Cognition 111 (2009) 187–211

Contents lists available at ScienceDirect

Cognition

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

The cognitive architecture for chaining of two mental operations

Jérôme Sackur [a,b,*], Stanislas Dehaene [b,c]

[a] Laboratoire de Sciences Cognitives et Psycholinguistique, EHESS/CNRS/DEC-ENS, Département d'Études Cognitives, École Normale Supérieure, 45, Rue d'Ulm, 75005 Paris, France

[b] Cognitive NeuroImaging Unit, INSERM–CEA, CEA/SAC/DSV/DRM/Neurospin Center, 91191 Gif sur Yvette Cedex, France

[c] Collège de France, 11, Place Marcelin Berthelot, 75005 Paris, France

ARTICLE INFO

Article history:
Received 28 April 2007
Revised 22 January 2009
Accepted 30 January 2009

Keywords:
Cognitive architecture
Composite operations
Mental arithmetic
Subliminal processing

ABSTRACT

A simple view, which dates back to Turing, proposes that complex cognitive operations are composed of serially arranged elementary operations, each passing intermediate results to the next. However, whether and how such serial processing is achieved with a brain composed of massively parallel processors, remains an open question. Here, we study the cognitive architecture for chained operations with an elementary arithmetic algorithm: we required participants to add (or subtract) two to a digit, and then compare the result with five. In four experiments, we probed the internal implementation of this task with chronometric analysis, the cued-response method, the priming method, and a subliminal forced-choice procedure. We found evidence for an approximately sequential processing, with an important qualification: the second operation in the algorithm appears to start before completion of the first operation. Furthermore, initially the second operation takes as input the stimulus number rather than the output of the first operation. Thus, operations that should be processed serially are in fact executed partially in parallel. Furthermore, although each elementary operation can proceed subliminally, their chaining does not occur in the absence of conscious perception. Overall, the results suggest that chaining is slow, effortful, imperfect (resulting partly in parallel rather than serial execution) and dependent on conscious control.

1. Introduction

The cognitive science turn in psychology has been greatly influenced by various mechanical models of the mind. Broadbent (1958) devised his information-flow description of the human mind as a communication system, while others (Newell, Shaw, & Simon, 1958; Simon, 1996) argued that computer simulations enable us to test hypotheses about how our mind operates. Common to all these descriptions is the notion that the workings of the human mind can be described in terms of information processing. Here, we use mental chronometry to probe one of the most basic aspects of human information processing architecture, namely the ability to perform a first processing step, then reutilize its result in a second step.

Many modern digital information processing devices rely on the so-called von Neumann architecture, within which a central processor executes one operation at a time on one block of data, and in which the list of elementary operations (the program) and the data are stored in memory. This architecture in turn is based on the notion of the abstract and general computing machine put forth by Turing (1936), the lesson of which is twofold: on the one hand Turing proved that any computation that can be formally described, however complex, can be implemented in a universal, abstract machine composed of a finite processor and an infinite memory tape where individual symbols

* Corresponding author. Address: Laboratoire de Sciences Cognitives et Psycholinguistique, EHESS/CNRS/DEC-ENS, Département d'Études Cognitives, École Normale Supérieure, 45, Rue d'Ulm, 75005 Paris, France. Tel.: +33 1 44 32 26 25; fax: +33 1 44 32 26 30.

E-mail address: jerome.sackur@gmail.com (J. Sackur).

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doi:10.1016/j.cognition.2009.01.010

can be stored; on the other hand, together with the American logician Alonzo Church (Church, 1935; Kleene, 1952; Turing,1948/1969), he proposed that any human computation can ultimately be described as a program of this universal logical machine.

This postulate, which has become known as the "Church-Turing thesis", suggests that at the formal level, the Turing machine is adequate as a description of complex human information processing. This was emphasized by Newell (1980), who stressed that the Church-Turing Thesis enables us to conceive of human minds as "physical symbol systems" on a par with computers. Yet this leaves entirely open the question of the psychological realization of the basic mechanisms that a Turing machine embodies. How complex serial processing is realized by the machinery of the human brain is an issue that was recognized since the time of Lashley (1951) and remains unresolved (for theoretical proposals, see Elman (1990), Roelfsema, Lamme, & Spekreijse (2000), Ullman (1984)). Indeed, although the computer metaphor of the mind has been helpful for the formal description of complex tasks, most researchers today would agree that the Turing machine is a very inadequate model of human brain architecture. As noted by Von Neumann himself (1958), the brain at the elementary level operates as a massively parallel collection of neurons, and its properties are widely different from those of a Turing machine: not only is it nearly impossible to tell apart the list of operations to be executed (the program) from the wiring of the device, but, even more importantly for us, the serial mode of operation which is the hallmark of a Turing machine is not apparent as a feature of the operations of the brain. Thus, perhaps the most basic assumption of the computer metaphor, namely that complex computations can be decomposed into elementary operations that can be processed in a serial sequence, is questionable at the brain level. Notice that seriality here does not mean that the flow of information in the processing is linear. There can be branches and loops, but at any point in time, the program is performing one operation and cannot proceed further on until this operation is completed. This implies, at the elementary level, that there is a chaining mechanism that ensures that two operations can be executed one after the other. Furthermore, the second operation must be in position to process information that it receives from the first one. This is precisely something that seems difficult to reconcile with the architecture of the brain.

The problem can be expressed using the three levels analysis put forth by Marr (1982): Marr distinguishes the computational level, which contains the description of the nature and goals of the computations; the algorithmic level which gives a description of the representations involved and the operations that are performed on them; and finaly the hardware implementation level. According to the Church–Turing thesis, the Turing machine is adequate at the computational level: it captures the goal of a vast class of human mental processes in which a complex operation is parsed into a series of simpler ones. Clearly, the neural implementation of this kind of processes remains largely unknown. In this paper we focus on the intermediate, algorithmic level. We ask how serial processing is enforced at the abstract level of representation and algorithm. We try to identify and characterize generic elementary operations which enable seriality. The most basic question in this regard is about transmission of information: when two operations are chained, some transmission of information must take place from the first to the second one. In the formalism of Turing machines, this is represented as the transition from one state of the machine to another or some symbol being written out on the tape. In the von Neuman architecture, this passing of information is realized by processes of input/output to memory. Thus, our study is about the elementary processes that enable multi-step cognition.

The question of the general organization of multi-step cognition has a long history in cognitive science. Starting with Miller, Galanter, and Pribram (1960), the theory of executive functions and planning behaviour has repeatedly shown that complex goal directed behaviour should be understood as hierarchies of behavioral subunits (see Botvinick (2008) for a recent review). Most relevant to our current concern is the body of work that has grown out of the seminal work of Anderson (1983). Building on the notion of "production system" in computer sciences (Newell, 1973). Anderson and colleagues developed a general framework for human cognition (Adaptive Control of Thought – Rational, see Anderson et al. (2004)). It consists in a general mechanism for selecting production rules fueled by sensory, motor, goal and memory modules. Along these lines, a number of cognitive tasks have been successfully modelled or analysed, including, algebraic and arithmetic tasks (Anderson, 2004; Qin et al., 2004), time estimation (Taatgen, van Rijn, & Anderson, 2007), task switching and multi-tasking (Byrne & Anderson, 2001; Sohn & Anderson, 2001), working memory (Sohn & Carlson, 2003), to name a few that are directly relevant to our purposes here. These models provide a principled account of human performance, rooted in a unified framework. These models, as well as other akin enterprises (see Meyer & Kieras,1997a, 1997b) emphasize the chained nature of cognition: at any moment in the execution of a task, information placed in buffers of specialized modules acts as data for the central production system, who in turn outputs new information to the buffers. Productions are considered if they match the input data, and selected according to their utility (see Anderson et al., 2004). Thus, both multi-steps cognition scheduling and information flow are the explicit targets of modelling within such general frameworks.

The issue we address here is different. We position ourselves at a lower level of analysis, and we target the more basic question of how two successive operations are performed one after the other, on a shared input stimulus. In other words, we are interested in the micro-level of control: not the broad question of how to organize thought processes, but assuming organization is defined (in our study this definition will be given by task design), how is it maintained. We do not present a general view of human cognition, but try to analyse in greater details the workings of the transmission of information from one process to the other (following the computer science concept (Ritchie & Thompson, 1974) we will sometimes use the term "piping"). Basically we ask: When does piping start? Is there a mechanism that controls piping and that can correct misfires and anticipations? and finally, Is piping typically associated with conscious processing?

In summary, we attempt to characterize more precisely the "chained" mode of processing, with the goal of ultimately becoming able to address the question of its brain implementation. We thus wanted to study a task that would meet the following requirements: it should be composed of two distinct operations; these two operations should involve cognitive processing on internal representations; they should share the same input representations, so as to be able to pass information from one to the other; and finally they should be as simple as possible, so as to allow for an examination of the simplest form of information piping. Elementary arithmetic was a natural choice, as arithmetical operations are typically meant to be chained. We thus devised a composite task made of two elementary operations on one digit numbers: Participants were required to perform an arithmetic operation (e.g. adding 2 to a stimulus digit), and then compare the result with five. By design, inputs to the second operation are similar to the inputs to the first operation. Our primary interest was in whether participants were able to maintain the very simple segmentation of the two sub-tasks or whether some parallel processing took place – noting that by design any such processing would be detrimental to performance. Thus, optimal performance should correspond to a direct transposition at the algorithmic level of the computational description of the task: complete the first operation before starting the second. This should be the goal maintained by control mechanisms. If this seriation is not straightforward (as will indeed be the case), some mechanism must intervene that should correct piping errors.

The simplest default model for our task is a simple serial model (see Fig. 1B) where the two sub-operations are performed sequentially, operation 2 starting only once operation 1 has completed. From this simple serial model we can derive very simple behavioral predictions. The first is that as compared to the simple comparison task, the composite task should add a measurable processing time. Analysis of this kind of model can proceed according to the logic of the additive factors method (Sternberg, 1969, 2001): if the two stages are indeed strictly serial, it should be possible to find experimental variables that separately influence each stage. Thus, we should find additive components in the response times, corresponding to each of the elementary operations. As these predictions are not substantiated in the data of our first experiment, we later propose more complex models that depart from strict seriality. Some cross-talk and parallelism occur between the two elementary operations. In Experiments 2 and 3, we try to pinpoint more precisely the time at which cross-talk intervenes. Finally, in our fourth experiment,we ask whether the control over information piping is able to act on subliminal representations. It seems indeed that the combination of novel and arbitrary sequences of operations is a kind of computation that requires consciousness (Dehaene & Naccache, 2001). We propose a direct test of this prediction by masking the stimuli on which participants work, thus engaging them in a kind of blindsight experiment. Moreover, this degradation of the stimulus enables us to assess which steps, in the elementary sequence of operations are more robust than others.

1.1. Terminology and general method

Let us now precise our terminology, for the description of complex cognitive tasks. We suppose the existence of *elementary operations* that are required in the description of any computation on abstract representations. These are akin to Ullman (1984) *routines*, although they are not limited to the visual domain. Notice that we do not suppose any simple correlation between elementary operations and cognitive or neurophysiological processors. It may or may not be the case that an elementary operation is performed by one single brain area. Elementary operations are building blocks in the computational definition and description of complex tasks. A task is the behavioral counterpart of an operation or series of operations, taking as input a stimulus and leading to a behavioral response. A task is either simple if its description contains only one operation, or composite if it contains more than one operation. Whenever a task is composite, the operations may be independent, if they operate on distinct inputs; this is the case in Psychological Refractory Period (PRP) paradigms (Meyer & Kieras, 1997b; Pashler & Johnston, 1998; Sigman & Dehaene, 2005; Telford, 1931; Welford, 1952) where participants are required to perform, within a single trial, two elementary operations (for instance choice response) on two temporally close stimuli. However, composite tasks can also comprise *chained* operations, if the output of one operation is used as input to the other. Such chaining in turn requires a mechanism for passing information across the two operations, *ie* a *piping* mechanism. Whenever two operations are chained, piping is needed to dispatch information from one processor to the next processor downstream. Presumably, some supervisory control system must take care of this chaining, that is the successive execution of the first operation, then piping, then the second operation.

Here, we only study one particular composite task made up of two chained sub-tasks, corresponding to two chained elementary operations. Throughout our experiments, the first operation in our composite task was always "add 2" or "subtract 2", performed on the limited set of target numbers 2, 4, 6, 8. We introduced a cycling rule (see Fig. 1A for a graphical version of the operations and tasks) so that the result of the first operation stayed within the set of the stimuli: thus when applied to 8, "add 2" would not yield 10, but 2; and similarly, "subtract 2" applied to 2 yield 8. We introduce the symbols $\oplus$ and $\ominus$ to denote our modified addition and subtraction. We should insist here that we need not, and do not, assume that these two operations are arithmetical in the sense of relying on the same psychological mechanisms as in more standard arithmetical paradigms. Clearly, the limited number of stimuli and the repetition of many trials with them encourages a simple memory retrieval strategy (see the work of G. Logan and

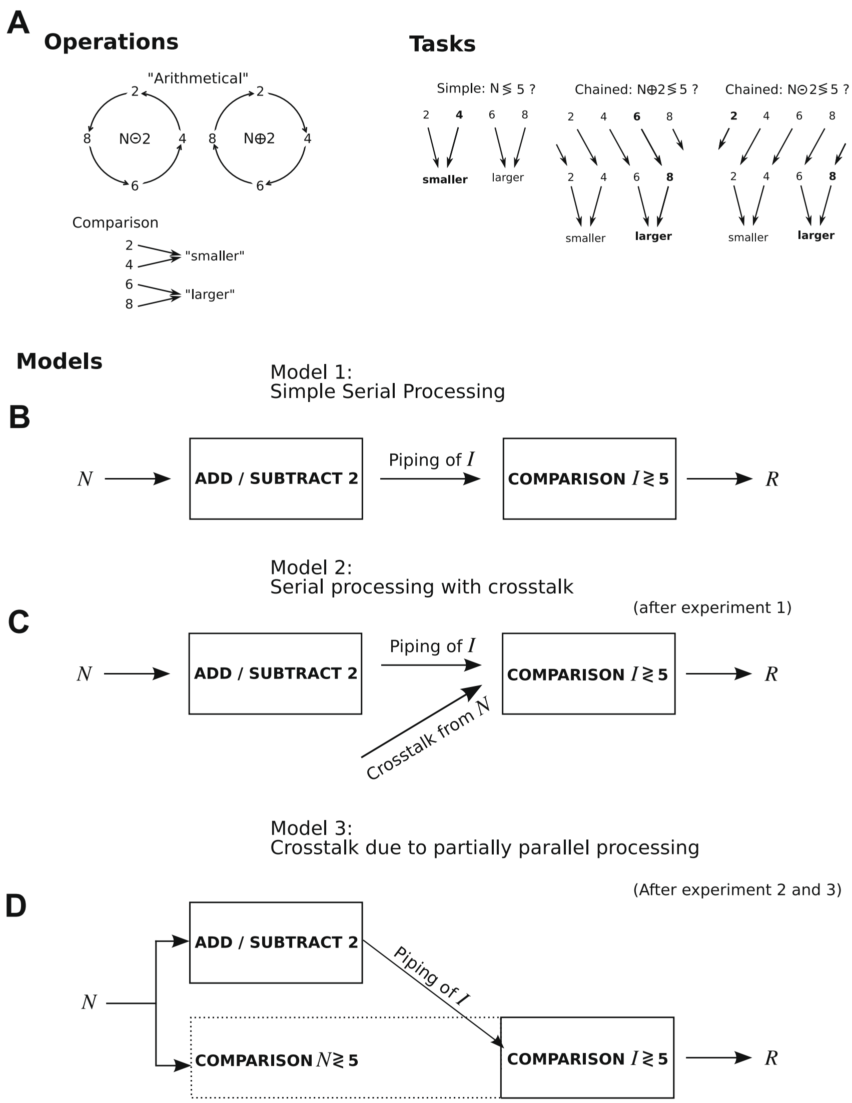

Fig. 1. Operations, tasks and models used in the four experiments. (A) Schematic representation of the operations that participants need to perform and of the tasks that are based on them. Note that the circular representation of the "arithmetical" operations, meant to emphasize the cycling rule, was never shown to participants. They were on the contrary instructed to perform an ordinary arithmetical operation, with some modifications for stimuli 2 and 8. For each task one example trial is emphasized in bold type. (B) Schematic representation of the three successive models. N represent the input digit, I its image according to one of the arithmetic operations (either $N \oplus 2$ or $N \ominus 2$) and R the response. Arrows represent information flow and operations are denoted in bold type. For the last revised model, the dotted box represent the premature application of the comparison operation on the input digit.

