Available online at www.sciencedirect.com
SciVerse ScienceDirect
Current Opinion in Neurobiology

From a single decision to a multi-step algorithm

Stanislas Dehaene[1,2,3,4] and Mariano Sigman[5]

Humans can perform sequential and recursive computations, as when calculating 23 × 74. However, this comes at a cost: flexible computations are slow and effortful. We argue that this competence involves serial chains of successive decisions, each based on the accumulation of evidence up to a threshold and forwarding the result to the subsequent step. Such serial 'programs' require a specific neurobiological architecture, approximating the operation of a slow serial Turing machine. We review recent progress in understanding how the brain implements such multi-step decisions and briefly examine how they might be realized in models of primate cortex.

Addresses
[1] Collège de France, F-75005 Paris, France
[2] INSERM, U992, Cognitive Neuroimaging Unit, F-91191 Gif/Yvette, France
[3] CEA, DSV/I2BM, NeuroSpin Center, F-91191 Gif/Yvette, France
[4] University Paris-Sud, Cognitive Neuroimaging Unit, F-91191 Gif/Yvette, France
[5] Laboratory of Integrative Neuroscience, Physics Department, University of Buenos Aires, Buenos Aires, Argentina

Corresponding author: Dehaene, Stanislas
(stanislas.dehaene@gmail.com)

Current Opinion in Neurobiology 2012, **22**:1–9

This review comes from a themed issue on
Decision making
Edited by Kenji Doya and Michael Shadlen

0959-4388/$ – see front matter

http://dx.doi.org/10.1016/j.conb.2012.05.006

Introduction: Turing's hunches and rational machines

The mathematician Alan Turing made at least two seminal contributions to computing. First, to help break the German Enigma code, Turing designed a sequential decision algorithm that consists in accumulating votes for the different options and using a threshold criterion to commit to a choice. This framework has become ubiquitous in the psychology and neuroscience of decision making [1,2]. Second, Turing formalized a sequential computing device, the famous 'Turing machine'. Although Turing conceived it as an abstract model of ''a man in the process of computing'' [3], this idea met with a strong resistance in the neuroscience community and, to this day, is still considered the wrong metaphor for brain-like computing. Part of this resistance is justified: unlike Turing devices, the brain is largely parallel, plastic, and computes over probability distributions rather than discrete symbols [2]. However, as we review here, conscious rational thought and more generally the assembly of multiple decisions into sequential routines might still be approximated by a Turing machine. We argue that the Turing view of serial computations provides a fruitful first-order approximation of the role of a central executive system in serial decision making and conscious thought.

From isolated decisions to mental programs: the brain's Turing machine

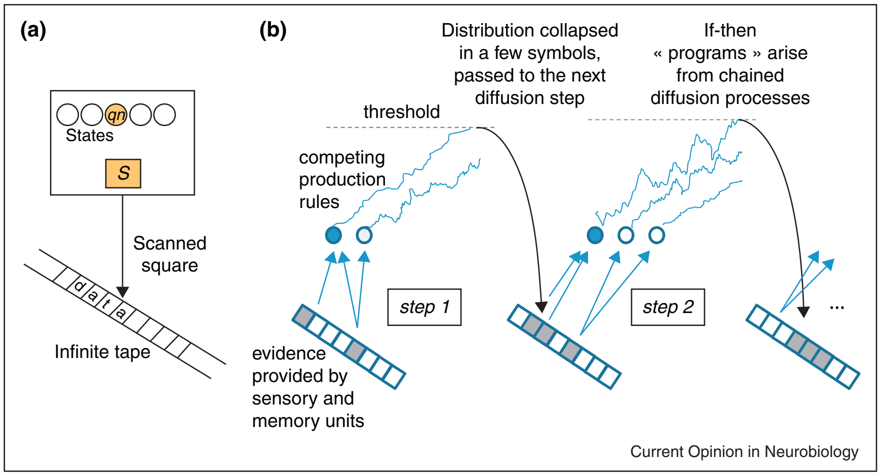
We have proposed a framework for the neural basis of serial computations that puts together Turing's two seminal contributions [4,5•]. Our framework (Figure 1) assumes that serial tasks (e.g. computing 23 × 14) are assembled as sequences of elementary decision steps, each involving a parallel competition between a subset of 'productions rules', implemented by pools of neurons that accumulate relevant evidence. When one of the competing pools encoding a production reaches a threshold, the race concludes and the production ignites. The consequence of the phasic ignition of a production might be an overt motor action, for instance moving the eyes towards a target, but also a covert effect, transiently changing the properties of a subset of cortical areas through an addressing mechanism [6]. This is equivalent to the action performed by a Turing machine in a single step: if a given condition is verified in the current memory state, it modifies the state of the memory, after which a new cycle begins.

This theory supposes that the circuits for sensorimotor decision making, instead of simply triggering motor actions, have been co-opted to implement a broader if – then logic. As noted by Shadlen *et al.* [7], ''*the 25 million years of evolution between macaque and humans has probably served to expand the cortical mantle in the service of this nested intentional architecture . . . This seems far more likely to have occurred than the evolution of brand new principles of neural computation.*''

Here, we argue that the configuration of this process requires a distinctive control mechanism that conveys flexibility at the price of slow serial performance. Our framework envisages human rational thought as a combination of two elements: (1) A vast parallel machinery for decision making by accumulation of multiple sources of evidence, which contributes to intuitions, hunches, and a very rapid ignition of relevant actions; and (2) a capacity to link each of this decisions into 'strategies' or 'programs', where the outputs of one decision become the inputs of the subsequent decision, thus creating serial programs.

