Cognition 119 (2011) 81–95

Contents lists available at ScienceDirect

Cognition

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

Effects of practice on task architecture: Combined evidence from interference experiments and random-walk models of decision making

Juan E. Kamienkowski [a], Harold Pashler [b], Stanislas Dehaene [c,d,e], Mariano Sigman [a,*]

[a] Laboratorio de Neurociencia Integrativa, Departamento de Fisica, FCEyN UBA and IFIBA, Conicet; Pabellon 1, Ciudad Universitaria, 1428 Buenos Aires, Argentina
[b] Department of Psychology 0109, University of California, San Diego, La Jolla, CA 92093, USA
[c] INSERM, U562, Cognitive Neuroimaging Unit, F-91191 Gif/Yvette, France
[d] CEA, DSV/12BM, NeuroSpin Center, F-91191 Gif/Yvette, France
[e] Collège de France, F-75005 Paris, France

ARTICLE INFO

Article history:
Received 5 April 2009
Revised 27 October 2010
Accepted 17 December 2010
Available online 4 February 2011

Keywords:
Learning
Task architecture
Dual-task performance
Psychological refractory period
Response time distributions
Cognitive processes

ABSTRACT

Does extensive practice reduce or eliminate central interference in dual-task processing? We explored the reorganization of task architecture with practice by combining interference analysis (delays in dual-task experiment) and random-walk models of decision making (measuring the decision and non-decision contributions to RT). The main delay observed in the Psychologically Refractory Period at short stimulus onset asynchronies (SOA) values was largely unaffected by training. However, the range of SOAs over which this interference regime held diminished with learning. This was consistent with an overall shift observed in single-task performance from a highly variable decision time to a reliable (non-decision time) contribution to response time. Executive components involved in coordinating dual-task performance decreased (and became more stable) after extensive practice. The results suggest that extensive practice reduces the duration of central decision stages, but that the qualitative property of central seriality remains a structural invariant.

1. Introduction

Several cognitive theories share the hypothesis that most mental and neural operations are modular and a dedicated architecture is required to establish flexible links amongst them (Baars, 1989; Chun & Potter, 1995; Dehaene, Kerszberg, & Changeux, 1998; Posner, 1994; Shallice, 1988). It has been proposed that this flexible architecture, capable of routing information according to any arbitrary program (task-setting) may result in serial information processing bottlenecks (Zylberberg, Fernandez Slezak, Roelfsema, Dehaene & Sigman, 2010). Processing bottlenecks are indeed ubiquitous in dual-task performance. For instance, when two tasks are presented simultaneously or sequentially at a short interval a systematic delay observed in the execution of the second task, a phenomenon referred to as the Psychological Refractory Period (Pashler & Johnston, 1989; Smith, 1967; Telford, 1931).

1.1. Mapping the PRP bottleneck

The exact nature of the processes causing the PRP bottleneck has been debated. A typical observation in the PRP design is that response time to the first task (RT1) is little affected while response time to the Task 2 (RT2) is greatly slowed as SOA is decrease (with a slope approaching -1). This can easily be explained in terms of a sequential processing scheme in which certain aspects of Task 2 cannot proceed until Task 1 is completed. Experiments investigating which aspects of Task 2 can proceed in parallel and which reflect serial queuing have mapped the bottleneck to the response selection process (Kamienkowski & Sigman, 2008; Pashler, 1984).

* Corresponding author.
E-mail address: sigman@df.uba.ar (M. Sigman).

0010-0277/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cognition.2010.12.010

However, while the response selection bottleneck is the principal source of the PRP, both psychophysical and physiological evidence have suggested systematic departures from the simple sequential bottleneck model (Allport, Styles, & Hsieh, 1994; De Jong, 1993, 1995; Jentzsch, Leuthold, & Ulrich, 2007; Logan & Gordon, 2001; Meiran, Chorev, & Sapir, 2000; Ruthruff, Pashler, & Klaassen, 2001; Sigman & Dehaene, 2006). In a classic PRP experiment, responses to Task 1 are independent of SOA, but they are slower than when performing the task in isolation (Jiang, Saxe, & Kanwisher, 2004; Sigman & Dehaene, 2005). We reasoned that this could be related to an executive control stage engaged before the execution of the first task. We hypothesized that in situations in which task order is unknown, this executive time should increase, reflecting a hierarchical decision processes: first, which task to respond to, and second, the specific decision involved in each task. This hypothesis was verified in a new series of experiments in which we concluded that in a situation of task uncertainty, executive components (engaging and disengaging in a task) had to be incorporated in order to account for a broad range of behavioral observations (Sigman & Dehaene, 2006).