colleagues on automatization as memory retrieval, notably in the case of arithmetic: Choplin & Logan (2005); Klapp, Boches, Trabert, & Logan (1991); Logan (2002); Logan (1992, 1988); Logan & Klapp (1991); Reder & Ritter (1992)). However, none of our predictions depend on this first operation being "truly" arithmetical in any sense of the term. What matters is (a) that it should be computationally distinct from the second operation (b) that it should take the same kind of input as the second operation. These two requirements would still be fulfilled even if the first operation was implemented as an arbitrary paired associate retrieval. Thus the term "arithmetical operation" can be safely understood as a purely conventional one, refering to our above defined operations.[1] The second operation was a comparison to 5 as a fixed reference, which we will denote by the symbols "$N \gtrless 5$?". The labels "first operation" and "second operation" are relative to the formal description of the composition. However, whether they are indeed processed in this order is one of the empirical questions that we ask. Therefore, in order not to beg the question, we will refer to the "arithmetic

1 However, to anticipate on the results, there are some clear indications in the data that participants do compute the results as with ordinary arithmetical operations – we address this point extensively in the discussion of Experiment 1.

operations" ($N \oplus 2$ and $N \ominus 2$) versus the "comparison operation". The two complete composite operations will thus be denoted by $N \ominus 2 \gtrless 5$ and $N \oplus 2 \gtrless 5$.

We will use the term *image* to denote the result of the arithmetic operation. For instance, the image of stimulus 4 by the $N \ominus 2$ operation is 2. We shall use this term without any sensory connotations, but only in the mathematical sense of the unique member of the set {2, 4, 6, 8} which is associated to the stimulus by either of the arithmetic operations. The existence of an internal intermediate representation of this image is an open empirical question that we shall address in our experiments. The stimulus digit will be denoted by the letter *s*, and its image by the letter *i* (in the more complex priming experiment, described below, where both prime and target stimuli were presented on each trial, we use the letters *p*,*t* for the external stimuli, and *i* again for the image of the prime on which the arithmetic operation is performed).

Finally, a major determinant of response time will turn out to be the *congruence* (noted $\equiv$) between the target number and other numbers involved in the experiment. Two stimuli are congruent whenever they call for the same response under the comparison task, i.e. they are both greater or both smaller than five. We thus write $2 \equiv 4$ (because both are smaller than 5) but $2 \not\equiv 6$. In Experiments 1, 2 and 4, where participants processed a single stimulus the term *congruent* will denote trials where the stimulus and its image are congruent ($s \equiv i$) and *incongruent* ($s \not\equiv i$) otherwise. In Experiment 3, where two stimuli are presented (a prime and a target), but in which the prime elicits an image which may be identical to, or different from the target, the same congruence relation will permit two different categorizations of trials: we can consider either whether the prime and the target, or whether the image and the target are congruent according to the same relation.

2. Experiment 1: chronometric exploration

In the first experiment, we collect basic chronometric data on our paradigm in order to assess first whether the chaining of operations introduces a measurable delay in the response times (RTs) and whether participants rely on an underlying chaining process to perform the task. This is obviously required if we are to analyze chaining with behavioral means. Second, we want to check whether we can find additive contributions of each operation in the total response times, as predicted by the simple serial model. Therefore, we engaged participants in a simple response times experiment where they were presented with three types of trials, either the simple comparison ($N \gtrless 5$), or one of the two composite chained operations $N \oplus 2 \gtrless 5$ and $N \ominus 2 \gtrless 5$.

2.1. Method

2.1.1. Participants

Nineteen participants recruited from local universities took part in the experiment. Eleven were female and eight male. Ages ranged from 21 to 34.

2.1.2. Instructions

Participants were told that they would have to compare the stimuli 2, 4, 6, 8 to the fixed reference 5, which itself would never appear on the screen. They were also instructed that the experiment contained three conditions two of which required them to apply a mental transformation to the stimulus before the comparison. In the explanation of the operations, care was taken not to suggest a possible direct association between stimuli and responses. We presented the operations as numerical transformations which involved a cycle in order to take into account the transitions from 2 to 8 and conversely.

2.1.3. Apparatus, stimuli and design

Stimuli were presented on a CRT monitor at a 70 Hz refresh rate, controlled by a i486 computer running E-prime 1.1 (PST software, Pittsburgh, USA). Participants sat at 60 cm of the screen. The stimuli were the four digits 2, 4, 6, 8 presented in a white arial font on a black background. Digits were 2.8 cm in width and 3.2 in height, subtending a visual angle of 2°, with a viewing distance of approximately 80 cm. The fixation cross was 0.6 cm in width and height, subtending a visual angle of 0.4°.

Each trial consisted first in the presentation of a white fixation cross in the center of a black screen for 1000 ms after which the stimulus was presented during 29 ms. The screen remained black for an interval of 1000 ms during which participants were to respond using the two keys "*f*" and "*j*" of the keyboard. Half of the participants used their left hand for "smaller than five" and the other half used the right hand. Failure to respond during this interval or errors triggered a negative feedback.

The three different operations were grouped in blocks of 20 trials with 5 randomized repetitions of the four stimuli (2, 4, 6, 8). We used short blocks, thus requiring frequent operation switching between blocks in order to prevent automatization and direct stimulus response mapping. Each block was preceded by the display of the name of the task, which stayed on the screen until participants pressed the space bar. A feedback was presented at the end of each block if participants committed more than three errors. The order of the tasks was randomly selected for each participant and ten repetitions of the three block types were presented, thus totaling 600 trials per participant.

2.2. Results

This first experiment provides three important results. First, it shows that chained blocks are processed 85 ms slower and with more errors (4.3% points) than simple blocks. Second, within chained blocks, we observed a congruence effect: when the stimulus and its image are not on the same side of the reference, processing is slower (by 23 ms) and produces more errors (4.4% points) than when the image and the stimulus are both either smaller or greater than five. Third, analyses of performances for the special "cycled" trials, that is, chained trials for which the first operation departs from the ordinary addition or subtraction, show that processing of these trials differ from processing of the non-cycled trials. The following paragraphs provide the detailed statistical analyses.

One subject with more than 15% errors was excluded from the analysis. Here and in all subsequent analyses, ANOVAs on RTs were performed on median correct RTs with subject as random factor.

We first checked the effect of operation complexity on RTs and error rates for each stimulus. Results are shown in Fig. 2. Chained blocks produced slower responses than simple ones, and within each block type, RTs differed for each stimulus. To test for these effects, we performed a 4×3 ANOVA with factor stimuli (2, 4, 6, 8) and operation ($N \ominus 2 \gtrless 5$, $N \gtrless 5$, $N \oplus 2 \gtrless 5$). The effect of operation was significant (430 ms for simple comparison versus 515 and 516 ms for the $N \oplus 2 \gtrless 5$ and $N \ominus 2 \gtrless 5$ operations, $F(2,34) = 19.901, p < .001, \eta^2 = .539$). We also found a significant effect of stimuli (483, 487, 501, 477 ms for stimuli 2, 4, 6, 8; $F(3,51) = 5.287, p < .005, \eta^2 = .237$). Most importantly, we found a significant operation $\times$ stimuli interaction ($F(6,102) = 3.967, p < .005, \eta^2 = .189$).

In the parallel ANOVA on error rates the main effect of operation appeared significant: error rates were lower (4%) in simple blocks compared to chained blocks (7.6% and 8.9% in $N \oplus 2 \gtrless 5$ and $N \ominus 2 \gtrless 5$ operations $F(2,34) = 27.613, p < .001, \eta^2 = .618$). There was no effect of stimulus, but the stimuli $\times$ operation interaction was also significant ($F(6,102) = 4.134, p < 0.001, \eta^2 = .195$). This interaction shows the same pattern of distance and congruence effects that we found for RTs: slower trials had the lowest accuracy.

Inspection of Fig. 2A and B reveals that the operation $\times$ stimuli interaction corresponds to two different effects: congruence effect in chained blocks and distance effect in simple blocks. In chained blocks, image congruent trials ($s \equiv i$), that is trials where the stimulus and its image bear the same relation to five, are faster and yield less errors than incongruent trials ($s \not\equiv i$). This interference effect may signal the application of the arithmetic operations and the existence of the temporary representation of the image i. We tested directly this congruence effect within chained blocks with a 2×2 ANOVA on RTs with factors of image congruence ($s \equiv i$ vs $s \not\equiv i$) and block type ($N \oplus 2 \gtrless 5$ and $N \ominus 2 \gtrless 5$). We found significant effect of congruence, $s \equiv i$ trials being 23 ms faster than $s \not\equiv i$ ones ($F(1,17) = 11.548, p < 0.005, \eta^2 = .404$). There was no main block type effect. However, we found a significant block type $\times$ congruence interaction in virtue of which the effect of congruence was 35.7 ms in $N \ominus 2 \gtrless 5$ blocks, but only 10.3 ms in $N \oplus 2 \gtrless 5$ ones ($F(1,17) = 4.712, p < 0.05, \eta^2 = .217$). The ANOVA on error rates showed a somewhat different pattern: the two main effects were significant, but not the interaction ($p > .19$). Congruent trials yielded less errors than incongruent (6.1% vs 10.5%, $F(1,17) = 6.087, p < 0.05, \eta^2 = .264$), $N \oplus 2 \gtrless 5$ blocks resulted in significantly less errors than $N \ominus 2 \gtrless 5$ (7.6% as opposed to 8.9%, $F(1,17) = 4.562, p < 0.05, \eta^2 = .212$). Overall, the results confirm the importance of stimulus - image congruence as a determinant of performance in the chained task, thus pointing to crosstalk between the successive arithmetic and comparison operations.

In simple comparison blocks, the classical distance effect was observed: stimuli closer to the reference (4 and 6) yield slower RTs (446 ms) and give rise to more errors (6.1%) than "far" (2 and 8) stimuli (RT: 412 ms, errors: 1.9%), and these effects were significant (RTs: $F(1,17) = 39.187, p < .001, \eta^2 = .697$; errors $F(1,17) = 21.053, p < .001, \eta^2 = .553$). Examination of Fig. 2B yields no evidence that a similar distance effect was present in chained blocks. Yet, a clear prediction of the Simple Serial Model is

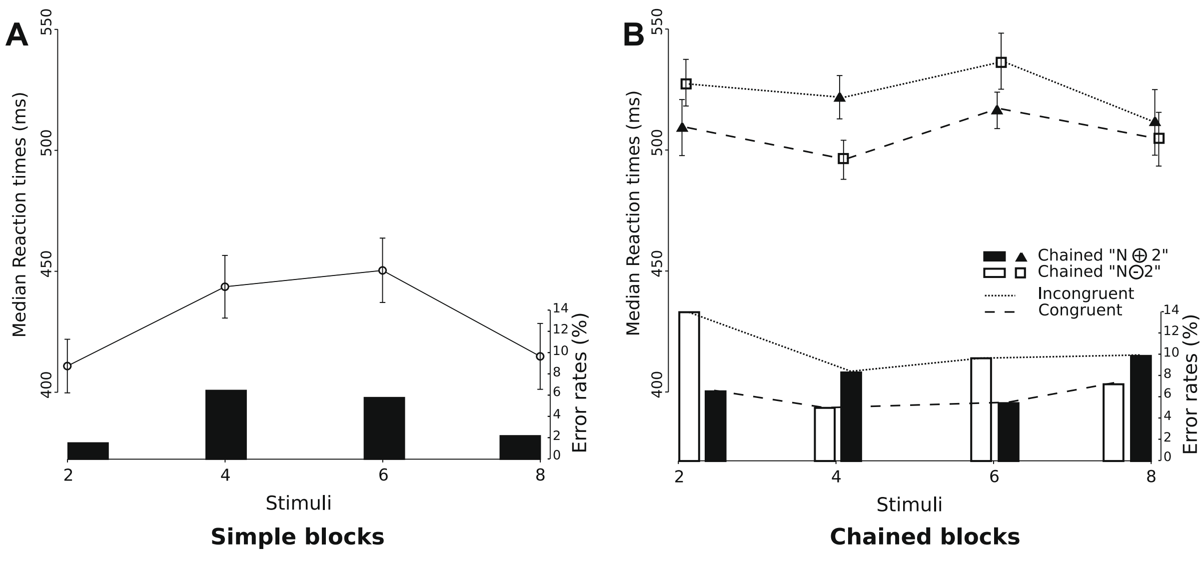

Fig. 2. Results of Experiment 1 (chronometric). (A) Median response times and error rates in the non chained blocks (simple comparison) for each of the four stimuli. (B) Median response times and error rates in the chained blocks. Notice that for the response times, congruent and incongruent trials are joined respectively by dotted and dashed lines, while individual symbols represent values for one block type. Error bars represent plus and minus one standard error of the mean after removal of the subject means.

that there should be a distance effect on the image. Indeed, if the comparator module operates on a representation of the stimulus minus or plus 2, participants should be slower and make more errors for stimuli whose images are close to the reference. We tested the existence of such an effect by running a 2 × 2 ANOVA with factors distance of stimulus (close: $s = 4$ or 6, far: $s = 2$ or 8) and distance of image (close: $i = 4$ or 6, far: $i = 2$ or 8). None of the main effects were significant ($ps > .5$). The interaction was significant ($F(1,17) = 8.668, p < .01, \eta^2 = .337$), but this interaction reflects only the $s \equiv i$ congruence effect. Thus, the simple serial model does not account for the data. The insertion of an "arithmetical" stage between the perceptual and the comparison stages does not obey the pure insertion hypothesis.