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

Figure 1



Current Opinion in Neurobiology

A neurobiological framework for assembling serial decisions into a mental algorithm. **(A)** Alan Turing's formal machine [3] implements programs as a series of state-dependent conditional rewriting operations on an infinite tape. **(B)** The proposed framework for the neural basis of serial computations brings together the Turing machine and the evidence-accumulation scheme [4,29•]. We propose a sequential/parallel device in which each step involves the parallel competition between a subset of 'productions rules', implemented by pools of neurons that accumulate evidence up to a threshold. Once a production attains a threshold, probability distributions are collapsed in a few symbols (mean, variance, confidence) and passed to the next operation. The production can have overt effects (actions) as well as covert effects in modifying the state of the memory, after which a new cycle begins. In this architecture, each elementary step represents a complex massively parallel process of inference resulting in a single decision. Individual steps are analog in nature, but each is followed by a discretization step with a threshold. The latter mechanism provides control over the propagation of noise in analog computation, a problem stressed by John Von Neumann in his 1958 book '*The Computer and the Brain*' [94].

Two theories on how the brain implements multiple decisions

Over the past years, Cisek, Kalaska, Shadlen and others have argued in favor of a parallel decision framework, and questioning the role of an executive system coordinating decision making. Their argument rests on the following observations. First, during a decision process, the same neuron may, at different times, encode stimulus properties, a decision signal, or a motor response [8,9,10•]. This argues in favor of distributed instead of centralized organization of decision variables. Second, when a monkey faces opposite actions that will be resolved after a delay, the monkey appears to prepare both movements simultaneously during the initial period of uncertainty, instead of storing target locations in a general-purpose working memory buffer [11].

However, we suggest that these data do not refute the influence of a central executive in the decision process. They merely argue against a naïve box-and-arrow implementation. During a single decision, the transfer from perception to decision and response is not strictly serial, but rather involves parallel computations and continuous flow [12] – a proposal with much support and a long history [13,14]. We argue, however, that a central executive plays an inescapable role in information routing, task setting, and task sequencing. This is manifest where patients with lesions of the executive system are unable to configure reliable decision paths [15,16]. Here we specifically review data on multiple decisions, which consistently show that, whenever several decisions have to be articulated, a slow sequential organization is observed.

Evidence for serial operations in the human brain

A classical psychological observation, the *psychological refractory period* (PRP), illustrates the limits that human brain architecture imposes on parallel processing. When a human subject is asked to process two near-simultaneous stimuli as fast as possible, a striking seriality emerges: one stimulus is processed with no trace of interference, as if it was presented in isolation, but the response to the second is massively delayed, often by hundreds of milliseconds [17,18•,19–21]. This delay is observed even when, in principle, the stimuli and responses could be dealt with by independent brain systems or even by two distinct hemispheres [22,23]. It cannot be eliminated by training [24–27], even after thousands of trials [28•], suggesting that it reflects a structural bottleneck.

Response-time studies have refined the localization of the bottleneck, suggesting that sensory and motor processes can operate in parallel during the PRP, while a central response selection stage establishes a serial bottleneck [18•,19]. We have proposed that this bottleneck stage coincides with the noisy accumulation-of-evidence postulated in drift-diffusion models of decision making [29•].

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

This conclusion derives from the decomposition of response times into decision and non-decision components (see, e.g. ref. [30]). Only the experimental factors that influenced both the mean and the variance of response time (thus affecting the decision stage) also caused a delay that propagates to a concurrent task (thus affecting the central stage). In fact, the full, complex distribution of response times in a dual task could be explained by a model in which non-decision stages proceed in parallel, and only decision times are serially convolved [29•].

In event-related potentials (ERPs), the dual-task bottleneck relates to a late decision-related component referred as the P300. While subjects perform the first task, the early components of the ERP evoked by a second target T2 remain time-locked to T2 onset (and thus occur in parallel to T1-evoked activity), but the P300 is consistently delayed until after the T1 task is completed [23,31–34]. Time-resolved functional MRI [35] similarly indicates a delayed activation of a broad network including parietal and lateral prefrontal cortex [23,27,36–38]. This evidence is consistent with the proposal that in humans at least, even two seemingly unrelated decisions tie up a central executive or flexible routing system that is shared between many tasks [39–41].

For more complex tasks, there may be an even longer string of serial decision stages. For instance, when the participant chooses which task to perform first, response-time decomposition indicates a nested arrangement of *three* stochastic decisions [42]: Which task should I do first? What is the response to task 1? What is the response to task 2?

At even longer time scales, we predict that, during complex thought (e.g. mental calculation, internal speech, etc.), brain activity should organize as a long series of elementary decision steps. Because each step involves a noisy accumulation of evidence up to a threshold, the resulting activity should be dominated by noisy-triangular waveforms (periods of drift-diffusion interrupted by resets; Figure 1). Such activity may account for two properties that characterize spontaneous brain activity [43]: scale-free distribution (over a range of frequencies, power is distributed as $1/f^{\beta}$, with $\beta = 2$ for a Brownian diffusion process) and nested frequencies (in a triangular wave, power in the high frequencies is concentrated at specific phases of the lower frequencies).

Seriality and conscious control

Psychologists have long speculated that serial effortful performance is associated with the deployment of strategies that are consciously controllable and reportable [44,45]. Indeed, the parieto-prefrontal network that is tied during dual tasking overlaps strongly with the 'global neuronal workspace' postulated to underlie conscious reportability [46•]. Furthermore, the mechanisms that lead to the postponement of the second task during the PRP are very similar to those that lead to the loss of conscious reportability during the attentional blink (AB) [[34], see also [38]]. In both cases, attending to a first target interferes with the central processing of a second one – in the PRP, by slowing it, and in the AB, by preventing it entirely. In both cases, early perceptual processing stages are intact, and only a late (>300 ms) stage is affected [34,47–50].

PRP and AB effects can even occur on intermingled trials of the same tasks [34,51], and the same variables are at play – for instance, slowing down the central stage of task 1 increases both the PRP and the AB [52,53]. Even the mere perception of an unexpected event [54] or the simple fact of becoming aware of a letter [55•], is sufficient to tie up central resources and create an attentional blink for an immediately subsequent stimulus.

