_1 ($p = .16$). Importantly, the interaction between β_0 and task was significant, $F(1, 22) = 4.29$, $p = .05$, $MSE = .024$. Planned comparisons revealed a significant difference between β_0 for small primes and large primes in the sum task, $F(1, 21) = 11.60$, $p < .005$, $MSE = .024$, but not in the mean task ($F < 1$; see Fig. 4).

A second logistic regression was performed to obtain the betas related to the influence of the position of each prime and target. A 2 (Task: Mean/Sum) × 2 (Stimulus: Primes/Targets) × 4 (Position) revealed a main effect of Stimulus, $F(1, 22) = 107.59$, $p < .001$, $MSE = .058$, a main effect of position, $F(3, 66) = 15.98$, $p < .001$, $MSE = .003$, and an interaction between stimulus and position, $F(3, 66) = 12.73$, $p < .001$, $MSE = .003$, but no main effect or interaction involving task. Similar to the first experiment the stimulus presented on the left weighted the most on the decision, in this experiment followed by the above, right and below stimulus. In contrast to Experiment 1, no such pattern was observed for the primes. A correlational analysis between the positions of the primes and targets revealed no significant correlation ($r = -0.004$, $t < 1$). Planned comparisons revealed no significant betas for the primes, suggesting that the priming effect was smaller than in Experiment 1. All beta values are presented in Fig. 5A.

Next, we obtained the betas for studying the effect of the numerical magnitude of the primes and targets. Analysis revealed a main effect of stimulus (target or prime), $F(1, 22) = 91.97$, $p < .001$, $MSE = .077$, and a main effect of order, $F(3, 66) = 5.96$, $p < .005$, $MSE = .060$. There was also a significant interaction between order and task, $F(3, 66) = 4.83$, $p < .005$, $MSE = .060$. Post hoc comparison showed that larger digits had higher betas in the sum task (significant linear trend; $F(1, 22) = 41.72$, $p < .0001$, only the beta for the digit with the smallest magnitude was not reliably different from 0, $p = .13$). No linear trend was observed in the betas from the mean task ($p = .24$; all magnitudes had betas significantly different from 0, p's $< .01$). The interaction between order and stimulus was also significant, $F(3, 66) = 5.28$, $p < .005$, $MSE = .085$: the above linear trend was only found for the target betas, $F(1, 22) = 29.25$, $p < .001$, $MSE = .074$, but not for the prime betas ($F < 1$). Beta values for primes and targets for both tasks are presented in Fig. 5B The overall pattern indicates that participants overweighed the larger target numbers in the sum task, but gave a more equilibrated weighting of the target numbers in the mean task (as should be the case for optimal responding).

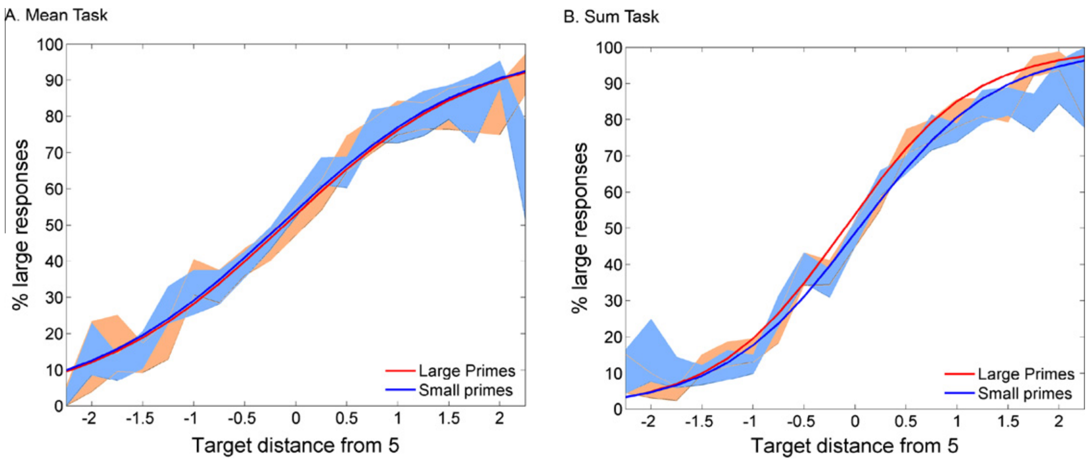

Fig. 4. Observed data for the (A) mean and (B) sum task of Experiment 2 and simulations from the regression models. A significant leftward shift is only observed in the sum task for trials with large primes, indicating more 'larger than' responses in these trials compared to trials with small primes. The shaded areas denote the observed data (mean ± squared error of the mean). The solid sigmoid curves are the fitted data using Eq. (1).