In addition to the basic analysis just presented, we also wanted to assess whether the cycling rule poses a special difficulty for participants. The fact that stimulus 2 is paired with 8 by the $N \ominus 2$ operation, and 8 paired with 2 by the $N \oplus 2$ operation, departs from the standard rules of addition and subtraction. This might lead to very different performances for these special conditions. We tested this with *t*-tests comparing response times and error rates for stimuli for which the cycling applies (stimulus 2 within $N \ominus 2$ blocks and stimulus 8 within $N \oplus 2$ blocks). There was no effect on RTs ($p > .36$), but there was an effect on error rates: participant made more errors when they had to apply the cycling rule than otherwise (errors 7% and 12% for trials respectively without and with cycling; $t(17) = 3.209, p < .01$). This significant difference is maintained even when we restrict the comparison to incongruent trials ($t(17) = 2.215, p < .05$), but interestingly, the difference is reversed: there are *less* errors for cycled (8.7%) than non cycled (9.0%) trials. Thus, there seems to be some trade-off between speed and accuracy on cycling trials. On the one hand this suggests that the conditions with and without cycling are not processed very differently, because participants were able to process them with comparable speed. Yet, the small differences in error rates shows that cycled trials are slightly *easier* than comparable incongruent non-cycled trials. Below we discuss this apparent paradox which, if anything, suggests that participants in part rely on the "natural" arithmetic operations, when engaged in the composite operation.

2.3. Discussion

This experiment establishes some basic facts about the simple and chained operations. Our chained task is feasible and the added complexity of chaining induces a measurable delay of 90 ms, and an increase in error rates. According to a simple serial model, this difference would be explained by the insertion of an arithmetic stage between stimulus encoding and comparison stages. However, we have here a clear case of a violation of the pure insertion logic (Donders, 1868; Ilan & Miller, 1994; Ulrich, Mattes, & Miller, 1999) that motivates the simple serial model. Essentially, insertion of the arithmetic operation would entail a distance effect on the image, which we do not observe. Distance effects are ubiquitous whenever comparison is involved (Pinel, Piazza, Le Bihan, & Dehaene, 2004), and notably in numerical comparison (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Moyer & Landauer, 1967, 1973; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). They give rise to slower RTs and increased error rates, as the to be compared item gets closer to the reference. If the arithmetic operation were purely inserted between the perceptual and the comparison stages, then the comparator should take as input the image computed by the arithmetic stage, and it should display a distance effect with respect to five. The absence of this effect suffices to reject the simple serial model.

Once the pure insertion of the arithmetic operation fails, we face two possibilities: first, it might be the case that participants do not at all perform the "composite" operation as composite, but treat it as a whole—most probably by using a direct Stimulus – Response (SR) mapping, without reference to the underlying components of the operations. A second possibility is that participants do keep separate representations of the elementary components of the composite operation, but that additional processes modify its intended serial organization. At first sight, it seems that the congruence effect is a good sign of the internal representation of the image of the stimulus according to the arithmetic operation. When the stimulus and its image are not on the same side of five, we observe slower RTs and more errors. This seems to show that the stimulus and its image are concurently represented, and that both are fed to the comparison stage, yielding slower RTs and more errors when they are contradictory. However, a lower level explanation is possible, by which congruence effects simply reflect a response level interference: perhaps participants cannot inhibit the response code associated to the simple comparison while they are engaged in the composite operation. Thus, the response code associated to the overtrained simple comparison and the response code associated to the new arbitrary operation might conflict, giving rise to the congruence effect – and this does not compel us to assume an intermediate representation of the image. The congruence effect is compatible with the notion that some failure of control processes yields parallel activation of two SR mappings, one for the simple comparison, the other for the new arbitrary operation.

However, this does not seem tenable for many reasons: First, this model predicts that when the response code for the two operations (simple comparison and new, arbitrary "composite" operation) are identical, RTs should be as fast as in the simple comparison. This is not the case: even congruent trials in chained blocks are much slower than the slowest trials in pure comparison blocks. Chained blocks suffer from an "overhead" that is best explained by supposing that participants do compute the internal image, even when it should not be necessary according to an SR mapping explanation. Second, results on cycled trials, which do not abide by the ordinary rules of addition and subtraction, suggest that participants do rely on these rules, when possible. Indeed, differences in error rates for cycled stimuli and non-cycled stimuli strongly suggest not only an independent process for the arithmetical operations, but even more, it suggests that it is implemented by participants as a real arithmetical operation. If participants were relying on a global SR mapping, there is no reason why cycled trials should be treated differently than non cycled trials. Most interesting in this respect is the apparently paradoxical effect on error rates between incongruent cycled and incongruent non cycled trials. The fact that incongruent cycled trials cause less errors than non-cycled ones shows that it is easier to process incongruent trials when the link between the stimulus and its image is arbitrary than when it follows one of the "natural" arithmetic operations. The arbitrary cycling rule creates weaker activation of the image than the standard addition and subtraction. This is indicative that the congruence effect does not merely reflect a response level conflict, but that the image of the stimulus according to the arithmetic operation is indeed internally computed. This computation is easier and produces stronger activation, hence stronger interference, when the operation is in accordance with the ordinary addition and subtraction.

Third, if the "arithmetical" operations were not somewhat independent and were not in part processed as standard additions and subtractions, there should not be any differences between $N \oplus 2 \gtrless 5$ blocks and $N \ominus 2 \gtrless 5$ blocks. Yet, we found at least to important differences: first, while RTs are not significantly different, error rates do significantly differ between the two kinds of chained blocks: participant make more errors in "subtraction blocks" ($N \ominus 2 \gtrless 5$) than in "addition" blocks ($N \oplus 2 \gtrless 5$)—a result that is in agreement with the notion that subtraction is more difficult and less routinized than addition. Second, and more important, the interaction between the congruence effect and the type of operation is a strong sign in favor of an independent representation of the image, or again, of an independent arithmetic processing stage. We found that the congruence effect is stronger when the arithmetic operation is $N \ominus 2$ rather than $N \oplus 2$. This, again, appears to make sense only in view of the fact that subtraction is more difficult and less automatized than addition (Dehaene & Cohen, 1997; Lemer, Dehaene, Spelke, & Cohen, 2003). Subtraction requires deeper processing (Craik & Tulving, 1975), thus creating a stronger image, which in turn may interfere more with the representation of the stimulus itself.

Thus, even though the congruence effects cannot by themselves disprove the hypothesis of a global SR remapping for the composite operations, the preceding reasoning strongly suggests that in part they are due to an internal representation of the image being computed by an independent process. Accordingly, a minimal revision of the serial model is to suppose that the comparison operator receives input from both the representation of the stimulus and from its image. We call this revised model the "Serial processing with crosstalk" model (see Fig. 1C). According to this model, the operations are organized in an overall serial manner but the second processor mistakenly receives input, not only from the appropriate image representation, but also from the (inappropriate) representation of the stimulus. Note that, with this revised model, it is possible to salvage the hypothesis of serial processing of the arithmetic and comparison operations. One can suppose that the comparison processor only starts once the arithmetic operation has terminated, as requested by the serial computational model, but that selection of input fails in excluding other sources than the internal image. Thus, the piping process mixes the image with some trace of the initial stimulus. This crosstalk would have the effect of interfering with the decision made by the comparison processor. If the stimulus and its image favor the same response, accumulation of evidence will be faster, while it will be slower if they are incongruent. Eventually, in both cases, the response favored by the image will win the competition either because the activation due to the remanence of the stimulus is weaker in the first place or because it tends to decay.

This revised model might also explain why we do not find any distance effect in our results. Supposing that the comparison stage indeed suffers from such cross-talk and works on a mixed input, it becomes quite difficult to predict which distance measure (the distance between the stimulus and the reference, or that between the image and the reference) should have a dominant influence on its speed. It is tempting to speculate that one should find concomitant effects of distance from both the stimulus and the image to the standard 5, but the limited size of the present stimulus set made it impossible to probe this possibility. Based on the present data, the most parsimonious interpretation of the results might be that the congruence effect is dominant and levels off any possible distance effect.

In summary, this first experiment suggests that the chained operation does involve the internal computation of an intermediate representation which is the image of the stimulus based on the arithmetic operation. However, it also suggests that the two chained operations, while possibly operating in an overall serial mode, are not as clearly separated and selective as the simple serial model supposes. The simplest modification of this model, compatible with the data of our first experiment, consists in adding a form of crosstalk, to the effect that what is piped to the second comparison operation combines both the internal image generated by the first operation and the representation of the stimulus itself.

Experiment 2 will try to probe this hypothetical sequential dynamics with a cue signaling when to respond. If the serial model with crosstalk is correct, then we should find two distinct stages: one without any information about the result of the second operation, and thus without any bias in favor of one or the other response; and a second stage during which we see the progressive build-up of information about the correct response. Cross-talk from the stimulus should emerge only in the latter stage.

3. Experiment 2: cued-response

In Experiment 2 subjects were engaged in the same simple and chained tasks, but they were interrupted and forced to respond at a variable interval after presentation of the stimulus. We therefore expected to gain access to the build up of accuracy, and by this means to be able to analyse the points of time at which information about the output of the second operation started to accumulate. The time course of this build up should give us some information on the time needed to complete the arithmetic operation. It should also give us some information regarding the period during which interference by irrelevant comparison occurs. If the serial model with cross-talk is correct, while the system is occupied with the arithmetic operation, we should not detect any bias for one or the other response. On the contrary if crosstalk occurs earlier in the processing stream, that is if the stimulus is piped to the comparison operation and starts being processed *before* the arithmetic operation is over, we might find a bias corresponding to the comparison of the input stimulus with 5. This should have an impact on how congruent and incongruent chained trials are processed: if the simple serial model with crosstalk is correct, accumulation of evidence for the two types of trials should start at the same time, but the rate of accumulation should differ, being slower for the incongruent and faster for the congruent trials. On the contrary, if crosstalk occurs before the arithmetic operation is completed, we expect to find some bias in favor of correct responses in the case of congruent trials before the final build up of accuracy due to the comparison of the image starts.

3.1. Method

3.1.1. Participants

Participants were eight students from local universities who were paid 10 euros per session for their participation in one practice session and four experimental sessions of one hour each. Five were male and three were female, two were left handed, all had normal or corrected to normal vision. All were naive to the tasks and the hypotheses of the study.

3.1.2. Apparatus, stimuli and design

Stimuli were presented on a standard CRT monitor at a 85 Hz refresh rate, controlled by a i486 computer running E-prime 1.1 (Psychology Software Tools, Inc. Pittsburgh, USA). Participants sat at 80 cm of the screen and wore headphones. The stimuli were the four digits 2, 4, 6, 8 presented in a white arial font on a black background. Digits were 2.8 cm in width and 3.2 in height, subtending a visual angle of 2°, with a viewing distance of approximately 80 cm. The fixation cross was 0.6 cm in width and height, subtending a visual angle of 0.4°. Participants responded using a microswitch response pad (Electrical Geodesics Inc.) connected to the parallel port of the computer. Each session comprised 24 blocks in which participants had to perform one operation: Simple, where participants had to compare the stimulus to 5; chained $N \oplus 2$, where they were required to compare to 5 the result of the application of the $N \oplus 2$ operation as defined in the previous experiment; chained $N \ominus 2$, where they had to compare the result of the application of $N \ominus 2$ operation. The order of each block changed across sessions. The basic structure of each trial was as follows: first a fixation cross stayed on the screen for 1 sec and was immediately followed by the stimulus. At a variable SOA of 50, 100, 200, 400 and 800 ms a pure tone of 2093 Hz lasting 300 ms was sounded, instructing the participants to respond. Participants received feedback about their performance only when they failed to respond during the tone, in which case they were informed of their failure (either: “no response”, “too fast” or “too slow”) in white courier font on a purple background for 2000 ms. When the participants did respond during the 300 ms of the tone, the screen stayed black for 1000 ms before the beginning of the next trial.

Each block was structured as follows: there were first two short training periods, the first one serving as reminder about the operation which was to be performed. In this training period, the tone was at a fixed SOA of 600 ms and participants had a systematic feedback on their accuracy with a reminder about the operation. Participants had a minimum of 6 random training trials, but received new series of 6 trials until they reached a criterion of 0 or 1 error on one series. Next, there was a training period on speeded response where the stimulus was always 5, and where participants were instructed to press the two keys simultaneously during the 300 ms tone, which was sounded at one of the five variable SOAs. In this case, participants had feedback about their speed performance. Participants had a minimum of five trials but training started anew until they reached a criterion of 1 or less untimely response. Finally the experimental block begun with 20 trials (one for each of the five SOAs × the four stimuli). Again, as in Experiment 1, we used short blocks, thus requiring frequent operation switching between blocks in order to prevent automatization and direct stimulus response mapping. Thus, during one session, there were 32 trials for each SOA × task conditions, and each participant contributed 128 trials over four sessions.

3.2. Results

Experiment 2 provides one critical set of results: when we analysed the build-up of accuracy as time from the stimulus elapses, we observed that chained congruent and chained incongruent trials differed very early in the processing. When interrupted 50 ms after stimulus presentation, participants were at chance for the chained incongruent trials, while they were largely above chance (70% correct) for the chained congruent trials. Significant differences in accuracy between the three major conditions (simple comparison, chained congruent and chained incongruent) were maintained up to 400 ms after stimulus presentation, but disappeared at an SOA of 800 ms. Detailed statistical analyses are presented in the following paragraphs.

We analysed the data of the four experimental sessions. We excluded anticipations (responses occurring before the probe tone onset) and slow responses beyond 400 ms after tone onset. This had the consequence that we retained as valid some trials that did not fit in the 300 ms window during which participants were instructed to respond, and it resulted in the exclusion of 6.6% of the trials.

One participant failed to perform the task, in that accuracy at the longest Stimulus – Probe SOA (800 ms) was at 60%, while for all other participants it was above 90%. This participant was therefore excluded from any subsequent analysis.

Our analysis focussed on the build up of accuracy as a function of stimulus – probe SOA. We wanted to determine the time at which crosstalk occured and its influence on the way accuracy increased: either congruent and incongruent trials differed only by the rate of accumulation of evidence once the second operation had started, or these two types of trials differed even before the starting point of the operation on the image of the stimulus. We therefore had to analyse the impact of congruence at various points in time after presentation of the stimulus. We thus plotted accuracy as a function of increasing stimulus – probe SOAs for three types of trials: simple operation, chained congruent and chained incongruent. The results is shown in Fig. 3. The increase in performance as time from the stimulus elapses is clearly different in the three conditions: initial performance (at the shortest stimulus - probe SOA) is high in the simple condition and in the chained congruent condition, whereas it is at the level of chance in the chained incongruent condition. Thus the build-up of accuracy seems delayed or shifted in time in the chained incongruent condition.