If the central decision stage that is tied during serial processing underlies consciously reportability, then it follows that, during the dual-task delay, the second stimulus whose processing is postponed is not consciously perceived until it is centrally processed. This prediction was successfully tested [56,57]. During the PRP, human participants are capable of faithfully reporting their first response time, but not their second, nor even exactly *when* the second stimulus was presented [56]. This demonstrates that a tight relationship exists between central decisions and conscious reportability. It offers a potential explanation for why serial strategies require conscious perception (Figure 2; [58•,59]), and why we can accurately report our multi-step strategies, intermediate steps and subgoals, but not how we take an individual decision [45].

Chaining: a missing link

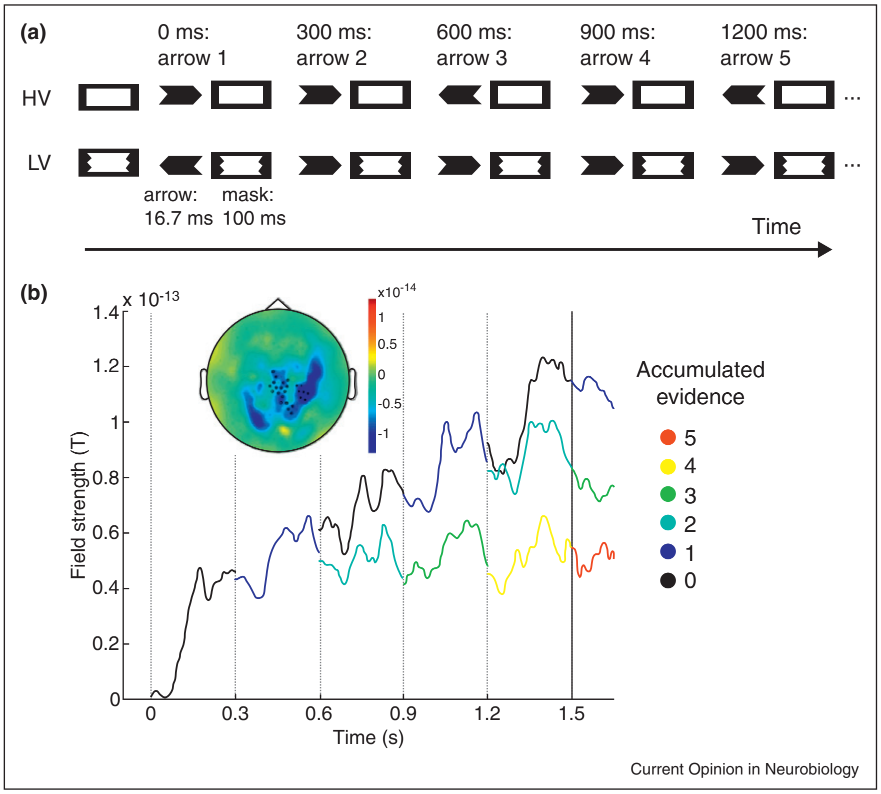
Of particular importance for building a mental program is the capacity to 'chain' operations, such that the output of the first one becomes the input to the second. Chaining is an understudied yet essential operation. It implies a flexible neural architecture for 'routing' information across any two brain processors, which is likely to involve prefrontal cortex [40,41,60,61].

Using behavioral response-time measurements, Fan *et al.* [62] demonstrated that in humans, even for identical tasks, stimuli and responses, chained operations are slower than independent operations by 60–70 ms. Thus, chaining corresponds to a measurable processing stage [see also [63]].

Two monkey electrophysiology studies suggest one possible mechanism for chaining: the maintenance of sustained activity in a relevant subset of neurons. Yang and Shadlen [64••] trained monkeys to make a saccade according to the total evidence provided by four

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

Figure 2



Current Opinion in Neurobiology

A complex sequential decision task in humans. De Lange *et al.* [58•,59] asked humans to click left or right, according to the sum of evidence provided by five successive arrows, each of which could point left or right. The arrows could be masked down to near-invisibility (LV = low visibility), or they could be unmasked (HV = high visibility; panel A, from ref. [58•]). Behavioral findings revealed that, in both cases, decisions were based on an accumulation of the total evidence: subjects were increasingly fast and accurate as the number of arrows pointing to one side increased. Interestingly, when the arrows were visible, humans deployed a rational strategy of progressively lowering their attention as their running count of arrows increased, resulting in a decreasing amount of bilateral parietal activity with increasing evidence (panel B, from ref. [59]). When the arrows were masked, the participants no longer deployed this rational strategy, although their responses remained affected by an unconscious accumulation of evidence [58•]. The results suggest that conscious executive control may be needed to advance through a multi-step serial program [see also [63]].

successive shapes (Figure 3). After each shape, the firing of LIP neurons was incremented or decremented by a roughly appropriate amount, suggesting that these neurons maintained a running count up to the final decision period (see Figure 2 for a similar task in humans). In the second study, capitalizing on previous demonstrations of serial curve tracing in human and non-human primates [65–68]. Moro *et al.* [69••] trained macaque monkeys in serial 'search-then-trace' and 'trace-then-search' tasks. Participants had to alternate between curve tracing and searching for a dot whose color matched the one found at a previous point (Figure 4). This series of purely mental operations was detectable as a sequence of precisely timed moments of amplified firing at the appropriate V1 locations [69••]. Thus, although retinotopic cortex is usually associated with early feedforward processing, it can also be recruited in a top-down manner during visual decisions [6,67,70,71] and maintain, via its sustained activity, a pointer to the current step in a series of decisions [69••].

