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Numerosity-duration interference: A Stroop experiment

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Abstract

The existence of a possible common mechanism for duration and numerosity processing was tested with a Stroop task. Participants had to compare either the duration or the numerosity of sequences of flashing dots for which the duration and numerosity were independently manipulated to create congruent, incongruent or neutral pairs. Results show that the numerical cues interfered with duration processing, whereas the temporal cues did not interfere with numerosity processing. These findings extend the idea of an automatic access to magnitude to non-symbolic sequentially presented material, and reflect a probable difference in the mandatory processing of numerosity and duration.

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1. Introduction

Animal data show that various species can discriminate numerosities (Breukelaar & Dalrymple-Alford, 1998; Davis & Pérusse, 1988) and duration (Roberts & Church, 1978) in experimental as well as in natural conditions (McComb, Packer, & Pusey, 1994). There is also clear evidence that newborn babies and young children experience time and have a precocious temporal representation (Pouthas & Jacquet, 1987). Moreover, they may be sensitive to the numerosity features of the stimuli with which they are confronted, this sensitivity resulting in a broad range of numerical skills (Starkey & Cooper, 1980; Xu & Spelke, 2000; but see Mix, Huttenlocher, & Levine, 2002, for a discussion of the alternative view that babies and young children may rely more on physical quantity than numerosity processing). It has been proposed that a single representational mechanism, namely an accumulator, could underlie these two estimation processes (Meck & Church, 1983). Such an internal accumulator would represent the duration or the numerosity of objects or events through different operative modes, by summing the impulses produced by a generator either at a given frequency for duration processing, or each time an event or an object was encountered for numerosity processing (Meck, 1997; Meck & Church, 1983; Meck, Church, & Gibbon, 1985). According to some authors, the human brain possesses an innate mechanism for the apprehension of numerical quantities inherited from the animal world (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 1992). Early numerical abilities in infants may be grounded on preverbal processes, similar to an accumulator, from which adult arithmetical abilities develop on a kind of mental number line. These elementary numerical skills shared by animals, infants and adults would rely on a cerebral network located in the inferior parietal cortex (Dehaene, 2002; Dehaene & Changeux, 1993; Dehaene & Cohen, 1997).

Anatomo-functional data partly support the idea of a common neural substrate for duration and numerosity processing mechanisms as these data show various degrees of implication of the parietal cortex in the processing of duration and numerosity. Neuropsychological and recent brain imaging studies suggest that time perception and processing involve the frontal cortex, the cerebellum and the basal ganglia, since lesions to these structures lead to impairments of time perception (Harrington, Haaland, & Knight, 1998; Jueptner et al., 1995; Nichelli, Always, & Grafman, 1996). Other studies reveal the involvement of the inferior parietal cortices in time-estimation and comparison tasks, mainly in the right hemisphere (Lejeune et al., 1997; Maquet et al., 1996), and a bilateral involvement of the intraparietal areas in auditory and visually presented temporal rhythmic patterns (Schubotz, Friederici, & von Cramon, 2000). Finally, the temporal allocation of attention (e.g., cued allocation of attention across delays) has been found to produce a left-sided activation in the intraparietal sulcus (Coull, 2004). The role of the parietal areas in numerical processing was demonstrated by neuropsychological studies with brain-damaged patients (Dehaene & Cohen, 1997; Takayama, Sugishita, Akigushi, & Kimura, 1994), and by brain-imaging studies using numerical comparison tasks (Pesenti, Thioux, Seron, & De Volder, 2000; Pinel et al., 1999) and simple arithmetic tasks (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). Areas along the intraparietal sulcus (perhaps its horizontal segment) appear to process numerical quantities whereas a bilateral posterior superior parietal system plays a role in attention orientation on the mental number line (Dehaene, Piazza, Pinel, & Cohen, 2003). The activation of a network including the intraparietal, dorsolateral prefrontal, premotor areas as well as the anterior cingulate cortex was observed when subjects had to estimate the numerosity of temporal series of visually and auditory presented stimuli (Piazza, Mechelli, Butterworth, & Price, 2002; Piazza, Mechelli, Price, & Butterworth, submitted). After reviewing a broad range of behavioural, physiological, developmental, lesional and neuroanatomical data on magnitude processing, Walsh (2003) recently proposed the existence of a generalised magnitude system for the processing of time, size, quantity and space, located in the parietal cortex. For example, the application of transcranial magnetic stimulation (TMS) to the parietal cortex was shown to affect the judgements of time, size and number (Göbel, Walsh, & Rushworth, 2001; Hodinott-Hill, Thilo, Cowey, & Walsh, 2002). The selective implication of parietal neurons was also identified in single-cell registration studies of a judgement of numerical quantity in non-human animals (Sawamura, Shima, & Tanji, 2002) and during the estimation of duration (Leon & Shadlen, 2003; Onoe et al., 2001).