In order to statistically assess these effects, we ran a 5 $\times$ 3 repeated measures ANOVA with factors Stimulus-Probe SOA (levels: 50, 100, 200, 400, 800 ms) and complexity (simple, chained congruent ($s \equiv i$) and chained incongruent ($s \not\equiv i$)). The two main effects were significant as well as the interaction: Stimulus-Probe SOA: $F(1,6) = 100.94$, $p < .001, \eta^2 = .944$; complexity: $(F(2,12) = 29.907, p < .001$, η^2=.833); stimulus - probe SOA $\times$ complexity interaction $(F(2,12) = 10.01, p < .005, \eta^2 = .625)$. Planned contrasts with two-tailed paired t-tests showed that for the three fastest stimulus - probe SOA (50, 100, 200 ms) all three conditions were significantly different from each other (minimum $t(6) = 2.492, p < .05$). At the slowest SOA (800 ms), there was no significant difference in accuracy between the three conditions (maximum $t(6) = 2.195$, $p > .05$). At the intermediate 400 ms, participants' accuracy was significantly worse for the chained incongruent ($t(6) = 3.83, p < .01$), while simple and chained congruent conditions did not differ ($t(6) = 2.04, p > .05$).

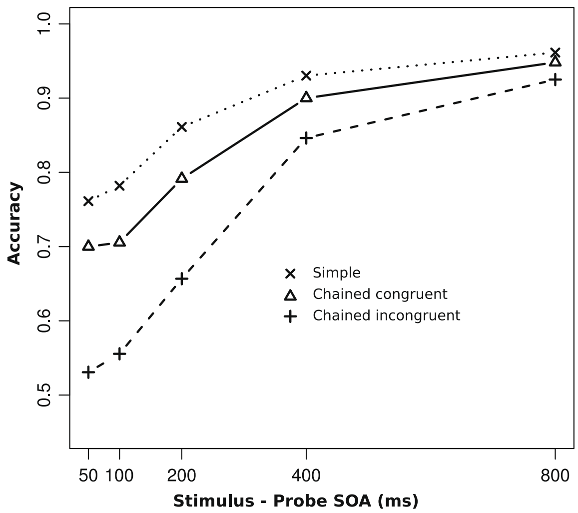

Fig. 3. Speed-accuracy results for Experiment 2 (cued-response procedure). Accuracy as a function of the stimulus – probe SOA for three types of trials: non chained (simple comparison), chained congruent (image of the stimulus on the same side of five as the stimulus), chained incongruent (image and prime on opposite sides of five).

One further question is whether performance at the shortest SOA, in the chained incongruent condition, was better or worse than chance level. Across participants, performance was at chance ($t(6) = .912, p > .3$). However, within participants, when analysed across sessions, we found that although five participants were at chance, one was above (73% correct, $t(3) = 9.62, p < .005$), while another was below (46% correct, $t(3) = -8.29, p < .005$).

Even though our main focus in this experiment was on accuracy, we analysed RTs to the probe, so as to have a measure of participants difficulty in performing the speeded response task. A 5 $\times$ 2 repeated measures ANOVA on median RTs (both correct and incorrect) with factors stimulus-probe SOA and chaining (chained *vs* non chained blocks) yielded a significant main effect of SOA $((F(1,6) = 22.73, p < 0.01, \eta^2 = 0.791))$ by which participants were consistently faster as the stimulus-probe SOA increased (SOA = 50: 245 ms, SOA=100: 241 ms, SOA = 200: 232 ms, SOA = 400: 215 ms, SOA = 800: 180 ms). The main effect of chaining did not reach significance $(F(1,6) = 5.78, p > 0.05)$. There was a significant interaction $(F(1,6) = 18.11, p < 0.01, \eta^2 = 0.751)$: RTs were faster for simple trials at the three shortest SOAs (the maximum difference was 14 ms at the 50 ms SOA), while this effect disappeared or even was inverted at the longest SOA (−4 ms). This interaction is consistent with the notion that participants prepare themselves differently for chained and simple trials. Chained trials demand a more complex task setting, so that full preparation for trial execution is not accomplished with the shortest SOAs.

3.3. Discussion

The logic of Experiment 2 was to probe the informational state of participants by interrupting them while they were performing the tasks. The main result is that there is a time shift in the build up of accuracy, which is slower in the chained than in the simple condition. This shift is the counterpart of the delay that we observed in the first experiment. We also find a measurable shift in the build up of accuracy between the congruent and incongruent trials (stimulus – image congruence), which reveals the interference that we already observed in Experiment 1. Again, this interference falsifies the simple serial model.

The cued-response method allows a preliminary analysis of the time course of the processes involved in the chained operations. It enables us to determine when crosstalk happens. Even at the shortest stimulus-probe SOA, when participants are interrupted early in processing, we already see a difference between congruent and incongruent trials. When the stimulus and its image are congruent, a high rate of correct responses is seen, while responses remain close to chance level on incongruent trials. This shows that cross-talk appears very early in the processing, suggesting that the second operation does not wait until after the arithmetic operation is completed.

With the present data the hypothesis of a serial organization of the two successive operations is no longer tenable. Rather the two operations must occur partially in parallel, with the comparison operation initially taking as input the stimulus itself before its image has been computed. This calls for a further revision of the processing model. We call our third model, depicted in Fig. 1D, the model of "crosstalk due to partially parallel processing". The new model assumes that the comparison operation starts even before the arithmetic operation is completed. At this point, the comparison process obviously has not yet received the appropriate data that it should work on. Nevertheless, we speculate that it is already active and initially takes as a default input the stimulus itself, thus leading to an early congruence effect. Only later does it eventually begin to process the stimulus image, as requested by the instructions.

In the end, the final model that we obtain is therefore one in which (1) the subject attempts to organize the two successive operations in the appropriate serial order (2) the second operation nevertheless starts too early and is executed partially in parallel with the first, momentarily taking as input an inappropriate number (the stimulus itself, rather than its arithmetic image).

In this respect, it is interesting that at all but the two longest SOAs, performance is worse on chained congruent trials than on simple comparison trials. This finding is compatible with the notion that on chained trials, the comparison operation indeed erroneously starts on the stimulus number, but with a lower speed and efficiency than on trials in which comparison is the desired operation. If crosstalk occured only at the response selection level, we should not expect to find any difference between simple and chained congruent trials, since in the latter, both the stimulus and its image code for the same response. Thus, the data provide evidence for a partial and imperfect control over serial operations: the comparison operation is active earlier than it should be under a strictly serial model, suggesting a "leakage" of executive control signals to the wrong operation. However, this pre-activation is definitely not as strong as when an operation is deliberately selected as task-relevant.

Finally, if comparison initially proceeds on the stimulus number, why do not we observe below-chance performance on incongruent trials, at least at the shortest SOA where the stop signal supposedly interrupts processing early on? A likely explanation is that, even at the shortest SOA, the stop signal does not really interrupt the decision at its earliest stage. Rather, we probably miss the initial part of the evidence accumulation process that leads to a final decision (Fig. 4). Indeed, the response time to the auditory stop cue was relatively slow (mean of 223 ms) and slowest at the shortest SOA of 50 ms (RT = 260 ms). Adding this RT to the SOA, we can infer that in the shortest case, the arithmetic task was interrupted about 310 ms after its onset – leaving quite enough time for the initial evidence accumulated from the stimulus number and from its image to cancel each other on incongruent trials. This interpretation would also explain why the level of performance in the congruent and simple task conditions was so high, even at the shortest SOA. We note that there is considerable interindividual differences on this precise point. Thus a more refined procedure, tuned to each participant's unconstrained speed, would perhaps enable us to uncover earlier stages, where performances might be below chance, in the chained incongruent cases. However, it may also be the case that our tasks are performed too fast for an effective application of the stop-signal procedure. Interestingly, previous studies using the stop-signal procedure (see for instance McElree & Dosher, 1989; McElree, Foraker, & Dyer, 2003), studied more difficult tasks (memory retrieval or linguistic judgments of acceptability), where chance performances were obtained at slower latencies of around 400 ms. Cued responding may not be the optimal way to analyse the time course of information accrual with very simple, elementary tasks. This is why we now turn to a priming study.

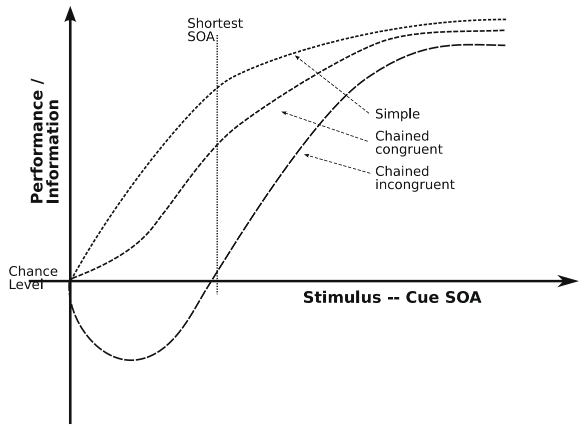

Fig. 4. Suggested rate of information accrual in Experiment 2 (cued-response procedure). The shortest stimulus – cue SOA may not be short enough to capture the below chance performance for the chained incongruent condition.

4. Experiment 3: priming

Experiment 2 gives us some information concerning the time course of information build-up, but it does that at the cost of an important perturbation of the execution of the tasks themselves. The cue that signals when to respond is not a neutral way to examine the informational state during a task. Rather, responding to the cue constitutes a task in and of itself, which interrupts the main task under study. Therefore, in Experiment 3, we use priming as a potentially less intrusive method. A prime digit was used to trigger the application of the arithmetic operation, while a target served as the stimulus on which participants were to respond with the comparison operation. With this use of priming, the target is an external stimulus corresponding to the intermediate image that participants compute. Therefore, with varying prime – target SOAs, we should be able to measure how far participant could go into the application of the operations – as revealed by the priming effects. If the model which assumes a partially parallel and concurrent processing of the stimulus and of its image by the arithmetic operation is correct, we expect to find first a period of priming by the stimulus, followed by a period where priming effects are mostly due to the image of the stimulus by the arithmetic operations. We therefore expected to find both strategic priming effects, at long SOAs, reflecting the extent to which subjects were able to perform the arithmetic operation, and automatic priming effects, at short SOAs, reflecting the untimely application of the comparison operation on the prime itself. This would parallel the initially high accuracy level in chained congruent conditions of Experiment 2. Notice that this opposition of "strategic" and "automatic" priming can be seen as an extension of the methodology of Neely (1977). However, we will be able to analyse more finely the levels of processing in each kind of priming, with the help of different congruence relationships between prime and target.

Accordingly, we engaged participants in a comparison task on numerical targets, each preceded by a prime (see Fig. 5B for the design of the task). We assumed that if we successively displayed two stimuli, the second of which could be the image of the first according to the arithmetic operation, and if we informed participants about this possible link, they would be able to use this information strategically. Thus we designed three types of blocks: one for each of our arithmetic operations, and the third without operation, serving as a baseline. In the first two types of blocks, the majority of prime–target pairs were predictable on the basis of one of the arithmetic ($N \oplus 2$ or $N \ominus 2$) operations. Therefore, denoting the prime by p, the target by t and the image of the prime by i, a majority of trials in these "chained" blocks were of a $t = i$ type, that is the target was the result of the application of the operation to the prime. The remaining trials were, in equal proportions, either prime repeated ($t = p$ trials), or followed the opposite operation (that is $t = p \oplus 2$ in $N \ominus 2$ blocks, and *vice versa*). These were violation of expectations ($t = \bar{\imath}$) trials. The design was known to the participants and they were instructed to use their knowledge of the operations to increase the efficiency of their responding. In the additional simple block, equal proportions of $t = p \oplus 2$, $t = p \ominus 2$ and $t = p$ trials were used, and participants were required to perform the simple comparison operation without processing the prime itself.

4.1. Method

4.1.1. Participants

Twenty students from local universities participated in the experiment. Thirteen were male and seven were female. Ages ranged from 18 to 32 years old.

4.1.2. Apparatus, stimuli and design

Stimuli were presented on a standard CRT monitor at 70 Hz refresh rate, controlled by an i486 computer running

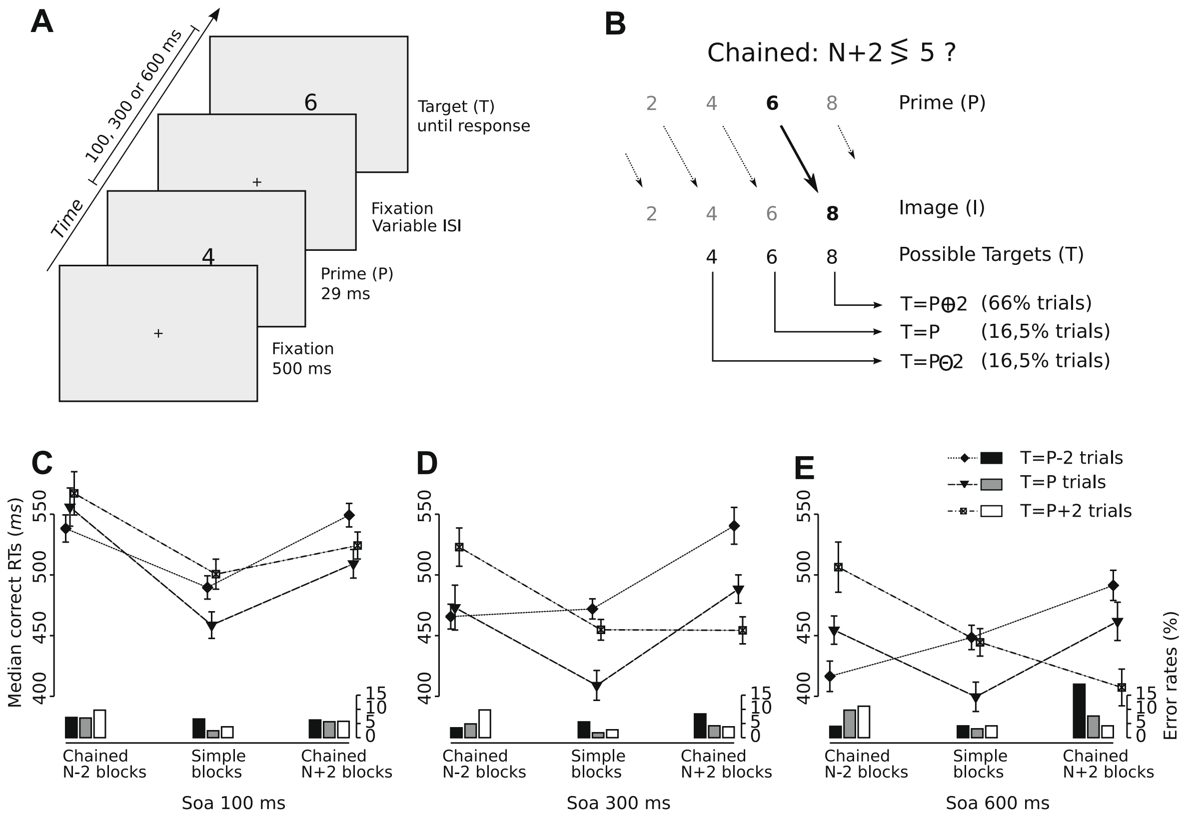

Fig. 5. Design and main results of Experiment 3 (priming). (A) Structure of one trial. All stimuli appeared at fixation. (B) Structure of the priming. The prime (*P*) was visually presented and participants were instructed to internally generate its image (*I*) according to one of the arithmetic operations (in this example, $N \oplus 2$). Then the target was visually presented and participants had to compare it to five. Since for a greater proportion of trials the target was the image of the stimulus, participants could benefit from a form of strategic priming based on the arithmetic operation. (C)–(E) Median response times and error rates as a function of trial and block types. Each panel shows the data for one of the three prime – target SOAs (100, 300 and 600 ms). Error rates and response times for trials with valid primes (for instance $t = p \oplus 2$ trials in $N \oplus 2$ blocks) diminishes as the SOA increases.

