Cognitive Psychology 65 (2012) 284–320

Contents lists available at SciVerse ScienceDirect

Cognitive Psychology

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

On the modularity of implicit sequence learning: Independent acquisition of spatial, symbolic, and manual sequences

Thomas Goschke *, Annette Bolte

Department of Psychology, Technische Universität Dresden, 01062 Dresden, Germany

ARTICLE INFO

Article history:
Accepted 19 April 2012
Available online 22 May 2012

Keywords:
Sequence learning
Implicit learning
Procedural memory
Serial reaction time task

ABSTRACT

Learning sequential structures is of fundamental importance for a wide variety of human skills. While it has long been debated whether implicit sequence learning is perceptual or response-based, here we propose an alternative framework that cuts across this dichotomy and assumes that sequence learning rests on associative changes that can occur concurrently in distinct processing systems and support the parallel acquisition of multiple uncorrelated sequences. In three experiments we used a serial search task to test critical predictions of this framework. Experiments 1 and 2 showed that participants learnt uncorrelated sequences of auditory letters and manual responses, as well as sequences of visual letters, spatial locations, and manual responses simultaneously, as indicated by a reliable response time (RT) cost incurred by occasional deviants violating either of the sequences. This RT cost was reliable even when participants showing explicit knowledge were excluded. In Experiment 3 learning of spatial and nonspatial sequences was functionally dissociated: whereas a spatio-motor distractor task disrupted learning of location but not of letter sequences, a phonological distractor task had the reverse effect. The distractor tasks thus did not reduce unspecific attentional resources, but selectively disrupted the formation of sequential associations within spatial and nonspatial processing dimensions. These results support the view that implicit sequence learning rests on experience-dependent changes that can occur in parallel in multiple processing systems involved in spatial attention, object recognition, phonological processing, and manual response selection. The resulting dimension-specific sequence representations

* Corresponding author. Address: Department of Psychology, Technische Universität Dresden, 01062 Dresden, Germany. Fax: +49 351 4633 3522.
E-mail address: goschke@psychologie.tu-dresden.de (T. Goschke).

0010-0285/$ - see front matter
http://dx.doi.org/10.1016/j.cogpsych.2012.04.002

support independent predictions of *what* will appear next, *where* it will appear, and *how* one will have to respond to it.

1. Introduction

Sequential organization is a hallmark of adaptive cognition and action. As was noted by Lashley (1951) in a seminal paper on serial order in behavior, a wide variety of genuinely human skills such as comprehending and producing language, type-writing, or playing musical instruments rest on the ability to process structured sequences of events (e.g., speech sounds, melodies, movements) and to assemble elementary responses into novel action sequences (e.g., key-presses on the piano, phonemes when uttering a word, or words forming a sentence). Knowledge about sequential regularities enables agents to predict what will happen next, where it will happen, and how to react to it, and thus constitutes the basis for the anticipatory control of perception and action. It is thus a question of central importance for cognitive psychology how knowledge about sequential structures is acquired, represented in memory, and expressed in performance.

A laboratory task that has been widely used to investigate sequence learning is the serial reaction task introduced by Nissen and Bullemer (1987). In its original version, participants have to indicate at which one out of four locations a stimulus appears by pressing one out of four response buttons. If the locations follow a repeating pattern, response times (RTs) usually decrease faster with practice than for a random sequence. Moreover, switching to a random sequence after sufficient practice produces marked RT costs, indicating that participants acquired specific knowledge about the sequential regularities. In the two decades since the publication of Nissen and Bullemer's seminal paper, considerable effort has been devoted to the question whether and under which conditions knowledge about sequential structures can be learnt and expressed in performance in an incidental or even implicit manner, i.e., even if the acquired knowledge is not accessible to conscious awareness (for reviews see Abrahamse, Jimenez, Verwey, & Clegg, 2010; Cleeremans, Destrebecqz, & Boyer, 1998; Clegg, DiGirolamo, & Keele, 1998; Goschke, 1997; Jiménez, 2003; Seger, 1994; Stadler & Frensch, 1998). Although it is a common observation that a portion of participants acquire at least partial explicit knowledge when performing serial reaction tasks (Perruchet & Amorim, 1992), reliable performance increments have repeatedly been demonstrated for participants showing no explicit knowledge as measured by direct reproduction, recognition, or prediction tests (e.g., Cleeremans & McClelland, 1991; Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Destrebecqz & Cleeremans, 2001; Eimer, Goschke, Schlaghecken, & Sturmer, 1996; Frensch, Buchner, & Lin, 1994; Jimenez, Mendez, & Cleeremans, 1996; Jiménez, Vaquero, & Lupiáñez, 2006; Mayr, 1996; Reed & Johnson, 1994; Willingham, Nissen, & Bullemer, 1989; Willingham, Salidis, & Gabrieli, 2002). In line with these findings, sequence learning has been reported to be relatively spared in amnesic patients despite their impaired declarative memory (Nissen, Willingham, & Hartman, 1989; Reber & Squire, 1998; Vandenberghe, Schmidt, Fery, & Cleeremans, 2006). It is, however, a matter of ongoing debate whether such findings constitute unequivocal evidence for unconscious learning or rather reflect the differential sensitivity of direct and indirect tests (e.g., Abrahamse et al., 2010; Shanks, 2010; Shanks & Johnstone, 1999; Shanks & St. John, 1994).

2. A modular theory of implicit sequence learning

While interest in sequence learning has to a considerable degree been fueled by the question whether it constitutes an instance of unconscious learning, in this paper our main focus is on the question which representations and processing mechanisms underlie the incidental acquisition of sequential structures. In fact, in recent years research has increasingly shifted from the question whether sequence learning can be implicit to investigations of the mechanisms mediating the acquisition of sequential structures and the kind of representations acquired during learning (for reviews see Abrahamse et al., 2010; Cleeremans & Dienes, 2008). A question that has received particular attention is whether sequence learning is primarily response-based and the presence of a regular sequence of