While these data correspond to the idea of a generalised magnitude system, possibly located in the parietal cortices, they should nevertheless be considered with caution for several reasons. Firstly, several studies have challenged the idea of common processes for numerosity and time estimation due to dissimilarities in animal data concerning the shapes of the functions fitting training curves (e.g., linear vs. power functions for numerosity and time discrimination; for a review, see Hobson & Newman, 1981). Secondly, some studies have shown that when animals were able to process the duration and the numerosity of events, they answered on the basis of numerosity only when other parameters (such as duration) were not available, suggesting that numerosity and duration processing may be more dissociated than previously assumed. For example, birds would rather base their choice on the time elapsed than on the number of events occurring during an interval (Lydersen & Crossman, 1974). This tendency was also found with rats in a task using ambiguous stimuli (i.e., with a different answer—left or right lever—for the temporal and numerical dimensions): the rats answered primarily according to the temporal dimension (Breukelaar & Dalrymple-Alford, 1998). Conversely, in other studies, numerosity constituted the fundamental condition of control for discriminations based both on time and on number (Rilling, 1967). In a tapping task, where human participants had to press a button as rapidly as possible until they felt that they had reached a given number of presses, and then had to reproduce a temporal interval equivalent to the time necessary to carry out the presses, performance on the numerical estimation task did not rely on an evaluation of the time elapsed (Whalen, Gallistel, & Gelman, 1999). Thirdly, the current anatomical precision of TMS does not allow a perfect localisation of the stimulated area and one cannot safely conclude that exactly the same areas were stimulated in all the reported studies. Whether numerical and temporal processes do or do not share the same mechanisms and the same neuroanatomical substrate in the parietal cortex is thus still an open question.

One way to identify the specificities and commonalities of two processes is to look at possible mutual interference effects in Stroop or dual-task paradigms. On the one hand, several studies have manipulated the temporal characteristics (e.g., duration of presentation of stimuli, stimulus onset asynchrony) by using masks or a sequential mode in a classic colour-word Stroop task and have shown a decrease in the interference effect proportional to the stimulus onset asynchrony, with a peak around 50 ms pre-exposure of the word (e.g., La Heij, van der Heijden, & Plooij, 2001). The temporal dimension was, however, only indirectly approached, and to date, only one study using a Stroop design has really integrated duration as a variable of interest in an auditory task. In this experiment the words *fast* and *slow* were pronounced slowly or quickly according to the condition (congruent or incongruent; Morgan & Brandt, 1989); here, duration corresponded to a psychoacoustic attribute of the word. This study did not show a significant difference between the two conditions, which suggested that duration did not interfere with linguistic processing. On the other hand, dual-task paradigms have shown that the duration estimation is affected by various types of concurrent tasks (visual search, pursuit rotor tracking and mental arithmetic; Brown, 1997).[1] More generally, filled intervals are perceived as longer than empty intervals, both in the auditory and the visual modalities (e.g., Gibbons & Rammsayer, 2004; Grondin, 1993). Finally, a recent study in children showed the numerosity-duration interference effects in a bisection task of a series of flashed dots (Droit-Volet, Clément, & Fayol, 2003).

How the estimation of time may interfere with other cognitive processes is thus still largely unknown. In the present study, we used a Stroop task to assess the presence of possible effects of facilitation and/or interference between the numerical and temporal dimensions. Participants had to compare either the numerosity or the total duration of two successive series of visually flashing dots. To avoid as far as possible potential explicit or implicit counting strategies, short duration (ranging from 1200 to 2100 ms) and non-subitisable numerosities (from 5 to 9 dots) were used. If the same representational mechanism underlies duration and numerosity processing, then a symmetric effect of interference or facilitation should be observed: the comparison of durations should be influenced by the irrelevant numerical dimension of stimuli and, conversely, the comparison of numerosities should be subject to the influence of the temporal dimension. On the other hand, if the two processes are independent, no mutual effect of interference/facilitation should be observed. Finally, an asymmetric effect of interference/facilitation would signal a faster or more efficient mandatory processing of one of the two dimensions.