Expe 6 software (Pallier, Dupoux, & Jeannin, 1997). Stimuli were the four digits 2, 4, 6, 8, presented in a sans serif font 0.6 cm in width and 1 cm in height, in white on a black background. With a viewing distance of approximately 60 cm, they subtended a visual angle of .6°. Responses were collected using a microswitch response pad (Electrical Geodesics Inc.) connected to the parallel port of the computer. Participants used the index fingers of their two hands to respond. Each trial (see Fig. 5A) began by the presentation of a fixation cross for 500 ms, which was immediately followed by the prime for 29 ms, a fixation cross for a variable interval and finally the target which stayed on screen until participants responded. The intermediate fixation screen was such that the prime–target SOA was either 100, 300 or 600 ms.

The experiment contained six blocks each containing 72 trials with 18 additional trials for training. Three kinds of blocks were used: chained $N \oplus 2$ blocks, where 48 trials (66%) were of the $t = p \oplus 2$ type, while 12 (16.5%) were $t = p \ominus 2$ and 12 (16.5%) were $t = p$ trials; chained $N \ominus 2$ blocks with similarly 48 (66%) $t = p \ominus 2$ trials and again 16.5% of $t = p \oplus 2$ and $t = p$ trials; and finally simple blocks with the same number (24) of each of the three trial types: $t = p \ominus 2, t = p \oplus 2$ and $t = p$. Each kind of block appeared twice. They were presented in the three possible orders balanced across participants. Within each block the task was to compare the target to five as a fixed reference, but in chained blocks, participants were informed about the operation and instructed to use it in order to improve their performance. For each participant, response side changed after the third block, so as to limit the possible effect of direct motor specification of the response. In each of these conditions the targets were equally often one of the four possible digits. Three stimulus onset asynchronies (SOAs) were used: 100, 300 and 600 ms. Within each block, SOA and trial type were fully crossed, in a randomized factorial design.

4.1.3. Instructions

Participants were told that they would see two numbers successively on the center of the screen, and that they would have to decide whether the second was smaller or larger than 5, as fast and accurately as possible, by pressing one of two keys. Participants were told that in some blocks, the second of the two numbers would most often be the result of the application of an arithmetical operation to the first number. They were asked to use this arithmetical operation to increase the speed and accuracy of their responses. The exact nature of the operations was explained at the beginning of the experiment. Before each arithmetical block, the name of the operation to be applied and the pairing of numbers according to it, was displayed on the screen as instructions, for unlimited study time. Before simple blocks, participants were instructed to use the first number as a signal for the apparition of the second number. Participants were told that the response sides for smaller and larger than five would change after the third block. Participants were not told the exact percentage of $t = i$ trials pairs in arithmetical blocks, nor the characteristics of the other prime–target pairs. Importantly, nothing was said about the variable prime–target SOAs.

4.2. Results

Experiment 3 provides four important results. First, Experiment 3 confirms that chained trials are associated with increased processing time (43 ms). Second, we find a stimulus based repetition priming effect (39 ms), and an image based repetition priming effect (23 ms). Both kinds of priming were present at the shortest prime–target SOA, and both increased with SOA. Third, in addition to repetition priming effects, we found congruence priming: when the prime is congruent with the target, participants are faster by 18 ms; similarly when the image of the prime is congruent with the target, participants are faster by 49 ms. Fourth, and most importantly, these two congruence priming effects had opposite temporal dynamics: both were present at the shortest SOA, but prime congruence effects *decreased* with SOA, and disappeared by 600 ms after prime presentation, while image congruence effects monotonously *increased* with SOA. The following paragraphs provide the detailed analyses.

4.2.1. Outliers and exclusion

Two participants with more than 10% errors were excluded from the analysis. Median correct RTs were then used to perform repeated measures analysis of variance (ANOVA), with participant as random factor.

4.2.2. Unfolding of priming by the image and priming by the stimulus

The first object of this experiment was to uncover how far participants could apply the arithmetic operations within various time constraints. We expected that participants would be faster and make fewer errors on trials in which the target matched the outcome of the requested operation, and that this gain would increase as the SOA increased. This is what we observed (see Fig. 5C–E): first, participants were faster in simple blocks than in chained blocks – which replicates the additional time taken by chaining already found in Experiments 1 and 2. But, second, within each block type, performance on different trial types were markedly different: in chained blocks, $t = i$ trials were faster and more accurate, as were $t = p$ trials in simple blocks. Finally, these priming effects, although already present at the shortest SOA (100 ms) increased with SOA and were maximal at the longest (600 ms).

These informal observations were confirmed by a $3 \times 3 \times 3$ ANOVA on median RTs with factors trial type ($t = p \oplus 2, t = p, t = p \ominus 2$), block type (chained $N \oplus 2$, simple, chained $N \ominus 2$) and SOA (100, 300, and 600 ms). The three main effects and all interactions (second and third order) were significant (see Table 1). Simple blocks were faster than $N \oplus 2$, which in turn were faster than $N \ominus 2$ blocks (453, 492, and 500 ms). SOA had a very significant effect: response speed increased as SOA increased (521, 476 and 448 ms for 100, 300 and 600 ms SOAs; $(F(2, 34) = 96.83, p < 0.001, \eta^2 = 0.851)$).[2] In chained blocks, participants were faster to respond to $t = i$ trials

[2] In further analysis, we do not report significance of the SOA factor, which obviously was always very high.

Table 1
Block type × trial type × SOA ANOVA.

	Response times			Errors		
	F	p	η^2	F	p	η^2
Block	$F(2,34) = 9.672$	$< .001$	.362	$F(2,34) = 8.446$	$< .01$	.332
Trial type	$F(2,34) = 9.59$	$< .001$	.361	$F(2,34) = 3.108$	.057	.155
SOA	$F(2,34) = 96.83$	$< .001$	.851	$F(2,34) = 3.347$	$< .05$	.164
Block × trial type	$F(4,68) = 18.812$	$< .001$	.525	$F(4,68) = 6.348$	$< .001$	.272
Block × SOA	$F(4,68) = 4.374$	$< .01$	.205	$F(4,68) = 2.077$	ns	
SOA × trial type	$F(4,68) = 2.495$	.0508	.128	$F(4,68) = 0.557$	ns	
Block × trial type × SOA	$F(8,132) = 2.16$	$< .05$	.113	$F(8,132) = 2.875$	$< .01$	.145

(467 ms), than to repeated trials ($t = p$, 490 ms), and faster again for repeated trials than for violation trials ($t = \bar{\imath}$, 529 ms). In simple blocks, repeated trials ($t = p$, 422.4 ms) were faster than $t = p \oplus 2$ and $t = p \ominus 2$ trials (both 468 ms). All these effects were qualified by an interaction with SOA, such that they all increased with SOA. The corresponding ANOVA on error rates yielded analogous results (see Fig. 5C–E), in that slower conditions yield higher error rates. Furthermore, error rates and RTs had a positive correlation ($R^2 = .225, p < .05$), showing that there was no trade-off of speed for accuracy. In more specific analysis below we therefore report only results on RTs.

4.2.3. Image and prime repetition effects

The preceding analysis again shows that it takes time to apply the arithmetic operation, since simple blocks are faster than chained blocks. However, within chained blocks, the extent to wich participants had time to compute the image of the prime before the target was presented is revealed by a gain in RT when the target does correspond to this image. This strategic priming effect increases with SOA. Furthermore, if the "crosstalk by parallelism" model suggested by Experiment 2 is correct, when the SOA is short, we should also find a non-strategic priming, in cases where the target does not correspond to the image but to the prime itself. This effect can be seen in the previous analysis: it corresponds to the fact that repeated trials are faster than violation trials. Thus, on the one hand we have an "image repetition effect" (a strategic facilitation when $t = i$) and on the other hand a "prime repetition effect" (an automatic facilitation when $t = p$) which have different temporal dynamics. Both effects can be seen in Fig. 6A: we see that the size of the strategic effect is monotonously increasing, starting at 16 ms at the 100 ms SOA and reaching 63 ms at 600 ms SOA, while the size of the automatic component starts at a higher value of 28 ms at 100 ms SOA but reaches a plateau at the 300 ms SOA, with a value of 51 ms.

We quantified statistically the automatic $t = p$ "prime repetition" effect with a $2 \times 3 \times 2$ ANOVA with factors prime repetition ($t = p$ vs $t \neq p$), SOA, and blocks (chained vs simple blocks), excluding $t = i$ trials in chained blocks. The three main effects were significant. Importantly, the prime repetition effect was significant ($t = p$) trials 42 ms faster than $t \neq p$ trials, $F(1,17) = 61.376, p < .001$, $\eta^2 = .783$. Moreover, the prime repetition × SOA interaction was significant (effect of repetition=30, 53 and 43 ms at 100, 300 and 600 ms, $F(2,34) = 4.54, p < .05$, $\eta^2 = .211$). We note that the block × SOA interaction was also significant ($F(2,34) = 4.065, p < .05, \eta^2 = .193$), with a decrease of the speed benefit of simple blocks as the SOA increases (72, 68 and 51 ms at 100, 300 and 600 ms SOA).

The strategic $t = i$ "image repetition" effect was tested in a 2×3 ANOVA within chained blocks, with factors of image repetition ($t = i$ trials vs $t \neq i$ trials) and SOA. Image repetition trials were 39 ms faster than $t \neq i$ trials, and this effect was significant ($F(1,17) = 18.197$, $p < .001, \eta^2 = .517$). The interaction was also significant ($F(2,34) = 4.282, p < .05, \eta^2 = .201$), showing that the strategic priming effect increased with SOA (16, 40 and 63 ms at 100, 300 and 600 ms).

We then tested whether $t = i$ and $t = p$ effects were already present at the shortest (100 ms) SOA. In chained blocks, at the 100 ms SOA, $t = i$ trials were found significantly faster than $t \neq i$ trials (16 ms, $F(1,17) = 4.773$, $p < .05, \eta^2 = .219$); and in the 2×2 ANOVA with factors prime repetition ($t = p$ vs $t \neq p$) and block (chained vs. simple) at the 100 ms SOA, excluding $t = i$ trials, the two main effects were found significant ($t = p$ trials 31 ms faster than $t \neq p, F(1,17) = 18.306, p < .001, \eta^2 = .518$; simple blocks 72 ms faster than chained blocks, $F(1,17) = 19.315, p < .001, \eta^2 = .532$), but importantly the interaction was not significant ($p > .5$). Therefore, it seems that both effects are found at the shortest SOA, suggesting that by 100 ms after stimulus presentation, participants have already some information pertaining to the comparison of the prime itself but also to the comparison of its image according to the arithmetic operation. This is in agreement with what we found in Experiment 2, where at the shortest interruption time, participants already had some information about the result of the arithmetic operation.

4.2.4. Image and prime congruence effects

The preceding analysis reveals that there are indeed both image repetition effects and prime repetition effects. It shows that the $t = i$ priming effect increases as the SOAs increased, while the $t = p$ priming effect is stationary after the 300 ms SOA. However, repetition effects reflect both low level mechanisms (stimulus feature repetition) as well as higher level decision effects. In order to assess more precisely the importance of these latter effects, we looked for congruence effects, both on the prime and on the image. These effects would presumably more closely correspond to how far the decision system has taken its input from the prime or the image. Again, we expect to find differences

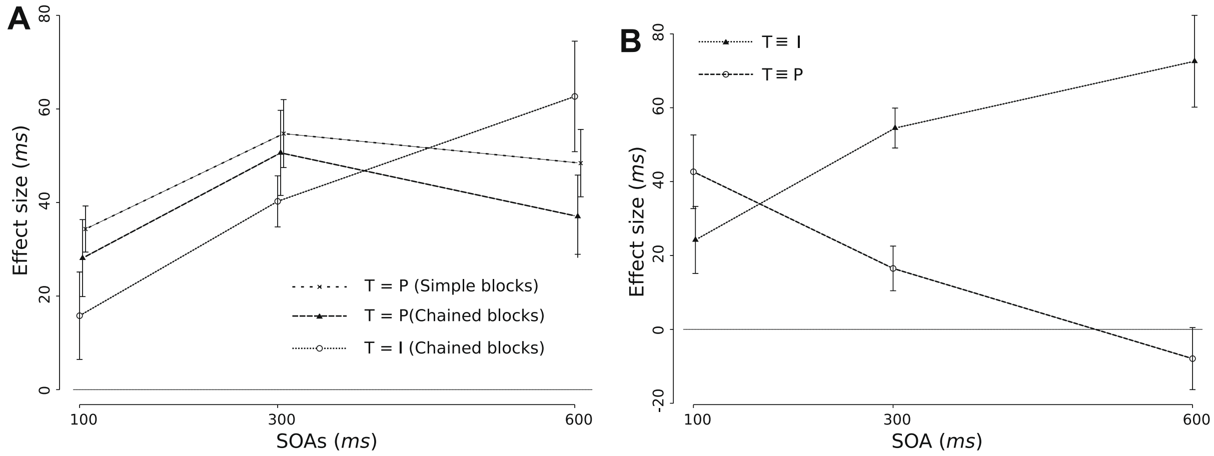

Fig. 6. Priming effects as functions of SOAs in Experiment 3 (priming). (A) Repetition priming effects. This priming effect is calculated as RTs for non chained (repetition and violation) trials minus RTs for chained trials; repetition priming in chained blocks is RT for violation trials minus RT for repetition trials; in simple blocks it is RTs for non repetition trials minus RTs for repetition trials. (B) Congruence priming effects within chained blocks. Prime – target congruence effects are calculated as RTs for trials where the prime and the target are not on the same side of 5 minus RTs for trials where they are on the same side. Similarly, image target congruence effects are calculated as RTs for trials where the image and the target are not on the same side of 5 minus RTs for trials where they are on the same side. Error bars represent plus and minus one standard error of the mean after removal of the participant mean.

in the temporal dynamics of the two kinds of congruence effects.

Trials are prime congruent ($t \equiv p$) when the prime and the target fall on the same side of five. Similarly trials are image congruent ($t \equiv i$) when the image and the target fall on the same side of five. Notice that a $t \equiv i$ trial need not be a $t = i$ trial: for instance in a $N \oplus 2$ block, a $p = 2, t = 2$ trial will have $i = 4$; but since 2 and 4 are on the side of the reference, it will nevertheless be image congruent. Similarly, prime congruent trials include trials where the prime is not repeated ($p = 6, t = 8$ trials for instance, whatever the block type is). Congruence effects show the extent to which a response has been prepared either based on the application of the arithmetic operation or on the prime itself. We thus contrasted $t \equiv p$ trials with $t \not\equiv p$ trials on the one hand; and $t \equiv i$ and $t \not\equiv i$ on the other, with the prediction that the first effect should decrease as the SOA increased while the second effect should follow an opposite time course.