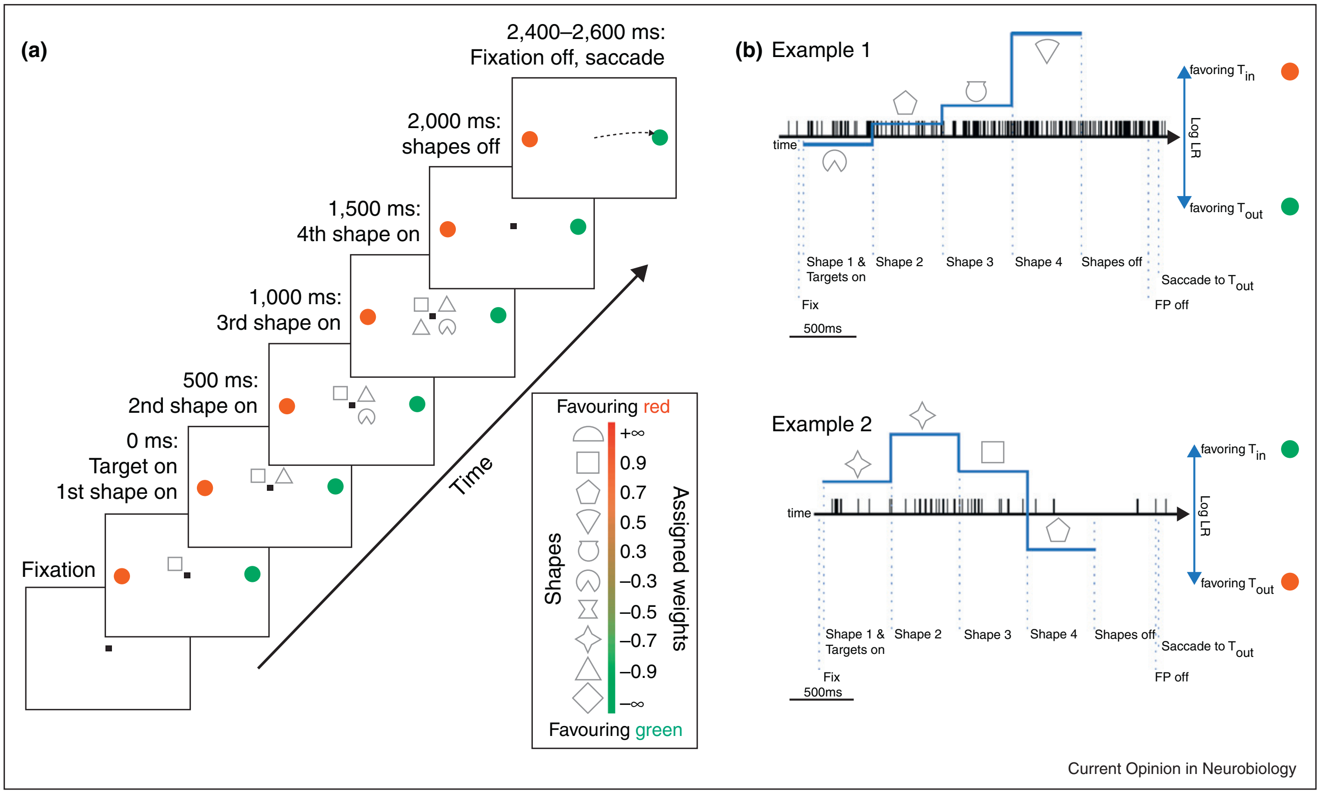
Approximate seriality in a parallel brain

Unlike a digital computer, the brain only implements an approximate form of seriality. Not only do a variety of automatized perceptual and motor operations operate in parallel, but even central decisions may be occasionally subject to partial time sharing [72]. During the PRP, the response to the second item may interfere with the first, suggesting the presence of 'cross-talk' [22,23]. During curve tracing, the successive stages of amplification may partially overlap in visual cortex [69••]. During serial arithmetic, participants may start the second operation before finishing the first [63]. A decision may also continue after the motor response has been emitted [73], leading to error detection and 'change of mind' [74••].

The human capacity for error detection and confidence monitoring suggests that even during a single decision, parallel hierarchical routes accumulate evidence at both motor and supra-motor levels [75]. In particular, the frontopolar cortex appears to implement a higher-order

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

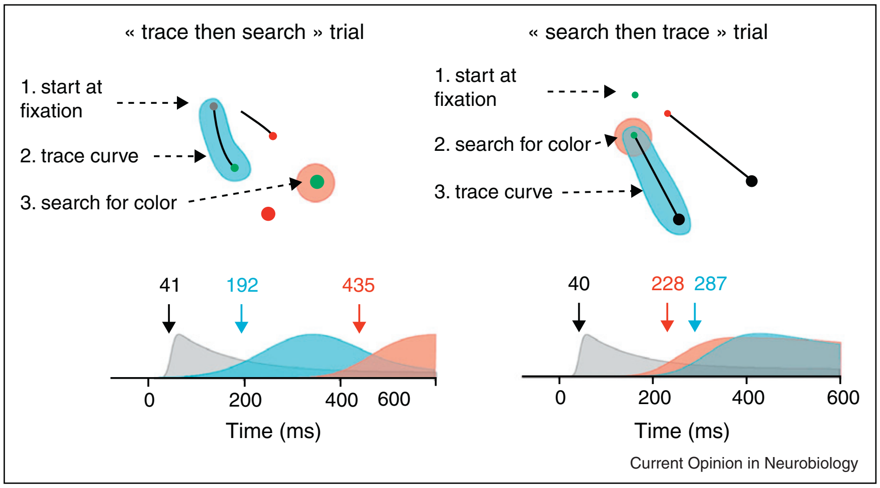
Figure 3



Current Opinion in Neurobiology

A complex sequential decision task in monkeys. Yang and Shadlen [64••] trained monkeys to decide between a red and a green target. The task required summing the evidence provided by four successive shape cues of variable strength. Behavior and single-cell recordings in LIP revealed a prolonged phase of serial decision making associated with accumulation of the total evidence. The sustained firing of LIP neurons tracked the evidence accumulated to date at each time step. In the two example trials presented in panels B and C, the firing rate of an individual LIP neuron (spikes) can be seen to roughly covary with the total amount of evidence objectively provided by the successive shapes (blue square curve).