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[1] Note, however, that only the mental arithmetic task was impaired by the temporal task, perhaps because both tasks draw on the same pool of executive functions (Brown, 1997).

2. Method

2.1. Participants

Thirty volunteers (3 left-handed, 6 males, mean age: 22 ± 1.4 years) participated in this study; 15 participants completed the numerosity comparison task and 15 completed the duration comparison task.

2.2. Tasks and stimuli

The experiment was composed of two distinct tasks: a numerosity comparison and a duration comparison of two successive series—constituting a pair or a stimulus—of visually flashing dots. For each task, three types of pairs were constructed: in *congruent pairs*, the series with more dots lasted longer; in *incongruent pairs*, the series with fewer dots lasted longer; and in *neutral pairs*, the numerosity was fixed (6 dots) and the total duration of the series varied in the comparison of the duration task, whereas the duration was fixed (1500 ms) and the number of dots varied in the numerosity comparison task. For the congruent and incongruent conditions, the same set of stimuli was used in the two tasks.

All series were composed of black dots (diameter: 3.5 cm) and were constructed using non-periodic signals so that temporal ratios did not constitute a potential confounding variable and rhythm biases and pattern recognition were avoided (Breukelaar & Dalrymple-Alford, 1998; see Appendix A for details). The total duration of the series (i.e., the duration of the dots/events plus the interdot/event intervals) ranged from 1200 to 2100 ms and the numerosities ranged from 5 to 9 dots (i.e., not subitisable but below 10). The durations of each dot/event (e_j) and the interdot/event intervals (i_j) were both variable (between 50 and 300 ms); to avoid pattern recognition, each series involved at least one e_j and one i_j of 50 ms and one longer than 200 ms, and each series began and finished with an i_j of 50 ms (see Fig. 1). Pairs of series were chosen to constitute two distances: a *large* distance (3 dots for numer-

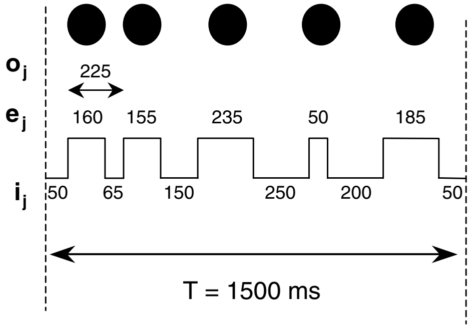

Fig. 1. Temporal attributes of the stimuli shown on an example of non-periodic series with five dots and a total duration of 1500 ms (T = total signal duration; o_j = event onset duration; e_j = event duration; i_j = interevent duration; see Appendix A for details).

osity, that is, pairs 5–8 and 6–9; 600 ms for duration, that is, pairs 1200–1800 and 1500–2100) and a *small* distance (1 dot for numerosity, that is, pairs 5–6 and 8–9; 300 ms for duration, that is pairs 1200–1500 and 1800–2100). The order of presentation of the two series within the pairs varied: half the pairs began with the shorter/smaller series (S–L) and the other half with the longer/larger (L–S).

2.3. Experimental procedure

A Macintosh computer interfaced with a 17″ AV screen controlled stimuli presentation and data collection. The viewing distance was approximately 50 cm. At the beginning of each trial, a white rectangle (9.5 cm × 16 cm) was presented on a black background and a first series of dots were flashed in its centre for a given duration, after which the rectangle disappeared and was replaced by a black screen for 1000 ms. Then a new rectangle appeared and a second series of dots were flashed, after which the rectangle disappeared and was again followed by a black screen for a period of up to 1500 ms during which the participants could answer. As soon as the answer was given, the next trial started. Each task was composed of 8 blocks of 24 trials; the three types of pairs were mixed and randomised within each block. A practice block was administered first, but was not included in the analyses.

Each participant was assigned randomly to one comparison task. In the numerosity comparison task, the participants had to decide which series contained more dots by pressing one of the two keys on the numerical pad (key 1 with the right index finger for the first series, key 3 with the right ring finger for the second series). In the duration comparison, they had to decide which series lasted longer from the appearance of the first to the last dots of the series, with the same key presses. The instructions clearly requested participants to focus on one of the two dimensions and did not mention the other one.