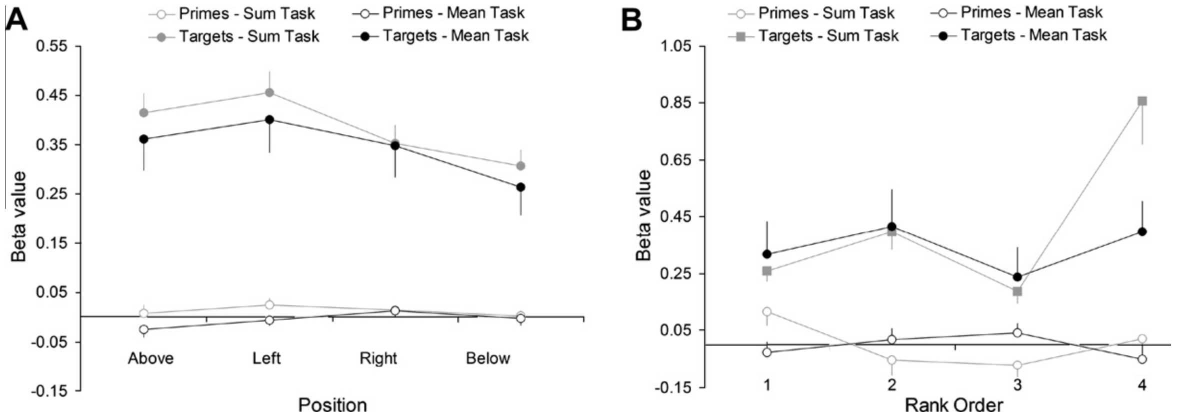

Fig. 5. Beta values from the logistic regression with (A) the position on the screen and (B) the rank order of the digits as independent variables for Experiment 2. Vertical bars denote the standard error of the mean.

3.3. Prime-awareness test

None of the participants reported having seen any symbols other than hash masks when they were asked after the main experiment.

The prime-awareness test consisted of 120 trials. Analysis of the prime visibility focused on trials with four stimuli only, because only these trials were relevant for the congruency effect in the main experiment. Analysis was thus performed on 81 trials per participant. Average d' was $-.014$ (49.8% correct), and differed not significantly from zero, $t(23) = .014$, $p = .85$. Regression results showed a significant congruency effect at zero d' (9.88 ms, $t(22) = 2.41$, $p < .05$), thus providing evidence for a priming effect without awareness.

3.4. Discussion

Experiment 2 overall replicated the findings of Experiment 1. However, the congruency effect in Experiment 2 was smaller than in Experiment 1. This might be simply because of the decrease in the number of trials, and by the difference in distances between the stimuli and the reference for the comparison (20 or 5, in the sum and mean task respectively). The absence of a constraint on the random selection of number stimuli caused the mean distance of the primes to be closer to the reference value in Experiment 2 compared to Experiment 1. Furthermore, the tasks were made more difficult in Experiment 2 by the introduction of trials with variable numbers of targets. Finally, as a result of the change in response deadline (now 1500 ms), participants responded more slowly which might have caused the priming effect to decay more in Experiment 2. All of these factors could have caused a decrease in the weights of the primes on the decision, leading to a smaller congruency effect. Nevertheless, its statistical reliability indicates supports Experiment 1's conclusion that four simultaneously presented numbers can have a subliminal impact on a complex arithmetic decision.

With respect to our other question, the difference between summing and averaging, Experiment 2 managed to make participants in the sum and mean groups behave differently. This fact was attested both on the three- and five-target trials, where responses were appropriately changed in the two groups, and on the identical four-target trials, where only the summing group was found to overweight the large target numbers relative to the small ones. Most importantly, a small difference in subliminal priming was now observed: the regression analysis now revealed a significant priming effect in the sum task, but not in the mean task. Interpretation should be cautious, however, because the effect was not as clear on response times where both groups did not statistically differ in congruity priming, but where congruity priming was close to significance in the sum task only.