Figure 4



Current Opinion in Neurobiology

Evidence for serial operations in monkey area V1 [adapted from ref. [69••]]. Macaque monkeys were trained to perform a sequential task requiring successive covert operations of curve tracing and color search, in variable order, before making one saccade to the final target location. The left panel exemplifies a difficult 'trace then search' trial, the right panel a 'search then trace' trial. Below each trial type, curves show, as a function of time, the best-fitting solution of a mathematical model of the experimentally observed normalized multi-unit activity (arbitrary units; see ref. 69 for detailed methods). Gray: initial stimulus-induced response; Blue and red, additional response modulations observed when the traced curve (blue) or the searched color (red) fell inside the neuron's receptive field. V1 neurons whose receptive fields fell on the relevant path showed temporally ordered phases of amplification of neuronal activity, faithfully reflecting the order of the corresponding mental operations.

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

meta-cognitive device that operates in parallel to the current decision, monitoring its success [76••] and controlling the switch to subsequent steps [77–80].

Where is the program? Neural mechanisms for coordinating multiple operations

The precise mechanism by which the executive system organizes serial decisions remains unknown. We emphasize that we do not advocate a homunculus or any dedicated localized structure that will perform such a role. As a first step to understand how executive control is deployed over many parallel cortical processors, we modeled how a network of spiking neurons could implement a sequence of two independent tasks (Figure 4) [5•]. In the model, seriality in dual-task performance results as a consequence of inhibition within the control networks that impose a precise routing of information flow. The same structure that avoids spontaneous responses, perseveration, erroneous mappings, or responses to irrelevant stimuli results in a slow and serial sequencing of responses in dual tasks. Multiple sources of evidence are encoded in parallel and sustained transiently in meta-stable memory buffers. However, the ignition of productions that triggers the responses is strictly sequential and slow ($\sim$300 ms duration). This time constant is a consequence of the characteristic times of NMDA receptors and recurrent cortical circuits. Our architecture accounts in great quantitative detail for error patterns, response time distributions and brain activity patterns in a wide range of interference experiments such as iconic memory decay [81], masking [82], attentional blink [47,83] and psychological refractory period [19,37].

Concluding remarks

How the architecture of the brain supports multi-step operations remains largely unexplored. We conclude by pointing to two prominent challenges for further research.

First, dissecting the electrophysiological mechanisms of seriality is hindered by the intrinsic difficulty of training non-human primates in complex multi-step tasks. Indeed, such tasks tap rostral and mesial prefrontal cortical systems [77,84•] that are more expanded and connected in the human brain than in other primates [85–87]. Nevertheless, simplified animal models of human sequencing abilities can be developed and illuminate the neural coding of task sequences [88•,89,90••,91,92].

Second, the brain may host serial programs, but not a programmer. The Turing-machine metaphor for the brain clearly breaks down here. Modeling studies are required in order to develop an understanding of how task-relevant sequences are assembled in prefrontal cortex, either by self-organization, through reward-based learning algorithms [40,93], or through linguistic instructions in humans [60].

Acknowledgements

Supported by INSERM, CEA, Collège de France, and an ERC grant 'NeuroConsc' to S.D. The authors are very grateful to Ariel Zylberberg and Mike Shadlen for stimulating discussions.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Gold JI, Shadlen MN: **Banburismus and the brain: decoding the relationship between sensory stimuli, decisions, and reward**. *Neuron* 2002, **36**:299-308.

2. Beck JM, Ma WJ, Kiani R, Hanks T, Churchland AK, Roitman J, Shadlen MN, Latham PE, Pouget A: **Probabilistic population codes for Bayesian decision making**. *Neuron* 2008, **60**:1142-1152.

3. Turing AM: **On computable numbers, with an application to the Entscheidungsproblem**. *Proc London Math Soc* 1936, **42**.

4. Zylberberg A, Dehaene S, Roelfsema PR, Sigman M: **The human Turing machine: a neural framework for mental programs**. *Trends Cogn Sci* 2011, **15**:293-300.

5. • Zylberberg A, Fernandez Slezak D, Roelfsema PR, Dehaene S, Sigman M: **The brain's router: a cortical network model of serial processing in the primate brain**. *PLoS Comput Biol* 2010, **6**:e1000765.

The first spiking network that captured the coexistence of serial and parallel processes observed in dual-task experiments in humans. It is an effort to bring together decision making in non-human primates, and the vast literature of dual-task performance in humans.

6. Gilbert CD, Sigman M: **Brain states: top-down influences in sensory processing**. *Neuron* 2007, **54**:677-696.

7. Shadlen MN, Kiani R, Hanks T, Churchland AK: **Neurobiology of decision making: an intentional framework**. In *Better Than Conscious? Decision Making, the Human Mind, and Implications For Institutions. Strüngmann Forum Report.* Edited by Engel C, Singer W. MIT Press; 2008.

8. Crammond DJ, Kalaska JF: **Modulation of preparatory neuronal activity in dorsal premotor cortex due to stimulus-response compatibility**. *J Neurophysiol* 1994, **71**:1281-1284.

9. Gail A, Klaes C, Westendorff S: **Implementation of spatial transformation rules for goal-directed reaching via gain modulation in monkey parietal and premotor cortex**. *J Neurosci* 2009, **29**:9490-9499.

10. • Hernandez A, Nacher V, Luna R, Zainos A, Lemus L, Alvarez M, Vazquez Y, Camarillo L, Romo R: **Decoding a perceptual decision process across cortex**. *Neuron* 2010, **66**:300-314.

A careful analysis of the dynamics of decision making in a tactile comparison task, using multiple single-neuron recordings to show how multiple areas contribute to the sequence of processing steps that bridge from sensation to decision and response.

11. Cisek P, Kalaska JF: **Neural correlates of reaching decisions in dorsal premotor cortex: specification of multiple direction choices and final selection of action**. *Neuron* 2005, **45**:801-814.

12. Selen LP, Shadlen MN, Wolpert DM: **Deliberation in the motor system: reflex gains track evolving evidence leading to a decision**. *J Neurosci* 2012, **32**:2276-2286.