3. Results

Firstly, a global analysis was carried out on both tasks to look for the possible presence of interference and/or facilitation effects. Secondly, separate analyses were run for the congruent and incongruent conditions of each task in order to test the order and distance effects. In this analysis, the *relevant distance* was that of the dimension that was to be explicitly processed (e.g., the numerical distance in the numerosity comparison) and the *irrelevant distance* was the distance of the dimension that was not to be explicitly processed (e.g., the duration distance in the numerosity comparison).

3.1. Interference and facilitation effects

An analysis of variance (ANOVA) was performed on the response latencies of correct answers with task (numerosity vs. duration) as a between-subject variable and condition (congruent, incongruent vs. neutral pairs) as a within-subject variable.

There was no difference between the tasks (mean latencies for duration: 529 ± 98 ms, for numerosity: 485 ± 80 ms; $F(1,28) = 2.01$, ns). A significant main effect was found for condition (mean latencies for congruent: 499 ± 80 ms, incongruent: 528 ± 106 ms, neutral: 494 ± 86 ms; $F(2,27) = 7.79$, $p < .002$). Post-hoc paired-sample t-tests indicated that the incongruent condition differed significantly from the congruent and neutral conditions (both $p < .001$). There was also a significant interaction between the condition and the task ($F(2,27) = 8.331$, $p < .002$). Separate ANOVAs for the duration and numerosity tasks with condition as within-subject variable revealed a main effect of condition in the duration task ($F(2,13) = 13.628$, $p < .001$): the congruent and neutral conditions were answered faster than the incongruent one in the duration task (mean latencies for congruent: 503 ± 81 ms, incongruent: 575 ± 108 ms, neutral: 508 ± 91 ms), whereas no effect was observed in the numerosity task (mean latencies for congruent: 495 ± 82 ms, incongruent: 480 ± 82 ms, neutral: 479 ± 81 ms; $F(2,13) = 0.832$, ns; see Fig. 2). It is worth noting that the neutral conditions did not differ significantly (mean latencies for neutral duration: 508 ± 91 ms, neutral numerosity: 480 ± 81 ms; $t(14) = 1.828$, $p = .089$).

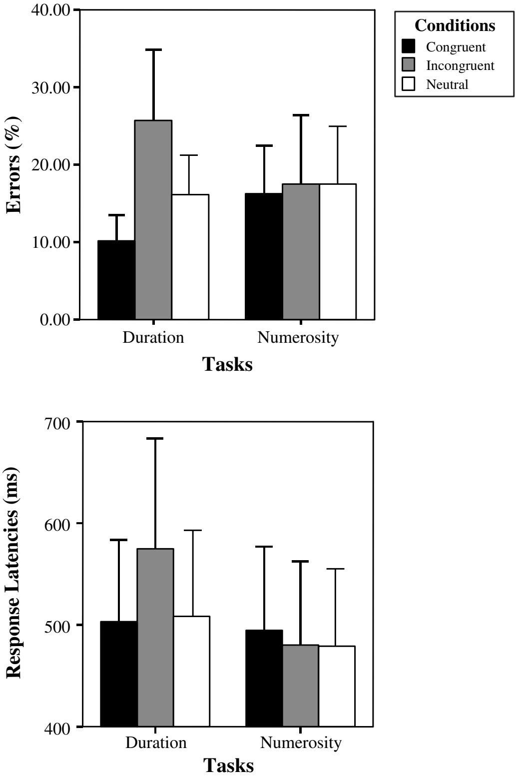

Fig. 2. Mean percentage of errors and response latency in ms for duration and numerosity tasks as a function of condition (congruent, incongruent, or neutral). Error bars indicate the standard errors of the mean.

To ensure that this marginal tendency for the numerosity judgement to be slightly faster did not mask a possible (in)congruency effect of duration, two complementary analyses were carried out in the numerosity task. Firstly, the participants were divided into two groups according to their mean response latency (fast: 407 ± 24 ms, slow: 561 ± 57 ms) in the neutral condition. An ANOVA again showed no main effect of condition ($F(2,9) = 0.224$, ns) and, most importantly, no group by condition interaction ($F(2,9) = 0.661$, ns): there was thus no (in)congruency effect of duration even in the slow group in which participants were slower than in the duration task. Secondly, to test for any specific task-related processing, fast and slow trials were distinguished for each subject. This ANOVA showed no main effect of condition ($F(2,13) = 0.085$, ns) and, no speed of trials by condition interaction ($F(2,13) = 1.145$, ns). These complementary analyses thus confirm the absence of an interference effect of duration on the numerosity judgement, whatever be the speed of processing.