A first analysis on the effect of number of targets on the reaction times provided no clear evidence for serial processing in the sum task. Although we observed faster RTs in both tasks when only three digits were presented no differences were observed in the sum or mean task when four or five stimuli were presented. The absence of a clearly linear increase of RTs with the number of targets in both tasks suggests that both tasks were primarily relying on parallel processing of the digits. This suggestion was strengthened by the fact that the sum group exhibited a bias towards overweighting the large targets, which implies that these participants were not performing the requested addition task (by definition, addition requires giving an equal weight to all numbers in the sum). Indeed, previous research on mental arithmetic (e.g., Ashcraft, 1992) suggests that within the observed mean RTs of less than 800 ms, it seems impossible to perform exact additions of 3, 4 or 5 digits with digital precision. Many aspects of the present evidence – high error rate, approximate sigmoid-shaped decision curve, overweighting of larger – suggest that participants were short-cutting the full operation of serial addition and basing their judgments on a partial guess based on the larger numbers present in the target set. The significant priming effect then suggests that this strategy was, in part, applied to the prime set. Thus, our findings should probably not be taken to indicate that full serial arithmetic was possible without awareness, but only that a fast approximation strategy was operative in our tasks.

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4. General discussion

The results of these experiments extend previous findings on ensemble statistics by showing that an ensemble code can be extracted from a set of abstract symbolic stimuli that are presented without the participant's awareness. Because Arabic numerals bear absolutely no resemblance to the magnitude they represent the current study clearly demonstrates that ensemble coding can go beyond surface perception and applies also to a higher level of analysis. These results extend those of Haberman and Whitney (2007) and Haberman and Whitney (2009) who showed ensemble coding for sets of faces: When people are presented with multiple faces they can quickly extract the average emotional expressions or the average gender. It was suggested that the capacity for ensemble coding could be unique for face perception because it would make sense from an evolutionary perspective (Haberman & Whitney, 2009). Extraction of the magnitude of a set of stimuli can also be seen as potentially relevant for survival. Indeed, the ability to quickly estimate the number of a set of stimuli, for example, has already been demonstrated in different animal species (Hauser, MacNeilage, & Ware, 1996), preverbal children (Starkey, Spelke, & Gelman, 1990), and human groups with reduced linguistic numerical labels (Pica, Lemer, Izard, & Dehaene, 2004). In fact, human adults have the capacity to enumerate up to three sets of stimuli in parallel (Halberda, Sires, & Feigenson, 2006). Although the capacity to extract the numerical magnitude of Arabic digits plays at a different level of analysis than the enumeration of dot stimuli, it is well known that Arabic digits automatically activate their magnitude representation (Dehaene, Bossini, & Giraux, 1993; Henik & Tzelgov, 1982). The capacity of human adults to extract statistics from Arabic digits could therefore be derivative upon the evolutionarily older capacity to enumerate different sets of stimuli in parallel.

Previous research on the automaticity of ensemble coding showed that reducing the attention to a set of stimuli does not restrain the representation of ensemble codes (Alvarez & Oliva, 2008). Furthermore, the irrelevant ensemble code of a set of stimuli can have an impact on the detection of a subsequently presented stimulus (Marchant & de Fockert, 2009). In the present study, we investigated if conscious access is a necessary precondition for ensemble coding. We resolved this issue by presenting the stimuli below the threshold of conscious perception. The subjective reports as well as the results from the prime-awareness test clearly indicate that participants were not aware of the prime stimuli: they were unable to report what was presented during prime presentation when they were asked if they saw something appear before the presentation of the target, and they scored at chance level when they were asked to explicitly classify the prime digits in a forced-choice task. Participants thus extracted the ensemble code without any awareness. This conclusion fits with previous work showing that humans could reliably estimate the average orientation of Gabor patches even in conditions in which they were unable to report the orientation of any individual patch (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). According to these authors, the orientation signals in primary visual cortex were pooled and averaged before they reached consciousness. Because our results unequivocally demonstrate that the representation of an ensemble code can take place without any awareness of the stimuli or the ensemble code itself, they nicely support this suggestion, but also indicate that such non-conscious pooling can occur in higher-order brain areas coding for magnitudes, far beyond primary visual cortex. Indeed, evidence from neurophysiological research in non-human primates suggests that approximate number is coded by a distributed neural population scheme that pools together the activation of several number-tuned neurons (e.g., Nieder & Miller, 2004). Such a code naturally lends itself to a simple implementation of the averaging operation as the pooling together of multiple units tuned to each other of the target digits. Assuming that a similar code is available in humans this model might plausibly explain the priming effects observed in the present research. Note that, for a single subliminal prime, number priming effects have already been demonstrated at the level of the HIPS region (Naccache & Dehaene, 2001), which is thought to be a plausible homologue of the monkey VIP region where number-tuned neurons are found.