13. Miller J: **Discrete versus continuous stage models of human information processing: in search of partial output**. *J Exp Psychol Hum Percept Perform* 1982, **8**:273-296.

14. Requin J: **Looking forward to moving soon: ante factum selective processes in motor control**. In *Attention and Performance X.* Edited by Posner MI, Marin OSM. Erlbaum; 1985:147-167.

15. Roca M, Parr A, Thompson R, Woolgar A, Torralva T, Antoun N, Manes F, Duncan J: **Executive function and fluid intelligence after frontal lobe lesions**. *Brain* 2010, **133**:234-247.

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

16. Woolgar A, Parr A, Cusack R, Thompson R, Nimmo-Smith I, Torralva T, Roca M, Antoun N, Manes F, Duncan J: **Fluid intelligence loss linked to restricted regions of damage within frontal and parietal cortex**. *Proc Natl Acad Sci USA* 2010, **107**:14899-14902.

17. Marois R, Ivanoff J: **Capacity limits of information processing in the brain**. *Trends Cogn Sci* 2005, **9**:296-305.

18. • Pashler H: **Processing stages in overlapping tasks: evidence for a central bottleneck**. *J Exp Psychol Hum Percept Perform* 1984, **10**:358-377.

An elegant and seminal psychological study demonstrating the coexistence of serial and parallel stages in dual-task and pointing the functional locus of the serial bottleneck to response selection mechanisms.

19. Pashler H: **Dual-task interference in simple tasks: data and theory**. *Psychol Bull* 1994, **116**:220-244.

20. Welford AT: **The "psychological refractory period" and the timing of high speed performance – a review and a theory**. *Br J Psychol* 1952, **43**:2-19.

21. Telford CW: **The refractory phase of voluntary and associative responses**. *J Exp Psychol* 1931, **14**:1-36.

22. Logan GD, Schulkind MD: **Parallel memory retrieval in dual-task situations: I. Semantic memory**. *J Exp Psychol Hum Percept Perform* 2000, **26**:1072-1090.

23. Hesselmann G, Flandin G, Dehaene S: **Probing the cortical network underlying the psychological refractory period: a combined EEG-fMRI study**. *Neuroimage* 2011, **56**:1608-1621.

24. Shin YK, Cho YS, Lien MC, Proctor RW: **Is the psychological refractory period effect for ideomotor compatible tasks eliminated by speed-stress instructions?** *Psychol Res* 2007, **71**:553-567.

25. Lien MC, McCann RS, Ruthruff E, Proctor RW: **Confirming and disconfirming theories about ideomotor compatibility in dual-task performance: a reply to Greenwald (2005)**. *J Exp Psychol Hum Percept Perform* 2005, **31**:226-229.

26. Lien MC, McCann RS, Ruthruff E, Proctor RW: **Dual-task performance with ideomotor-compatible tasks: is the central processing bottleneck intact, bypassed, or shifted in locus?** *J Exp Psychol Hum Percept Perform* 2005, **31**:122-144.

27. Dux PE, Tombu MN, Harrison S, Rogers BP, Tong F, Marois R: **Training improves multitasking performance by increasing the speed of information processing in human prefrontal cortex**. *Neuron* 2009, **63**:127-138.

28. • Kamienkowski JE, Pashler H, Dehaene S, Sigman M: **Effects of practice on task architecture: combined evidence from interference experiments and random-walk models of decision making**. *Cognition* 2011, **119**:81-95.

After training subjects for thousands of trials in a dual-task paradigm, the authors demonstrate that extensive practice can reduce the duration of serial decision stages, but that the qualitative property of central seriality remains a structural invariant.

29. • Sigman M, Dehaene S: **Parsing a cognitive task: a characterization of the mind's bottleneck**. *PLoS Biol* 2005, **3**:e37.

A dissection of the sources of variability in response times in a dual-task setting. Introduces the hypothesis that the 'central bottleneck' stage identified by dual tasks is the same as the 'evidence accumulation' stage of stochastic decision-making models, and is responsible for the bulk of the variance in response times.

30. Wagenmakers E-J, van der Maas HLJ, Grasman RPPP: **An EZ-diffusion model for response time and accuracy**. *Psychon Bull Rev* 2007, **14**:3-22.

31. Dell'acqua R, Jolicoeur P, Vespignani F, Toffanin P: **Central processing overlap modulates P3 latency**. *Exp Brain Res* 2005, **165**:54-68.

32. Arnell KM, Helion AM, Hurdelbrink JA, Pasieka B: **Dissociating sources of dual-task interference using human electrophysiology**. *Psychon Bull Rev* 2004, **11**:77-83.

33. Sessa P, Luria R, Verleger R, Dell'Acqua R: **P3 latency shifts in the attentional blink: further evidence for second target processing postponement**. *Brain Res* 2007, **1137**:131-139.

34. Marti S, Sigman M, Dehaene S: **A shared cortical bottleneck underlying Attentional Blink and Psychological Refractory Period**. *Neuroimage* 2012, **59**:2883-2898.

35. Sigman M, Jobert A, Lebihan D, Dehaene S: **Parsing a sequence of brain activations at psychological times using fMRI**. *Neuroimage* 2007, **35**:655-668.

36. Dux PE, Ivanoff J, Asplund CL, Marois R: **Isolation of a central bottleneck of information processing with time-resolved FMRI**. *Neuron* 2006, **52**:1109-1120.

37. Sigman M, Dehaene S: **Brain mechanisms of serial and parallel processing during dual-task performance**. *J Neurosci* 2008, **28**:7585-7598.

38. Tombu MN, Asplund CL, Dux PE, Godwin D, Martin JW, Marois R: **A unified attentional bottleneck in the human brain**. *Proc Natl Acad Sci USA* 2011, **108**:13426-13431.

39. Dehaene S, Changeux JP, Naccache L, Sackur J, Sergent C: **Conscious, preconscious, and subliminal processing: a testable taxonomy**. *Trends Cogn Sci* 2006, **10**:204-211.