Results are shown on Fig. 6B: the prime congruence effect ($t \equiv p$ trials vs $t \not\equiv p$ trials) is maximal at the shortest SOA (43 ms) and is monotonously decreasing to the point that it vanishes at the longest SOA (−8 ms). The prime congruence effect was significant ($F(1,17) = 10.357, p < .01, \eta^2 = .378$), as well as its interaction with SOA ($F(2,34) = 6.191, p < .01, \eta^2 = .267$). The image congruence effect ($t \equiv i$ trials vs $t \not\equiv i$ trials) is significant ($F(1,17) = 33.028, p < .001, \eta^2 = .66$) and monotonously increasing with SOA ($F(2,34) = 4.489, p < .05, \eta^2 = .209$). It is already present at the shortest SOA (24 ms) and reaches a maximum of 73 ms at the longest SOA.

4.3. Discussion

In this experiment, we used a methodology reminiscent of Neely, 1977 in order to assess the time courses and parallelism of the arithmetic and comparison operations. A prime was presented that participants had to process strategically according to the arithmetic operation. The results showed that the prime is subject to an automatic comparison, even though the instruction and the optimal algorithm imply that it should only be the basis for the arithmetic operation. Thus, we again observed an untimely application of the second operation. The results of this experiment are in line with the results of the first two experiments: at the most basic level, the delay that we found in Experiment 1 for the composite operations and the shift in the build up of accuracy of Experiment 2 is here evidenced by faster responses in simple than in chained blocks. However, the main novelty of this experiment, is in the details of the priming effects in the chained blocks themselves. The mere fact that we find a strategic priming effect in trials where the target corresponds to the image in a chained block shows that participants are able to anticipate on the most probable target. This signals the computation of the image of the prime according to the arithmetic operation. This anticipation is both present as an image target repetition effect ($t = i$) and as an image target congruence effect ($t \equiv i$), showing that participants could prepare their response even before the target required them to respond.

These effects are already present at the shortest (100 ms) SOA. This is also in line with the results of Experiment 2, where we found that congruent trials were faster than incongruent trials, at the shortest SOA (50 ms). This implies that participants had time to compute the image of the stimulus even at this short delay. However, these effects increased as the SOA increased, and this observation suggests that the accumulation of evidence produced by the computation of the arithmetic operation is a slowly growing process. This corresponds to the observation, first made in Experiment 2, of a gradual build-up of information in chained trials.

In the previous experiments, we had indirect evidence for a stage where the stimulus itself was subject to the comparison operation. Here, prime - target priming effects allow a more direct confirmation and a refined analysis. Indeed, we can distinguish a prime–target repetition effect and a prime – target congruency effect. The first one is first increasing with increasing SOAs and then stationary, while the second is decreasing and ultimately absent. The prime–target repetition effect presumably involves low-level repetition and therefore does not inform us only about the automatic comparison of the prime. The congruency effect however reflects more closely the extent to which the prime is compared to the reference, because it reveals the influence of either the prime or the image in the preparation of the response. If there is a prime congruency effect, it means that participants have benefited from the fact that the prime elicits the same response as the target, whether or not the target is identical to the prime. The same is true for the image congruence effect: it measures the influence of the image on the preparation of the response. Therefore, we can use these effects to assess the relative build up of the information from the stimulus and from its image. As seen in Fig. 6, these two priming effects are mirror-images of each other, suggesting a progressive replacement of the evidence arising from the stimulus by the evidence arising from its image, as it is being computed. Furthermore, the prime congruency effect vanishes at the 600 ms SOA, at which point the image congruency effect is maximal. This observation suggests that by this time, there has been a complete replacement of the stimulus by its image by the arithmetic operation. Note that this interpretation of the disappearance of the prime congruency effect is not incompatible with the permanence of the prime repetition effect, since the latter reflects also lower level mechanisms. Thus when the target is a physical repetition of the prime, there may be some processing benefits, due to the perceptual similarity of the two stimuli, even at the 600 ms SOA; yet, the disappearance of the prime-congruency effect suggests that by this time participants have a response prepared only on the basis of a representation of the image of the prime.

Overall, Experiment 3 confirms that the serial model with crosstalk is inadequate. According to this model, applied to the priming paradigm, the serial organization of the elementary operations should be preserved, but input to the comparator processor should be a mixture of the computed image, the target stimulus and of the prime stimulus itself. Thus, this model predicts that congruence effects due to the stimulus should be essentially constant with variable SOAs. Quite the contrary, we find that the target-stimulus congruence effect vanishes with time. This result is, however, compatible with the "crosstalk due to partially parallel processing" model. According to this model, the target stimulus probes the ongoing activation state of the comparison processor. When the SOA is short, this processor is dealing with the input stimulus, and the information related to the image is not yet fully available. Therefore, the main congruence effect comes from the stimulus. When the target-stimulus SOA is long, the situation is reversed, and the main congruence effect comes from the image.

At this point, we have a tentative model of the flow of information in our chained task. Its subcomponents can be separated into processors and control mechanisms. In addition to the two arithmetic and comparison processors, we have gathered evidence that their chaining poses specific difficulties which presumably require higher-level control operations. In particular, the comparison task should be started after completion of the arithmetic operation, yet we found that imperfect executive control lead to its being activated at an earlier time and to initially process the stimulus number itself rather than its image by the arithmetic operation.

It thus seems that serial processing in this situation is not a natural and simple mode of operation for the human brain. Quite on the contrary it is difficult, prone to failures, requires cognitive control. This leads to question the relationship of this cognitive architecture to consciousness, as consciousness is the hallmark of controlled processes. Simple addition (LeFevre, Bisanz, & Mrkonjic, 1988) and comparison (Dehaene et al., 1998) have been found to operate even when the target number is masked and cannot be consciously perceived. Indeed, many theories of conscious access associate such simple automatic operations with non-conscious processing (Baars, 1988; Dehaene & Naccache, 2001; Jack & Shallice, 2001; Posner & Klein, 1973; Shallice, 1972). Global workspace theory, for instance, stipulates that conscious processing is associated with the operation of a dense network of "workspace neurons" and their interconnections, which breaks the modularity of automatized processors by enabling them to share information and to recombine into novel complex operations. According to this model, we should expect that the piping of a result across two tasks, and more generally the serial coordination of multiple processors into a single complex task, should only be possible under conditions of conscious perception.

To address this issue, in Experiment 4, we study our simple and composite tasks in subliminal conditions, as a means to tell apart which operation is dependent on conscious access and control, and which is not. More specifically, we ask which components of the processing flow involved in the chained task can be executed without consciousness, and which require consciousness. A simple prediction is that consciousness will have a special role in the piping of information. We hypothesize that the piping operation will be especially fragile under masking conditions and that failure to inhibit execution of the comparison operation before the arithmetic operation is complete will dominate under conditions of subliminal processing.

5. Experiment 4: masking

In this experiment, the operations were the same as in the previous ones, but we introduced some novel features in order to explore their processing under subliminal conditions. First, as in Experiment 1 there was only one stimulus, but it was backward masked, with variable SOAs between the stimulus and mask (see Fig. 7B). Second, in different blocks, participants performed one of four tasks (see Fig. 7A). The first two tasks were verbal: a naming task which required participants to simply name the digit, and an arithmetic task, where subjects were to say aloud the

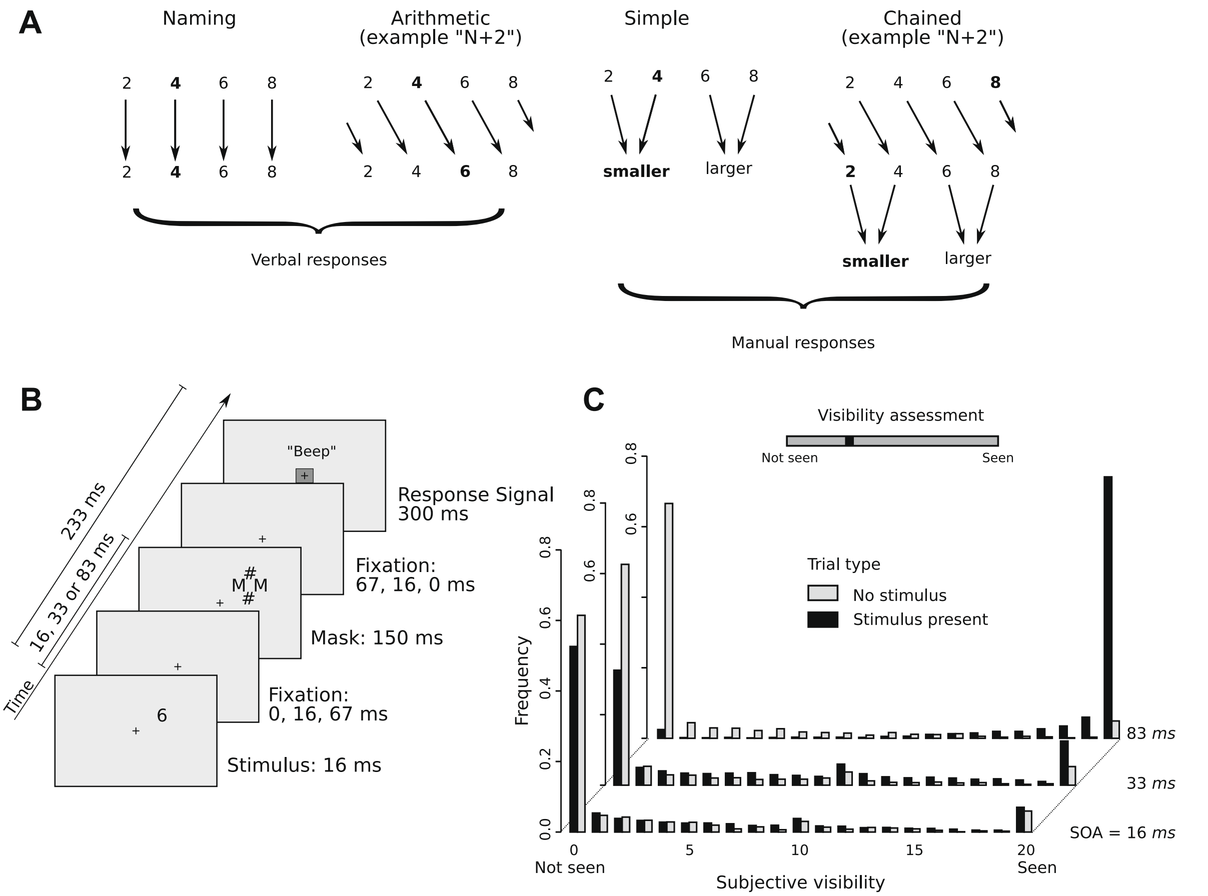

Fig. 7. Design and visibility results for Experiment 4 (masking). (A) Design of the tasks. Simple and chained tasks are the same as the ones explored in Experiments 1–3. Naming and arithmetic tasks are introduced here as new verbal tasks. For arithmetic and chained tasks, only example of the $N \oplus 2$ version is given, while the experiment comprised also the similar $N \ominus 2$ version. (B) Structure of one trial. (C) Subjective visibility results. Participants moved the dark cursor on the scale to represent their subjective vision of the stimulus. Histograms show that for the short SOAs (16 and 33 ms) subjective visibility remained close to nil, while it jumped to the maximal degree for the 83 ms SOA.

result of one of the operations $N \oplus 2$ or $N \ominus 2$. The other two tasks were the simple comparison and composite tasks already explored in the previous experiments. Participants compared the stimulus or its image to five, and responded with one of two buttons. The masking of the stimulus, which has been used in other studies from our group (Del Cul, Dehaene, & Leboyer, 2006, 2007), shared properties with both metacontrast (Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003) and object substitution paradigm (Di Lollo, Enns, & Rensink, 2000; Enns, 2004). Digit stimuli were presented randomly at one corner of an imaginary square centered on fixation, and the mask was a group of four symbols closely placed around the stimulus.

We used a subjective scaling methodology to assess conscious access on a trial-by-trial basis by means of a response scale (Sergent & Dehaene, 2004; Sergent, Baillet, & Dehaene, 2005; Del Cul et al., 2006, Del Cul, Baillet, & Dehaene, 2007). On each trial, participants first performed one of the four tasks, then rated the subjective visibility of the stimulus by placing a cursor on a scale labeled "not seen" on the left and "seen" on the right. Thus, we could categorize trials as subjectively "seen" or "not seen" and analyze performance of participants on the simple or chained tasks within these categories.

5.1. Method

5.1.1. Participants

Eighteen college students recruited among the community of local universities participated in the experiment and were tested individually by the same experimenter on two successive days. The first session lasted one hour and a half, the second one hour.

5.1.2. Apparatus and stimuli

Stimuli were presented on a PC running E-Prime (PST software, Pittsburgh, USA). Refresh rate was set at 60 Hz. Stimuli were in a 36 points courier font presented in black on a white screen. On each trial (see Fig. 7B), the stimulus appeared randomly at one of the four corners of an imaginary square (6 cm in size, stimuli at 2.9° of eccentricity at 60 cm viewing distance) centered on the fixation cross. Following a sequence of eight moving converging crosses (duration 500 ms), meant to facilitate fixation, the target digit was flashed for one frame (16 ms), followed either immediately or with an intervening blank screen by the mask. The mask (150 ms) consisted in four symbols, two flanking "*M*" and two hash marks (#) above and below, immediately surrounding the location of the target. The mask was followed either immediately or with an intervening blank screen by a response signal, a green square at fixation in the naming and arithmetic tasks, and a tone heard through headphones in the simple comparison and chained tasks. The SOA between the target and the mask was 16, 33 or 83 ms, and the interval between target onset and the response signal was fixed (249 ms). In arithmetic or naming trials, participants responded by naming the result of the operation in a microphone attached to a voice key. The experimenter coded the response with a four buttons response box. In simple comparison and chained trials, participants responded by pressing on a standard French keyboard the "*f*" key for "smaller than five and the "*j*" key for "larger than five". Immediately after participants made their response, the visibility scale appeared on the screen. Participants moved the cursor with the arrow keys of the keyboard and initiated the next trial by pressing the space bar.