A similar ANOVA on error rates revealed no differences between tasks (mean percentage of errors for duration: 17.3 ± 9.1, for numerosity: 17 ± 7.4; $F(1,28) = 0.017$, ns), but a main effect of condition (mean percentage of errors for congruent: 13.1 ± 5.8, incongruent: 21.5 ± 9.9, neutral: 16.8 ± 6.5; $F(2,27) = 9.214$, $p < .001$) and a significant interaction between the task and condition ($F(2,27) = 6.827$, $p < .004$): the three conditions differed in the duration task (mean percentage of errors for congruent: 10.1 ± 3.4, incongruent: 25.6 ± 9.3, neutral: 16.0 ± 5.8; $F(2,13) = 23.7$, $p < .001$) but not in the numerosity task (mean percentage of errors for congruent: 16.15 ± 6.3, incongruent: 17.4 ± 9.0, neutral: 17.5 ± 7.2; $F(2,13) = 0.213$, ns). In the duration task, all the conditions differed significantly from each other (congruent–incongruent: $p < .001$; congruent–neutral: $p < .003$; incongruent–neutral: $p < .001$; see Fig. 2).

3.2. Relevant and irrelevant distance effects

A second analysis was performed on the response latencies of correct answers with task (duration vs. numerosity) as between-subject variable, and the condition (congruent vs. incongruent),[2] relevant distance (large vs. small) and irrelevant distance (large vs. small) as within-subject variables.[3] There was a significant main effect of condition ($F(1,28) = 6.57$, $p < 0.02$) that interacted with task ($F(1,28) = 15.15$, $p < 0.001$): the congruent condition was answered faster than the incongruent one in the duration task but not in the numerosity task (see above). A main effect of

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[2] The neutral condition was not included in this analysis as it was impossible to integrate all the levels of the distance variables.

[3] In a separate analysis, the order of presentation of the series (short–long vs. long–short) was introduced as a supplementary within-subject variable. A main effect of order was revealed for the latencies (mean latencies for short–long = 462 ± 15 ms, for long–short = 564 ± 17 ms; $F(1,28) = 95.755$, $p < .000$). This effect suggests that the participants could anticipate the correct answer only when the short series was presented first. This variable entered into some interactions but, as it never changed the direction of the main effects of other factors, it was not included in the main analysis.

the relevant distance was also found: the large distance was answered faster than the small one (mean latencies for large distance: 475 ± 118 ms, small distance: 552 ± 114 ms; $F(1,28) = 40.811, p < .001$). Finally, there was also a statistically marginal interaction between the condition and relevant distance ($F(1,28) = 3.158$, $p = .086$): there was no difference between the congruent and incongruent conditions for large distances whereas there was a significant difference for the small distance (congruent was faster than incongruent). The irrelevant distance had no significant main effect or interaction with the other variables; the other main effects and interactions were also not significant.

The same ANOVA performed on the mean percentage of errors revealed the main effects of condition (mean percentage of errors for congruent: 13.1 ± 5.8, incongruent: 21.5 ± 9.9; $F(1,28) = 19.03, p < .001$), relevant distance (mean percentage of errors for large distance: 9.6 ± 10.1, small distance: 25 ± 14.1; $F(1,28) = 166.396, p < .001$), and irrelevant distance (mean percentage of errors for large distance: 18.5 ± 15.8, small distance: 16.1 ± 12.9; $F(1,28) = 4.483$, $p = .043$). The condition and task interacted ($F(1,28) = 13.78$, $p < .001$), in that the congruent condition produced fewer errors than the incongruent one in the duration task but not in the numerosity task (see above). There was also a significant interaction between the relevant distance and task ($F(1,28) = 7.115, p < .02$). With large relevant distance participants made more errors during the duration task, whereas there was no difference between large and small relevant distance in the numerosity task. Moreover, a significant triple interaction between the condition, relevant distance and task was found ($F(1,28) = 6.006$, $p < .03$): in both tasks, the small and large distances differed but this difference was smaller in the congruent conditions of the duration task, and the congruent conditions differed from the incongruent ones only on the duration task (see Fig. 3).