40. Dehaene S, Kerszberg M, Changeux JP: **A neuronal model of a global workspace in effortful cognitive tasks**. *Proc Natl Acad Sci USA* 1998, **95**:14529-14534.

41. Duncan J: **The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour**. *Trends Cogn Sci* 2010, **14**:172-179.

42. Sigman M, Dehaene S: **Dynamics of the central bottleneck: dual-task and task uncertainty**. *PLoS Biol* 2006, **4**:e220.

43. He BJ, Zempel JM, Snyder AZ, Raichle ME: **The temporal structures and functional significance of scale-free brain activity**. *Neuron* 2010, **66**:353-369.

44. Posner NI, Snyder CRR: **Attention and cognitive control**. In *Information Processing and Cognition: The Loyola Symposium.* Edited by Solso RL. L. Erlbaum; 1975:55-85.

45. Ericsson KA, Simon HA: **Verbal reports as data**. *Psychol Rev* 1980, **87**:215-251.

46. • Dehaene S, Changeux JP: **Experimental and theoretical approaches to conscious processing**. *Neuron* 2011, **70**:200-227.

An extensive review of recent experimental research on the brain events that characterize conscious processing.

47. Sergent C, Baillet S, Dehaene S: **Timing of the brain events underlying access to consciousness during the attentional blink**. *Nat Neurosci* 2005, **8**:1391-1400.

48. Vogel EK, Luck SJ, Shapiro KL: **Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink**. *J Exp Psychol Hum Percept Perform* 1998, **24**:1656-1674.

49. Vogel EK, Luck SJ: **Delayed working memory consolidation during the attentional blink**. *Psychon Bull Rev* 2002, **9**:739-743.

50. Gross J, Schmitz F, Schnitzler I, Kessler K, Shapiro K, Hommel B, Schnitzler A: **Modulation of long-range neural synchrony reflects temporal limitations of visual attention in humans**. *Proc Natl Acad Sci USA* 2004, **101**:13050-13055.

51. Wong KFE: **The relationship between attentional blink and psychological refractory period**. *J Exp Psychol Hum Percept Perform* 2002, **28**:54-71.

52. Jolicoeur P: **Concurrent response-selection demands modulate the attentional blink**. *J Exp Psychol Hum Percept Perform* 1999, **25**:1097-1113.

53. Jolicoeur P: **Restricted attentional capacity between sensory modalities**. *Psychon Bull Rev* 1999, **6**:87-92.

54. Asplund CL, Todd JJ, Snyder AP, Gilbert CM, Marois R: **Surprise-induced blindness: a stimulus-driven attentional limit to conscious perception**. *J Exp Psychol Hum Percept Perform* 2011, **36**:1372-1381.

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

55. Nieuwenstein M, Van der Burg E, Theeuwes J, Wyble B, Potter M:
• **Temporal constraints on conscious vision: on the ubiquitous nature of the attentional blink**. *J Vis* 2009, **9**:11-14.
A series of behavioral experiments pursue the minimal conditions under which the attentional blink occurs. The results suggest that the mere conscious perception of the first target T1 suffices to induce a bottleneck on the processing of a subsequent target T2.

56. Marti S, Sackur J, Sigman M, Dehaene S: **Mapping introspection's blind spot: reconstruction of dual-task phenomenology using quantified introspection**. *Cognition* 2010, **115**:303-313.

57. Corallo G, Sackur J, Dehaene S, Sigman M: **Limits on introspection: distorted subjective time during the dual-task bottleneck**. *Psychol Sci* 2008, **19**:1110-1117.

58. de Lange FP, van Gaal S, Lamme VA, Dehaene S: **How awareness**
• **changes the relative weights of evidence during human decision-making**. *PLoS Biol* 2011, **9**:e1001203.
This paper uses magneto-encephalography to analyze the dynamics of a serial decision task in humans, while modulating the consciousness of the targets using masking. The results demonstrate evidence accumulation in near-invisibility conditions.

59. de Lange FP, Jensen O, Dehaene S: **Accumulation of evidence during sequential decision making: the importance of top-down factors**. *J Neurosci* 2010, **30**:731-738.

60. Dumontheil I, Thompson R, Duncan J: **Assembly and use of new task rules in fronto-parietal cortex**. *J Cogn Neurosci* 2010, **23**:168-182.

61. Miller EK, Cohen JD: **An integrative theory of prefrontal cortex function**. *Annu Rev Neurosci* 2001, **24**:167-202.

62. Fan Z, Singh K, Muthukumaraswamy S, Sigman M, Dehaene S, Shapiro K: **The cost of serially chaining two cognitive operations**. *Psychol Res* 2011. Published online 30 August 2011.

63. Sackur J, Dehaene S: **The cognitive architecture for chaining of two mental operations**. *Cognition* 2009, **111**:187-211.

64. Yang T, Shadlen MN: **Probabilistic reasoning by neurons**.
•• *Nature* 2007, **447**:1075-1080.
A detailed behavioral, electrophysiological and theoretical analysis of how monkeys achieve a decision that requires pooling the evidence provided by four serially presented visual cues.

65. Roelfsema PR, Khayat PS, Spekreijse H: **Subtask sequencing in the primary visual cortex**. *Proc Natl Acad Sci USA* 2003, **100**:5467-5472.

66. Lefebvre C, Dell'acqua R, Roelfsema PR, Jolicoeur P: **Surfing the attentional waves during visual curve tracing: evidence from the sustained posterior contralateral negativity**. *Psychophysiology* 2011, **48**:1510-1516.

67. Roelfsema PR, Lamme VA, Spekreijse H: **The implementation of visual routines**. *Vision Res* 2000, **40**:1385-1411.

68. Jolicoeur P, Ullman S, Mackay M: **Visual curve tracing properties**. *J Exp Psychol Hum Percept Perform* 1991, **17**:997-1022.