5.1.3. Tasks and design

There were four types of tasks: two verbal tasks "naming" and "arithmetic" where participants had to name either the stimulus itself or the result of the application of one arithmetic operation (either $N \oplus 2$ or $N \ominus 2$); and two manual tasks: "simple comparison" and "chained task".[3] The chained task had, as before, two versions "chained $N \oplus 2$" and "chained $N \ominus 2$". Each task was presented in blocks of 30 trials, during which each of the four digits was presented twice at each of the three stimulus - mask SOAs, plus two blank trials (without a stimulus) at each SOA. The stimulus absent trials were introduced in order to have a baseline for the individual use of the visibility scale. Prior to each block, participants were reminded of the instructions for a given task. They could perform it when the stimuli were visible (most trials at SOA = 83 ms), and were encouraged to guess when they did not see the stimulus. Each block began with a training list where each number was presented once without masking and with negative feedback only for errors; no feedback was delivered during the main experimental blocks. Each session comprised 18 such blocks (three times the six tasks of naming, simple comparison, arithmetic $N \oplus 2$, arithmetic $N \ominus 2$, chained $N \oplus 2$, chained $N \ominus 2$ in randomized order). Half of the participants performed the simple comparison and chained tasks on one day, with naming and arithmetic the following day, and the other half had the opposite assignment. Each session began with training on the three tasks that the participant would perform that day (3 blocks of 20 trials), and on the use of the visibility scale (48 trials).

[3] We introduced the naming task in order to make sure that some subliminal processing of the stimuli was indeed possible, with our masking protocol. We used verbal responses for the arithmetical tasks in order to capture the bare arithmetical operations, and so as not to transform this task in a classification task.

5.2. Results

Experiment 4 provides two critical sets of results. First, it shows that all simple operations were performed better than chance on unconscious stimuli (naming: 43.1% correct, chance = 25%; comparison: 55.5%, chance = 50%; arithmetic: 35.2%, chance = 25%). On the contrary, participants were at chance for the unconscious chained trials. Second, when they tried to perform the chained operations on unseen stimuli, participants did in fact perform the comparison of the stimulus – this appears in the analyses of congruent versus incongruent chained trials. Further analyses explore the time course of unconscious processing and try to model performances on chained trials as determined by the performances on the underlying simple operations. The following paragraphs provide the detailed statistical analyses of these results.

Three participants whose error rate exceeded 20% at the longest SOA were excluded.

5.2.1. Definition of conscious and non-conscious trials

As previously observed with the same masking procedure (Del Cul et al.,2006, 2007) and in an attentional blink task (Sergent & Dehaene, 2004; Sergent et al., 2005), the distributions of visibility ratings revealed a bimodal pattern (see Fig. 7C): participants either saw the stimulus well, or did not see it at all. This bimodal distribution is unlikely to reflect response bias, since in other control conditions participants proved capable of using all intermediate positions of the visibility scale (Sergent & Dehaene, 2004). As seen in Fig. 7C, some trials at short SOA were classified as "seen". This is consistent with the fact that the masking that we used has strong attentional components, and may fail when participants happen to have their spatial attention focused where the stimulus appears. Thus, it would be improper to investigate unconscious performance by selecting trials at the short SOAs, because the results would be contaminated by a proportion of conscious trials. To investigate non-conscious processing, for each participant and each session, we used as a criterion the mean visibility score for trials where no target digit was presented. The median value of this criterion across participants was 5% of the scale range (maximum = 40% in one subject). Only trials at SOA 16 or 33 ms where the visibility rating was below this criterion were considered as non-conscious. Likewise, only trials at SOA 83 ms where the visibility rating was above 75% were considered as conscious. There were too few trials in the other categories (conscious trials at short SOAs, non-conscious trials at the long SOA) to allow for further analysis.

5.2.2. Performance in the four tasks

The mean performance in each of the four tasks is shown in Fig. 8A. We tested the deviation from chance first with χ^2 tests. As expected performance was way above chance on conscious trials (all $ps < .0001$). On non-conscious trials, performance was above chance in naming (43.1% correct; chance = 25%; $\chi^2(9, N = 859) = 197.5$, $p < .0001$), arithmetic (35.2% correct; chance = 25%; $\chi^2(9, N = 1572) = 100.4, p < .0001$) and Comparison (55.5% correct; chance = 50%; $\chi^2(1, N = 794) = 4.783, p < .05$).

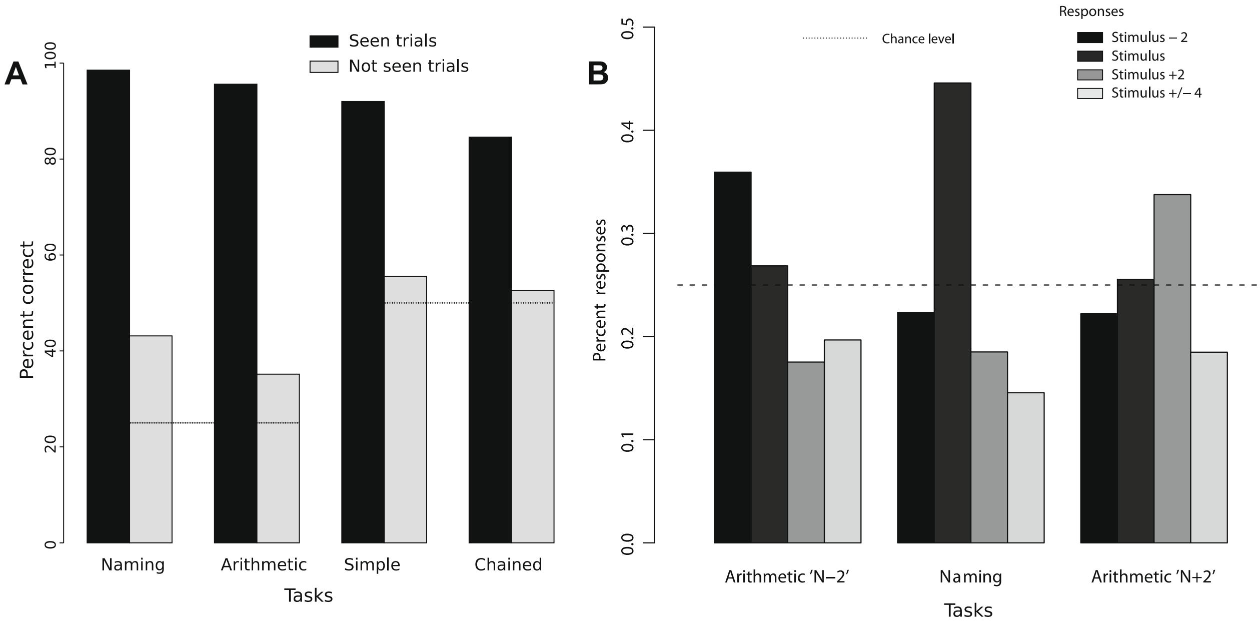

Fig. 8. Accuracy results for Experiment 4 (masking). (A) Performance in the four task types, for conscious and non-conscious trials. Dotted lines represent chance levels (50% in simple and composite tasks and 25% in naming and arithmetic tasks). (B) Decomposition of performance in verbal (naming and arithmetic $N \ominus 2$ and $N \oplus 2$).

However, in the chained task, performance did not differ from chance (52.5% correct; chance = 50%; $\chi^2(1, N = 1540) = 0.2365, p > .5$). These results also held across participants, as shown by t-tests (naming: $t(14) = 5.487$, $p < .0001$; arithmetic: $t(14) = 3.784$, $p < .01$; comparison: $t(14) = 2.546, p < .05$; chained: $t(14) = 1.416, p > .15$). The difference in performance between the simple comparison and chained tasks was close to significance (paired t-test, $t(14) = 1.497, p = .078$, one-tailed). From now on, we concentrate exclusively on non-conscious trials.

We further tested how participants performed the arithmetic tasks unconsciously, in order to rule out the possibility that their above-chance performance resulted from some other strategy than the computation of the arithmetic result. Our tasks are such that some numbers are never paired together: for instance stimulus 2 can be associated with response 2 (in the naming task), with response 4 (in arithmetic $N \oplus 2$), or with response 8 (in arithmetic $N \ominus 2$ task), but never with response 6. Thus, participants might have achieved 33% correct performance by simply excluding this response. However, their performance did not result from such a strategy. As shown in Fig. 8B, an examination of the response emitted on each trial showed that participants did not merely exclude one response, but responded most frequently with the number that corresponded precisely to the application of the appropriate operation.

Several analyses validated this result. First, a comparison of response distributions in the $N \ominus 2$ and $N \oplus 2$ blocks revealed a significant difference ($\chi^2(3, N = 1572) = 66.47, p < .0001$). Second, we classified responses across the two arithmetic tasks as correct, identity (naming of the stimulus), inverse (application of the other operation, for instance $N \oplus 2$ instead of $N \ominus 2$) and other (responding with the response never associated to the target) and ran a repeated measures one-way ANOVA on percent responses. The main effect was significant ($F(3, 42) = 12.36$, $p < .0001, \eta^2 = .468$, correct = 35.16%, identity = 26.1%, inverse = 19.4%, other = 19.4%). Crucially, the planned contrast obtained by omitting the other responses was also significant ($F(2,28) = 11.62, p < .0001, \eta^2 = .453$), whereas the contrast between inverse and other responses was not ($F(1, 14) < .001, p > .9$). In summary, (1) participants were able to perform the arithmetical operations non-consciously, often emitting precisely the correct response while denying seeing any target digit; (2) they also showed a tendency to name the stimulus itself; and (3) they did not exclude the never associated number more often than the response to the other operation.

In summary, the results indicate that all simple tasks, but not the chained task, can be performed above chance under subjectively defined conditions of subliminal perception, where a sensitive visibility index shows that subjects perceived the trial as identical to a target-absent trial. This result is far from trivial, because the subjects' success in naming the unconscious target indicates that they could extract information about its identity. In the chained blocks, if participants had simply named the target to themselves (which they can do with 43% accuracy), then performed the requested computation, they should have reached 71.5% accuracy ($43 + 0.5 \times (100 - 43)$). They scored significantly lower, however (52.5%, $t(14) = 7.654, p < .0001$). This result indicates that the manner in which they attempted to execute the chained task prevented the exploitation of available subliminal information.

5.2.3. Further analyses of performance in the chained task

Why did participants fail in the chained task? As a first approach, we can analyze performance on congruent and

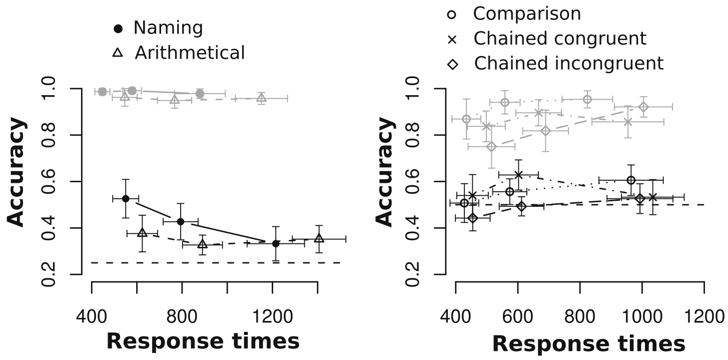

Fig. 9. Speed-accuracy decomposition for each task, in conscious (light gray) and unconscious (black) trials. Dashed lines are chance levels. Error bars represent plus and minus one standard error of the mean after removal of participants' means. Horizontal error bars are for the center of each quantile, while vertical error bars are for the mean accuracy in the quantile. (A) Speed-accuracy decomposition for verbal tasks (naming and arithmetic). (B) The same for simple comparison and composite tasks. For composite tasks, we separate congruent and incongruent trials.

incongruent trials ($s \equiv i$ and $s \not\equiv i$) as we did in Experiments 1 and 2. Performance was significantly better on congruent than on incongruent trials (respectively 57% and 49% correct, $t(14) = 2.597, p < .05$). Only the congruent trials deviated from chance (57% correct; $t(14) = 2.01, p < .05$, one-tailed). The incongruent trials remained strictly at chance level (49% correct, non significant) and their performance differed significantly from that of the non-conscious comparison trials ($(t(14) = 2.827, p < .05)$. Thus it seems that when participant tried to perform the chained operations on a subliminal stimulus they only achieved the simple comparison of the stimulus.

We further analyzed whether processing time contributed to failure in the composite task. On conscious trials, t-tests on median response times indicated that the composite task (mean = 684 ms) was slower than the comparison task (558 ms). On non-conscious trials, however, the difference was reduced (592 versus 562 ms), although still significant ($(t(14) = 2.252, p < .05)$. This finding might suggest that participants failed in the non-conscious composite task merely because they responded too fast. To evaluate this possibility, for each task we separated the non-conscious trials into three quantiles of response time (see Fig. 9). As seen in Fig. 9B, in the slowest quantile, responses to the composite task were not faster than responses observed on conscious composite trials. Thus, processing time should have been sufficiently long to achieve good performance. Nevertheless, even on those slow non-conscious trials, only the comparison task was above chance, while the composite task was not (Comparison 60.5% correct, $t(14) = 3.109, p < .01$; Composite 52.6% correct, $t(14) = 0.984, p > .34$). Thus, speed of response per se failed to explain failure in the composite task. We statistically assessed these effects for the comparison and chained tasks: we subdivided trials in congruent and incongruent and ran a 3×3 repeated measures ANOVA on percent correct responses with factors speed (fast, intermediate, or slow trials) and task (comparison, chained congruent $s \equiv i$, chained incongruent $s \not\equiv i$ trials). It revealed a significant effect of task ($F(2,28) = 5.014$, $p < .05$, $\eta^2 = .264$), and speed ($F(2,28) = 4.57, p < .05, \eta^2 = .246$) but no significant interaction. However, sub-analyses restricted to comparison versus composite congruent trials showed that, in this case, the interaction between task and speed was close to significant ($F(2,28) = 2.883$, $p < .08, \eta^2 = .171$), suggesting different temporal dynamics for comparison and composition tasks. Whereas performance increased with time in comparison, there was a peak of automatic comparison in composition at intermediate RTs (see Fig. 9B).

For naming and arithmetic tasks, the same ANOVA revealed significant effects of task ($F(1,14) = 7.409$, $p < .05$, $\eta^2 = .346$), speed ($F(2,28) = 8.369, p < .01$, $\eta^2 = .374$) and their interaction ($F(2,28) = 6.554, p < .01$, $\eta^2 = .319$). Subanalyses showed that performance decreased with time for the naming task ($F(2,28) = 10.943$, $p < .01$, $\eta^2 = .439$), and remained constant for the arithmetic tasks ($F(2,28) = 1.311, p > .28$). Altogether, these analyses suggest that the four tasks obey different subliminal dynamics: a rapid decay of information in the naming task, a longer availability of information in the arithmetic task, and a progressive growth of information in the comparison task. At no time was there any availability of information in the composite task. However, when participants attempted to chain operations, we did observe a peak of automatic comparison on congruent trials at intermediate SOAs.