There was also a marginally significant interaction between the condition and irrelevant distance ($F(1,28) = 3.298$, $p = .08$): in the incongruent condition, subjects made more errors when the irrelevant distance was large whereas there was no difference between large and small distance in the congruent condition. Finally, another

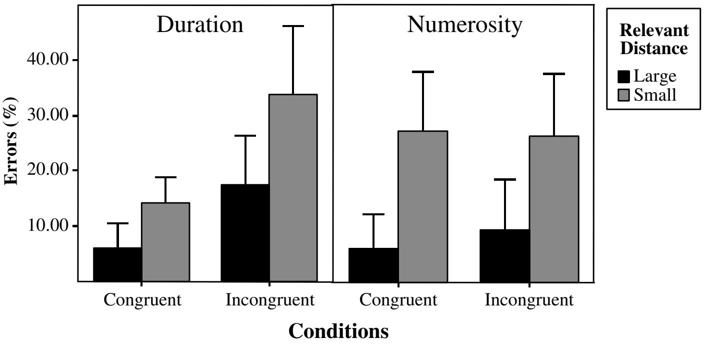

Fig. 3. Mean percentage of errors for duration and numerosity tasks as a function of condition and relevant distance (for numerosity and duration, respectively: Large = distance 3 and difference 600 ms, Small = distance 1 and difference 300 ms for numerosity and duration, respectively). Error bars indicate the standard errors of the mean.

statistically marginal interaction between the irrelevant distance and task was observed ($F(1,28) = 4.11$, $p = .052$). A post-hoc paired *t*-test showed that the large and small irrelevant distances differed on the numerosity task only (the large irrelevant distance producing more errors than the small distance).

4. Discussion

The aim of the present study was to investigate the relationship between the numerosity and duration processing with a Stroop design and to test whether they share the same mechanisms. We will first summarise the major findings of this study, and then discuss how they improve our understanding of the mental processing of the numerosity and duration.

4.1. Interference/facilitation and distance effects

Firstly, the results showed that in the range of selected durations and numerosities, the duration and numerosity judgements were globally of similar complexity with performance being equally fast and accurate on both tasks. The differences observed are therefore probably not related to differences in attentional or difficulty demands across the tasks. In the duration comparison, there was a clear interference effect of numerical cues on response latencies (incongruent slower than neutral and congruent), and both facilitation and interference effects on error rates (fewer and more errors in the congruent and incongruent conditions, respectively, compared to the neutral condition). On the other hand, in the numerosity comparison task, there was no difference between the three conditions (congruent, incongruent and neutral) either on responses latencies or on error rates, suggesting that the temporal cues did not influence the numerosity judgements.

Secondly, a classical effect of the relevant distances (e.g., Moyer & Landauer, 1967) was observed in both tasks: the closer the numerosities, the longer and the more error-prone the judgements in the numerosity comparison; the closer the durations, the longer and the more error-prone the judgements in the duration comparison. This effect shows that the participants actually performed the comparisons using the appropriate dimension (i.e., numerosity in the numerosity comparison, duration in the duration comparison). Moreover, the interaction between the pertinent distance and the condition for latencies shows that the incongruent information from the other dimension only interfered for the small distance; that is, when the decision based on the relevant distance was slower and thus possibly more difficult. For the large distance, there was no difference between the congruent and incongruent conditions. For error rates, this was true for the duration task only: in the numerosity condition, there was no difference between the congruent and incongruent conditions, confirming again that duration cues did not affect the numerosity judgement.

This conclusion may, however, be qualified by the marginal interactions involving the irrelevant distance on the error rates. Surprisingly, there was no difference between small and large irrelevant (numerical) distances in the duration task but there was a difference between the small and large irrelevant (temporal) distances in the numerosity task, with large distances leading to more errors. This can be explained by considering the pattern of the non-significant interaction between the conditions, irrelevant distance and tasks. The absence of an effect in the duration task was in fact due to averaging over the expected facilitation and interfering effects of the irrelevant (numerical) distances in the congruent and incongruent conditions, respectively. On the other hand, in the numerosity task, the irrelevant (temporal) distances did not modulate the error rates differentially in the congruent and incongruent conditions but rather led to a global—perhaps attentional—interference effect in both conditions. Thus, although these marginal interactions suggest that temporal cues have some weak effect on numerosity judgements, they do not seem to correspond to real interactions between duration cues on numerosity judgements.