Evidence for the involvement of such executive components could also be derived from human electrophysiological studies of the PRP. In an event-related potential (ERP) study in which a visual number comparison task was performed as Task 1 and an auditory pitch discrimination task was performed as Task 2, it was found that the peak of an early sensory component of Task 2 (Auditory N1 wave) occurred at a fixed delay after S2 presentation, indicating that certain perceptual stages of Task 2 can occur in parallel with Task 1. By contrast, the peak of the P3 wave, another ERP component which relates mostly to distributed parietal, temporal and frontal sources and thought to be involved in working memory, flexible routing of information and conscious perception (Donchin & Coles, 1998), showed a strictly serial delay. While this was in very good accordance with the predictions of the bottleneck model (Sigman & Dehaene, 2008), several other observations deviated from this simple model. First, the amplitude of the sensory N1 component of the second task decreased slightly during the interference regime. Second, the temporal course of the N1 component of Task 2 started prior to stimulus presentation, probably reflecting task expectation and preparation. Finally, a Task 2 related P3 component emerged at long SOAs, even before the Task 2 stimulus (auditory tone) was presented. This anticipatory component peaked around 500 ms, thus coinciding closely with the end of the visual P3 evoked by Task 1 (Sigman & Dehaene, 2008). This ERP sequence is compatible with the hypothesis that as soon as Task 1 was completed, subjects re-oriented their attention to prepare for Task 2, reflecting an executive component of task engagement (De Jong, 1993; Logan & Gordon, 2001; Meiran et al., 2000; Ruthruff et al., 2001; Sigman & Dehaene, 2006). In addition, it suggests that the absence of attentional top-down control may explain the amplitude attenuations observed during interference (Gilbert & Sigman, 2007). Overall, these data indicate that PRP experiments involve both a central bottleneck and an active process of task-oriented attention.

1.2. Can the PRP bottleneck be bypassed? Effects of practice on dual-task interference

Another unsolved matter which has attracted the attention of many scientists in cognitive psychology is whether central resources can be bypassed with extensive practice or in very "natural" stimulus–response mappings (McLeod, 1977; Posner & McLeod, 1982) such as responding with the right-hand to a right pointing arrow (Greenwald & Shulman, 1973; Lien, McCann, Ruthruff, & Proctor, 2005; Pashler, Carrier, & Hoffman, 1993; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001). Recent results suggest that even under conditions of high ideomotor compatibility, the locus of the central processing bottleneck may be reduced but not completely eliminated (Lien et al., 2005). This suggests that establishing a temporary mapping between otherwise independent processors involves the engagement of a strictly serial processing stage which can be drastically reduced for highly practiced or non-arbitrary tasks (Greenwald, 2003; Lien, Proctor, & Allen, 2002; Lien et al., 2005).

Logan and colleagues have extensively studied the process of automatization, using an alphabet arithmetic task (e.g. H + 3 = K) (Compton & Logan, 1991). Based on subjective reports and on an analysis of the time-course of the response time variability during the course of learning, they provided substantial evidence in favor of a race model. According to this model, different strategies to solve the task co-occur: an algorithmic computation and a memory retrieval process. These two mechanisms operate simultaneously and the selection process is determined by a race. During the course of learning, memory retrieval is consolidated and becomes faster than the slow algorithmic computation, thus dominating the race and leading to automatic performance (Compton & Logan, 1991). An important assumption of such model is that practice does not affect the qualitative organization of the system, but rather changes the parameters of an invariant architecture. Evidence for such continuous progression in the automaticity process with practice came from a study in which an alphabet arithmetic task, at different stages of practice, was performed concurrently with a speech task (Klapp, Boches, Trabert, & Logan, 1991a, 1991b).

1.3. Random-walk models can decompose processing stages in a cognitive task

Virtually all PRP research – including the study of the effects of practice – has focused exclusively on mean RTs. It is possible however, that certain effects of practice do not directly affect the mean response time, but rather result in a change of the relative contributions of distinct processing stages to RT. Alternatively, of course, learning could result in a combination of both effects. How can one parse a task, simply relying on response time information, into different processing stages and understand the relative contribution of each processing stage to response time?

A separate psychological research tradition seeks to answer these questions, investigating how the decision to respond is achieved. The decision-making process has been