A possible cause for the failure of composition under subliminal conditions might be the sequential accumulation of successive errors. Although performance was higher than chance in arithmetic and comparison tasks, the non-conscious success rate remained low (respectively 35% and 56%). We tried to predict performance in the composite task assuming that these probabilities are combined when these two tasks must be performed sequentially. Let p_a be the probability of being correct in the arithmetic task and p_c the probability of being correct in the simple comparison. We assumed that participants would respond correctly if they were first correct in the arithmetic task and then in the comparison (with probability $p_a \times p_c$), and that they would respond at random ($p = 1/2$) if they were not correct in the arithmetic task. Therefore, the probability of a correct response in the composite task is $p_a \times p_c + (1 - p_a) \times 1/2$. This model correctly predicted be-

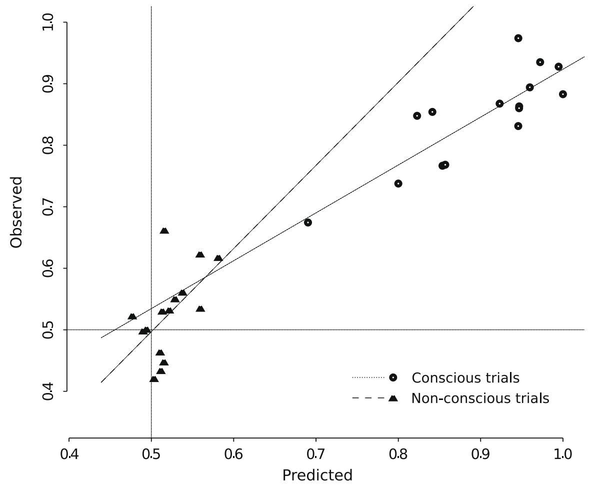

Fig. 10. Prediction of individual performance (percent correct) in the composite task in Experiment 4 (masking). Each point represents the data of one participant, separately for conscious (circles) and unconscious (triangles) conditions. The prediction of performance in the composite task is made according to the following formula: $p_{predicted} = p_a \times p_c + 1/2 \times (1 - p_a)$. Dotted and dashed lines represent the regression line in conscious and non-conscious conditions.

tween-subject variations in performance of the composite task on conscious trials ($r = .778, p < .001, R^2 = .683$); it also predicted performance on non-conscious trials, however with a much lesser fit ($r = 0.351, p < .05, R^2 = .241$) (see Fig. 10).

5.3. Discussion

Although this experiment used a somewhat different approach compared to the three first experiments, we again found that composite tasks are slower and give rise to more errors than simple tasks – in conscious as well as in non-conscious settings. The main novel finding in this experiment is that simple operations (comparison and arithmetic $N \oplus 2$ or $N \ominus 2$), but not their composition, are performed above chance level under conditions of subliminal processing. As the breakdown of performance shows, participants actually applied the arithmetic instructions non-consciously, without relying on any shortcut. It is particularly noteworthy that the tasks alternated quickly in short blocks of 30 trials, among which only about 8 contained visible stimuli. This points to a high flexibility of conscious control over non-conscious processing – to which we come back in the general discussion. It also reinforce our designation of such tasks as based on "simple" elementary operations, which can be performed in isolation outside of consciousness.

By contrast, performance in the composite task did not exceed chance level, suggesting that composition of two operations cannot be performed in the absence of consciousness. Two main interpretations are however still open: either participants simply could not chain two operations and never went past the first operation under subliminal conditions; or they attempted to perform the whole operator chain, but errors accumulated very quickly such that after two steps little or no information remained that could be used to determine response. In the first option the explanation would be that chaining and piping as such depend on a central executive system whose operation requires consciousness. One may find support for this interpretation in the fact that there is a peak of comparison information at intermediate response speed in unconscious composite trials. The second alternative would be that the organization of operations is preserved even under conditions of subliminal processing, but that without consciousness, information decays at each step in such a way that virtually no information is left at the end of the second operation. This would suggest that consciousness is required for the control of decay of information. The fact that performance in composite operation is still somewhat predictable in subliminal conditions by a combination of participants' score on each individual operation, suggests that the latter may be the correct interpretation. In addition, the fact that the difference between mean response times in simple and composite tasks diminishes under subliminal processing conditions does suggest a lack of control: it seems that without consciousness, participants cannot withhold their response until they accumulated enough evidence.

6. General discussion

Our investigation of a very elementary composite task by four different methods yielded convergent results. First, we showed that we can instruct participants to follow a simple algorithm: results of the simple chronometric experiment as well as results of its masked version show that participants do compute the image of the stimulus according to the two arithmetic operations. We can therefore ask how this algorithm is implemented by the human cognitive system. Our data converge to suggest that participants are unable to maintain the strict serial organization of operations that is explicit in the computational description of the composition. The second operation, which should wait until some information about the result of the arithmetic operation is available, actually starts ahead of time. Early on during processing, it is applied on the only available representation, namely the input digit. Evidence for this premature application of the second operation comes both from the cued-response experiment where we see that fast composite responses are very much like simple comparison responses, and from the priming experiment where we discovered a prime – target congruence effect which is maximal at the shortest SOA. Therefore, seriality of the composition is defeated by a specific form of crosstalk. There seems to be a partially parallel execution of the two operations, thus supporting the model of "crosstalk due to partially parallel processing" presented in Fig. 1D.

One might wonder whether our results will generalize to other task contexts. We should insist here on the fact that, although the stimulus set is rather small, participants still process our tasks by relying on real numerical operations – as was discussed in relation to Experiment 1. It is thus highly plausible that our results will at least generalize to other numerical tasks, where participants are very often required to chain many operations. The fact that the second operation takes as input the same numbers as the first is a specific feature of our tasks. This is the cause of a the special interference effects that we studied, and this of course might not generalize to other situations. However, this specific feature was here crucial, as it enabled the study of the time course of the processing.

Ever since the pionneering article of (Stroop, 1935, for a review of the Stroop effect see MacLeod, 1991) interference has been used to demonstrate imperfections in the cognitive architecture for selective attention, so that irrelevant stimuli or irrelevant dimensions of a stimulus cannot be totally filtered out. Our study extends this idea to the domain of cognitive control of serial tasks. We show that a similar "informational leakage" occurs with respect to the order of processing. Thus, control processes cannot prevent the premature execution of a processor, even when its intended starting point in the algorithm is further down the stream. Importantly, the results of our cued-response and priming experiments show that this failure is not a simple case of imperfect attentional filtering, as would be the case if the second processor started its operations at the correct moment, but was still influenced by the stimulus. We show that interferences arise because of a failure to maintain the organization the components of the composite task, and not because of incorrect filtering of inputs to these components.

Our main results argue strongly against a strictly serial model of processing. This model would be a specific version of "discrete stages models" such as are assumed for instance in the additive factor method (Sternberg, 2001, 1969). Our results seem to be easier to account for within the framework of models of parallel-contingent processing, such as cascade models (McClelland, 1979; Miller, 1993). In such models, the basic assumption is that there is a hierarchy of processors, as in discrete stages models, but that these processors are at work at all times. Higher level processors do not wait until lower level ones have finished processing information before they start their own processing. Each of them processes continuously whatever partial information is available from lower level processors.

Nevertheless, our results also impose some clear departure from the basic cascade framework, which still assumes that the hierarchy of subprocesses is strictly maintained. For instance, McClelland (1979) sets forth as Postulate 4 in his definition of the cascade model: "Processing at each level is based on the result of the preceding level only. Outputs are passed in only one direction through the system of processes, with no skipping or bypassing of subprocesses". Yet we found precisely the contrary. Our results suggest that there is some bypassing of information across processors. In our tasks, the second-level processor takes as input the stimulus itself, although it should only access its image after preprocessing by the first processor. This causes an overlap, with several processes working at the same time on the same information. A similar result has been already found in simpler tasks of perceptual discrimination (Miller & Hackley, 1992; Osman, Bashore, Coles, Donchin, & Meyer, 1992; Trevena & Miller, 1998). The present results extend these findings in the domain of higher-level cognitive processes.

We do not mean to imply that all serial models as such should be rejected. It is now widely accepted that the question is not so much whether one broad class of models (discrete vs continuous, serial vs parallel) is the right one, than what are the conditions that favor one type of processing (Meyer, Yantis, Osman, & Smith, 1985; Trevena & Miller, 1998). Our experiment strongly suggest that composition and chaining of elementary operations might be especially prone to cause overlap in processing stages. The reason might be that two task sets must be prepared simultaneously and both of them can be applied to the same stimuli.[4] This might be analogous to "mixing costs" in multitasks paradigms. In task switching paradigms, analyses show (Mayr, 2001; Steinhauser & Hübner, 2005) that there are costs for preparing for more than one task, independently from costs for switching between tasks. In our study, each composite trial requires participants to prepare for two sub-tasks, and this happens to be an effortful process that cannot be performed perfectly.

Our finding of a partially parallel stage in the execution of composite operations can also be compared with results from another multiple tasks paradigm, namely the Psychological Refractory Period (PRP) paradigm (Pashler & Johnston, 1998; Sigman & Dehaene, 2005, 2006; Telford, 1931; Welford, 1952). At first sight, our results may seem to conflict with those from the PRP paradigm, where subjects are asked to perform two tasks in rapid succession, in response to two successive stimuli. The basic phenomenon observed is that as the SOA between the two stimuli gets shorter, the response time on the second is increased while the response time on the first task is approximately constant. One classical interpretation of PRP results (Pashler, 1984, 1994a, 1994b) is that subjects maintain a full separation between two successive processing stages corresponding to the two central stages of the two tasks. This conclusion seems to conflict with our finding of a parallel execution of an irrelevant comparison operation while the subject should be focusing on the initial arithmetic operation. However, more recently PRP studies have uncovered evidence compatible with a partial overlap of stages, which is often interpreted as "central resource sharing" (Hommel, 1998; Miller, 2005; Miller & Alderton, 2006; Tombu & Jolicoeur, 2003, 2005). The most crucial finding, similar to ours, is that of crosstalk between responses to the first and to the second stimuli: even the response times to the first task can be accelerated or slowed down depending on response congruence between

[4] Notice that our discussion of the debate over serial and parallel processing leaves aside the classic debate over seriality in such tasks as memory scanning or visual search (Sternberg, 1966; Treisman & Gelade, 1980; Townsend & Wenger, 2004; Wolfe, 1998). In this case, the same elementary operation is to be performed on arrays of more than one stimulus. The question asked is under which conditions these operations are performed serially or in parallel. Notice that in this case, both types of algorithms are available, and the empirical question is whether one of them is applied, and under which conditions. Our approach is very different inasmuch as we impose a serial algorithm and test whether and how participants implement it.

the two tasks (Logan & Delheimer, 2001; Logan & Schulkind, 2000).

It thus seems probable that some conditions favor partially parallel processing of two decisions, while others induce a serial bottleneck. If we contrast our study and the PRP conditions that elicit a central bottleneck, the main aspect of our experiment that might favor partially parallel processing and "resource sharing" is that we require two distinct successive operations on a single external stimulus while most PRP studies require that participants process two distinct and successive stimuli. Contrariwise, one cause of the PRP bottleneck may be the independence of the two operations, which a supervisory system must accommodate. Thus the bottleneck phenomenon might be due principally to a change in tasks which is absent in our experiments. This interpretation would be consistent with the results of Logan and Schulkind (2000) who found crosstalk between the two tasks only when the task was the same on two successive stimuli (but see Pashler, 1994b who found a response selection bottleneck without task set reconfiguration). Performance of two completely independent tasks may impose a radical separation of the central stages of the operations, while chaining, because it requires keeping the two successive operations in an active state, might on the contrary promote a greater amount of processing overlap. Testing these speculations will require further research aiming at a direct comparison between chained and independent operations.

With the last, masking experiment, we tried to establish a link between cognitive architecture and the distinction between conscious and unconscious processing. This experiment adds to the growing literature on the flexibility of non-conscious processing. Recent studies showed that unconscious processing is sensitive to temporal context (Naccache, Blandin, & Dehaene, 2002), task context (Eckstein & Perrig, 2007; Greenwald, Abrams, Naccache, & Dehaene, 2003; Kunde, Kiesel, & Hoffmann, 2003 – but see Kiesel, Kunde, & Hoffmann (2007) who report relative unflexibility of unconscious priming effects) and that unconscious stimuli can trigger cognitive control (Lau & Passingham, 2007; van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008). Here, we show that novel and arbitrary operations can be very quickly performed unconsciously. Not only naming and comparison but also our rather arbitrary arithmetic operations are partially amenable to non-conscious processing. However, our use of unconscious stimuli was not primarily meant to explore the depth of unconscious processing. Rather, we tried to use subliminal stimuli as analytical tools in order to dissect the various parts of the cognitive architecture. Our results point the simple operations as resistant to heavy masking, while they suggest that the piping of information from one operation to the next is especially fragile and dependent on consciousness. We see at least two non-exclusive interpretations of this finding. First, piping itself may require conscious access, as suggested by "conscious workspace" models of consciousness (Baars, 1988, 2002; Dehaene, Kerszberg, & Changeux, 1998; Dehaene & Naccache, 2001; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). Second, conscious access may be essential to the control of information accumulation and decay throughout mental processes. Overall, conscious access may be crucial in the processing of multi-steps operations in possibly two ways: the effortful maintenance of the overall organization of simple operations and information flow; and the control of the amount of information transmitted at each step, and its relation to decision making.

In his 1958 book *The Computer and the brain*, Von Neumann asked how a biological organ such as the brain, which is an analog, parallel and prone to errors system, could perform multi-step calculations. Von Neumann pointed out that, in an analog machine, errors accumulate at each step so that the end result quickly becomes imprecise or even useless. This is essentially what we found under non-conscious conditions. We therefore tentatively propose that the architecture of the "conscious workspace" may have evolved to address Von Neumann's problem. One function of conscious access would be to control the accumulation of information in such a way that a discrete decision is reached at each stage, before it is dispatched to the next processor. Such a discretization of the information flow would produce, at each step, new reliable internal representations that can further be operated upon. According to this view, during conscious processing, accumulation of evidence up to a well-defined threshold would ensure that error rate is kept below a predefined probability level. This idea is familiar in accumulation models of response time, where decision is based on the progressive accumulation of evidence up to a fixed level, equivalent to a predefined acceptable error rate (Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Laming, 1968; Ratcliff, 1978; Stone, 1960). Here, we extend this idea to multi-step tasks by assuming that conscious processing consists in multiple serial stages of stochastic accumulation of evidence, each successively occupying the central workspace. This proposal is consistent with recent findings from the PRP paradigm, where response time in a dual-task situation was shown to result from the succession of several successive stochastic accumulation periods (Sigman & Dehaene, 2005, 2006).

In summary, we suggest that conscious information processing is characterized by the ability, at each of several serially organized processing stages, to accumulate stimulus information until a predefined probability of being correct at the given step is attained. When the stimulus is masked below the threshold for conscious access, evidence accumulation may begin, thus biasing the response to a higher-than-chance level, but without attaining the decision threshold. As a consequence, errors quickly accumulate, and the response is no longer based on a well-defined internal criterion, but relies on guessing or on some external criterion such as a response signal. While those speculations clearly require experimental validation and extension, they would suggest that conscious processing is intimately associated with the operation of the human brain as an approximately serial, Von Neumann-like machine.

Acknowledgements

This work was supported by INSERM and the Human Frontiers Science Program. We are particularly grateful to

Lionel Naccache, Emmanuel Dupoux, Sid Kouider, Mariano Sigman and Pieter Roelfsema for useful discussions. We also thank two anonymous reviewers and Eric-Jan Wagenmakers for very helpful remarks regarding the argument and clarity of the paper. We thank Sarah Kouhou, Alessandro Pignocchi and Anne–Caroline Fievet for their help with data acquisition.

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