4.2. Mandatory processing of numerosity but not duration?

The interference effect of numerosity found in the present study using series of dots extends previous results using symbolic material. Several behavioural studies have shown the automatic activation of magnitude information with Arabic or verbal numerals in Stroop tasks (Algom, Dekel, & Pansky, 1996; Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992) or simply in tasks where the numerical magnitude is not the key dimension to be processed (e.g., identity judgements: Dehaene & Akhavein, 1995; phoneme monitoring: Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; orientation judgements: Fias, Lauwereyns, & Lammertyn, 2001). These results supported the idea of involuntary and irrepressible access from Arabic numerals to the representation of numerical quantities. In adults, such automatic access to magnitude from non-symbolic material had previously been suggested by a priming task (Koechlin, Naccache, Block, & Dehaene, 1999) and a recent study using an adaptation paradigm (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004) with identity (same–different) or numerosity (smaller–larger) judgements of simultaneously presented patterns of dots, requiring an explicit or implicit processing of numerosity. The present study extends the demonstration of the automatic activation of magnitude to non-symbolic sequentially presented material: the numerosity cues strongly interfered with the judgement of duration, and, most critically, in a context where numerosity did not have to be processed to carry out the task.

As performance did not differ globally across tasks, the asymmetrical interference effect observed in the present study may reflect a difference in the mandatory processing of numerosity and duration: whereas numerosity processing appears to take place automatically, duration processing is not automatic—or, at least, not in a way which leads to strong interference effects. Similar results have recently been observed in adults and 5- to 8-year-old children during a bisection task of series of flashed dots displayed for 2–8 s (Droit-Volet et al., 2003). Numerosity interfered with performance in the duration condition, indicating that children and adults did not process these two dimensions independently when asked to explicitly process duration; however duration did not interfere with numerical discrimination in the numerosity condition for either age group. In that study, the asymmetry in interference was interpreted in terms of attentional load: it was considered easier to ignore duration than numerosity because the former requires more attentional resources. This was especially true for the youngest children, who could dissociate duration and numerosity in the duration task only when allowed to use a counting strategy that reduced the interfering effect of numerosity. In the present experiment, there is no behavioural evidence of a differential attentional demand between the two tasks. Moreover, the very short durations we used probably made a counting strategy very difficult, if not impossible, to apply. This may explain why numerosity still interfered, even with adult participants. Finally, as suggested by an anonymous reviewer, explicit judgements on numerosity are frequent, whereas judgements on duration are generally made implicitly and prospectively rather than retrospectively. Short durations, such as those used in this experiment, are mainly relevant for anticipatory or programming actions, but not for comparative judgements. This lack of expertise in explicit comparative judgements of short durations may be one of the reasons underlying this asymmetry.

4.3. A common mechanism for numerosity and duration processing?

The observed asymmetry of interference does not allow us to draw strong conclusions concerning a possible common mechanism for the numerosity and duration processing as postulated by some authors (Meck & Church, 1983; Walsh, 2003). This asymmetry could arise with or without such a common mechanism, simply as a consequence of a faster and/or more automatic processing of numerosity. As the neutral conditions of the two tasks did not differ significantly, the hypothesis of faster processing can probably be rejected. Therefore, the fact that both estimation processes take place simultaneously, as suggested by the present results, challenges the idea of a single accumulator underlying the two estimation processes, unless the accumulator works simultaneously in its two operative modes. Alternatively, several accumulators could work in parallel (e.g., numerosity and duration could be processed independently by two different accumulators before converging on a common response-selection system). Caution should be exercised with this conclusion given the marginal trend for numerosity judgements to be slightly faster. However, the absence of an (in)congruency effect of duration in the slowest group of subjects and also in the slowest trials indicates that duration cues had no effect, even with the slow numerosity judgements. Neuroimaging data would help resolve the issue. Indeed, it has been suggested that the interference from irrelevant information would be stronger if the relevant and irrelevant dimensions rely on the same neuronal structures (Fias et al., 2001), and that a common functional mechanism should lead to common brain activations in the same cerebral structures, even if one of the two processes is faster and/or more automatic. In a positron emission tomography study we carried out recently, preliminary analyses revealed no common activation in the parietal cortex in the numerosity and duration of flashed dots comparison tasks (Pesenti, Thioux, Dormal, De Volder, & Seron, 2003). These anatomo-functional results must, however, be replicated before a firm conclusion can be drawn.