Analysis of the impact of the position of the digit on the screen was consistent across the two experiments: Independent of the task, the left digit weighed the most on the decision, followed by the right, upper and digit below fixation in that particular order. This is not surprising given that all participants were Western readers accustomed to these reading directions. Results on the impact of the magnitude of the digits were less clear: Although it sometimes appeared that the decision was most strongly influenced by the larger digits, this pattern was not consistent for primes and targets: Only target betas showed a linear trend. This effect of the magnitude of the target digits suggest that the larger digits are weighted more. Such an effect might arise if the set-averaging strategy adopted by the participants involved attributing lesser attention to the smaller digits – a somewhat intuitive, yet not fully rational strategy. These results do, however, show that attention was not distributed equally across the entire set and argue against the idea that set averaging is part of an early structuring of the visual scene at a preattentive stage (Chong & Treisman, 2005).

Were all four digits in the prime necessarily processed simultaneously on any trial? An alternative possibility, is that, on a given trial, only a single prime digit was sampled and processed. When averaging across the entire experiment, such sampling could have created an impression that the entire set was averaged. This hypothesis is very hard to refute formally, because behavioral priming methods necessarily require intertrial averaging and do not allow for single-trial analysis. However, the results from our regression analyses allow us to rule out weaker versions of this hypothesis. First, subjects did not always sample from a single screen location, because we found a significant effect of priming at all four positions of the prime digits. Second, as concerns digit magnitude, we did observe that the priming effect reached significance only

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for this largest prime digit, suggesting that perhaps only that prime digit was sampled and processed. However, logically, it is impossible to identify the larger prime digit without processing them all – and thus, this effect, in itself, supports parallel processing of all prime digits. Furthermore, for targets, we obtained positive evidence that all the magnitudes of the four target digits (from the smallest to the largest) contributed significantly to the decision. Since there was a correlation between the spatial weightings of the primes and of the targets (Fig. 3), the most economical account is that all prime and target digits were submitted to a similar parallel processing, with identical spatial and magnitude weightings. Thus, we believe that the nature of the observed priming effect strongly suggests that all digits were processed non-consciously, not just the largest, and that the most economical assumption is that all of them were entered into the same weighting process.

Because neither the size of the set nor attentional cueing affected the accuracy of mean size discrimination, Chong and Treisman (2005) suggested that ensemble coding is a parallel process. Parallel processing was further tested here by changing the statistic that has to be extracted from the set of stimuli (sum or mean). The results of Experiment 1, however, revealed very few differences between the sum and the mean task. Because participants could have been using the same solving strategy in both tasks, Experiment 2 was designed to encourage participants to behave according to the task requirements, i.e. to sum in the sum task and to average in the mean task. Analysis of the error rates on a subset of trials calling for distinct responses confirmed that participants indeed adopted the required tasks. As a result, clearer differences between the two tasks were now observed, and on response decision (but not on response times), a priming effect was only found in the sum task, resulting in a significant interaction. However, as discussed above, given that it is still unclear how participants performed the sum task, the implications of this finding are uncertain and will require further research. If it was assumed that the mean task, compared to the sum task, required an additional serial step (division by the number of items), then the results would appear in line with the recent demonstration that the concatenation of two tasks (i.e., serial processing) is impossible without awareness (Sackur & Dehaene, 2009). Arguably, the increase in reaction times from 3 to 4 and to 5 target digits in the mean task in Experiment 2 could indeed suggest that calculating the mean relies on a serial process. At any rate, and most importantly, the findings that four simultaneous digits can be processed non-consciously and jointly influence decisions at a semantic level supports the view that massively parallel processing is possible without conscious access, as predicted by several theories of cognitive architecture (Posner & Snyder, 1975; Chun & Potter, 1995) and the global neuronal workspace model of consciousness (Dehaene et al., 2006).

Acknowledgments

FVO is a Postdoctoral Fellow of the Research Foundation – Flanders (FWO-Vlaanderen).

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