69. Moro SI, Tolboom M, Khayat PS, Roelfsema PR: **Neuronal activity**
•• **in the visual cortex reveals the temporal order of cognitive operations**. *J Neurosci* 2010, **30**:16293-16303.
A striking demonstration, using monkey electrophysiology, that different orderings of two visual subroutines are reflected in a serial organization of spiking activity in the primary visual area V1.

70. Supèr H, Spekreijse H, Lamme VA: **A neural correlate of working memory in the monkey primary visual cortex**. *Science* 2001, **293**:120-124.

71. Sigman M, Pan H, Yang Y, Stern E, Silbersweig D, Gilbert CD: **Top-down reorganization of activity in the visual pathway after learning a shape identification task**. *Neuron* 2005, **46**:823-835.

72. Tombu M, Jolicoeur P: **A central capacity sharing model of dual-task performance**. *J Exp Psychol Hum Percept Perform* 2003, **29**:3-18.

73. Jentzsch I, Leuthold H, Ulrich R: **Decomposing sources of response slowing in the PRP paradigm**. *J Exp Psychol Hum Percept Perform* 2007, **33**:610-626.

74. Resulaj A, Kiani R, Wolpert DM, Shadlen MN: **Changes of mind in**
•• **decision-making**. *Nature* 2009, **461**:263-266.
A careful analysis of the humans' hand trajectories reveals occasional 'changes of mind', sudden revisions of the subject's goals that suggest that two successive decisions were taken.

75. Del Cul A, Dehaene S, Reyes P, Bravo E, Slachevsky A: **Causal role of prefrontal cortex in the threshold for access to consciousness**. *Brain* 2009, **132**:2531-2540.

76. Fleming SM, Weil RS, Nagy Z, Dolan RJ, Rees G: **Relating**
•• **introspective accuracy to individual differences in brain structure**. *Science* 2010, **329**:1541-1543.
Inter-individual variability in second-order decision making (the capacity to assign confidence to a first-order judgment) is shown to relate specifically to fronto-polar cortex and its connections.

77. Koechlin E, Summerfield C: **An information theoretical approach to prefrontal executive function**. *Trends Cogn Sci* 2007, **11**:229-235.

78. Koechlin E, Hyafil A: **Anterior prefrontal function and the limits of human decision-making**. *Science* 2007, **318**:594-598.

79. Koechlin E, Ody C, Kouneiher F: **The architecture of cognitive control in the human prefrontal cortex**. *Science* 2003, **302**:1181-1185.

80. Koechlin E, Basso G, Pietrini P, Panzer S, Grafman J: **The role of the anterior prefrontal cortex in human cognition**. *Nature* 1999, **399**:148-151.

81. Gegenfurtner KR, Sperling G: **Information transfer in iconic memory experiments**. *J Exp Psychol Hum Percept Perform* 1993, **19**:845-866.

82. Enns JT, Di Lollo V: **What's new in visual masking**. *Trends Cogn Sci* 2000, **4**:345-352.

83. Raymond JE, Shapiro KL, Arnell KM: **Temporary suppression of visual processing in an RSVP task: an attentional blink?** *J Exp Psychol Hum Percept Perform* 1992, **18**:849-860.

84. Charron S, Koechlin E: **Divided representation of concurrent**
• **goals in the human frontal lobes**. *Science* 2010, **328**:360-363.
Using fMRI, this study identifies a remarkable subdivision of labor whereby, during dual tasking, left and right prefrontal areas encode the specific reward contingencies underlying each individual task.

85. Allman J, Hakeem A, Watson K: **Two phylogenetic specializations in the human brain**. *Neuroscientist* 2002, **8**:335-346.

86. Elston GN, Benavides-Piccione R, DeFelipe J: **The pyramidal cell in cognition: a comparative study in human and monkey**. *J Neurosci* 2001, **21**:RC163.

87. Schoenemann PT, Sheehan MJ, Glotzer LD: **Prefrontal white matter volume is disproportionately larger in humans than in other primates**. *Nat Neurosci* 2005, **8**:242-252.

88. Fujii N, Graybiel AM: **Representation of action sequence**
• **boundaries by macaque prefrontal cortical neurons**. *Science* 2003, **301**:1246-1249.
Neurons in the prefrontal cortex of the macaque fire in relation to dynamic start-state and end-state computations. The prefrontal cortex thus contains phasic information that marks the transitions in a sequential program.

89. Fujii N, Graybiel AM: **Time-varying covariance of neural activities recorded in striatum and frontal cortex as monkeys perform sequential-saccade tasks**. *Proc Natl Acad Sci USA* 2005, **102**:9032-9037.

90. Sigala N, Kusunoki M, Nimmo-Smith I, Gaffan D, Duncan J:
•• **Hierarchical coding for sequential task events in the monkey prefrontal cortex**. *Proc Natl Acad Sci USA* 2008, **105**:11969-11974.
Using simultaneous recordings of multiple prefrontal neurons, the authors identify a hierarchical neuronal code, whereby distinct firing patterns label successive events of a complex sequential task. The authors suggest that "by orthogonal coding, the frontal lobe may control transitions between the discrete steps of a mental program."

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006

91. Shima K, Isoda M, Mushiake H, Tanji J: **Categorization of behavioural sequences in the prefrontal cortex**. *Nature* 2007, **445**:315-318.
92. Saga Y, Iba M, Tanji J, Hoshi E: **Development of multidimensional representations of task phases in the lateral prefrontal cortex**. *J Neurosci* 2011, **31**:10648-10665.
93. Rougier NP, Noelle DC, Braver TS, Cohen JD, O'Reilly RC: **Prefrontal cortex and flexible cognitive control: rules without symbols**. *Proc Natl Acad Sci USA* 2005, **102**:7338-7343.
94. von Neumann J: *The Computer and the Brain*. New Haven: Yale University Press; 1958.

Please cite this article in press as: Dehaene S, Sigman M. From a single decision to a multi-step algorithm, Curr Opin Neurobiol (2012), http://dx.doi.org/10.1016/j.conb.2012.05.006