5. Conclusions

The present study was aimed at testing the existence of a possible common mechanism for duration and numerosity processing. Comparisons of the duration and numerosity of series of flashing dots were tested in a Stroop design in which the two dimensions were controlled to create congruent, incongruent and neutral pairs. This allowed us to investigate whether and how the temporal cues interfered with the processing of numerosity, and inversely whether and how the numerical cues interfered with duration processing. Results show that numerical cues interfered with the duration processing (they facilitated duration processing when the numerosity and duration were congruent, but interfered with it when they were incongruent), whereas temporal cues did not affect numerosity processing. These findings extend the idea of automatic access to magnitude to non-symbolic sequentially presented material, and reflect a probable difference in the processing of numerosity and duration.

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Appendix A. Control of temporal and pattern ratios

Breukelaar and Dalrymple-Alford (1998) pointed out that using classical periodic signals (i.e., signals with constant event-interval durations) introduces two potential biases in number/duration discrimination tasks. Firstly, the periodic event sequences allow discriminations to be based on the uncontrolled and unintended temporal attributes of the event sequence, confounded with numerosity. Indeed, when a fixed number of identical events occur periodically, the ratios of the intervals between the event onset (o_j), event duration (e_j), and inter-event duration (i_j) to the total duration (t) remain constant (respectively, o_j:t, e_j:t, and i_j:t; see Fig. 1), irrespective of the total signal duration. This has been called the *temporal ratio*. This temporal ratio always covaries with the number of events even when the duration and numerosity are not confounded (by holding constant one of the two dimensions while the other varies). Secondly, when only a few sequence patterns are used, participants may learn to respond to a signal by matching it to a specific standard stored in memory. The solution to both problems is to use unique non-periodic signals: in every trial, the temporal pattern for each numerosity—or duration—relevant signal is randomly generated by adjusting the o_j's, e_j's and i_j's. The *ratio deviation score* (DS ratio) provides a measure of deviation in terms of the o_j:t ratio, and a *pattern deviation score* (DS pattern) provides a measure of deviation in terms of the signal patterns. Both scores can be derived from the following formula:

$$\mathrm{DS} = \sqrt{\sum_{j=1}^{j=n} (D - d_j)^2}. \tag{1}$$

For the DS ratio, D is the event duration of the corresponding periodic signal, d_j is the current event onset, and n the number of events. For the DS pattern, D is the event or interval duration of the corresponding periodic signal, while d_j is the current event or interval duration (so that j is odd for events and even for intervals), and n is the total number of events and intervals. The more distant the ratios are from 0, the less the numerosity-duration confounding and the pattern regularity. For example, say a signal is composed of the following succession of five events and five intervals for a total duration of 1500 ms: $\mathrm{event}(e)_1 = 160$ ms, $\mathrm{interval}(i)_1 = 65$ ms, $e_2 = 155$ ms, $i_2 = 150$ ms, $e_3 = 235$ ms, $i_3 = 250$ ms, $e_4 = 50$ ms, $i_4 = 200$ ms, $e_5 = 185$ ms, and $i_5 = 50$ ms. The various ratios derived from (1) are as follows:

$$\begin{aligned}
&n:\ 5;\\
&D(\text{for ratio}) : (1500/5) = 300;\\
&D(\text{for pattern}) : (300/2) = 150;\\
&\text{DS ratio} = \Big\{(300-(160+65))^2 + (300-(155+150))^2 + (300-(235+250))^2\\
&\qquad\quad +(300-(50+200))^2 + (300-(185+50))^2\Big\}^{1/2}\\
&\qquad = 216;\\
&\text{DS pattern} = \sqrt{(150-160)^2 + (150-65)^2 + (150-155)^2 + \cdots + (150-50)^2} = 220.
\end{aligned}$$

All series of items are equated, so that the mean DS ratio for the five items of each category of series varies between 243 and 244. The DS pattern is always maintained above 150. Moreover, within each item, the two series have exactly the same DS ratio.

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