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Short Communication

The nature of the memory buffer in implicit learning: Learning Chinese tonal symmetries

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ABSTRACT

Previous research has established that people can implicitly learn chunks, which (in terms of formal language theory) do not require a memory buffer to process. The present study explores the implicit learning of nonlocal dependencies generated by higher than finite-state grammars, specifically, Chinese tonal retrogrades (i.e. centre embeddings generated from a context-free grammar) and inversions (i.e. cross-serial dependencies generated from a mildly context-sensitive grammar), which do require buffers (for example, last in-first out and first in-first out, respectively). People were asked to listen to and memorize artificial poetry instantiating one of the two grammars; after this training phase, people were informed of the existence of rules and asked to classify new poems, while providing attributions of the basis of their judgments. People acquired unconscious structural knowledge of both tonal retrogrades and inversions. Moreover, inversions were implicitly learnt more easily than retrogrades constraining the nature of the memory buffer in computational models of implicit learning.

1. Introduction

Humans are equipped with powerful learning mechanisms for acquiring unconscious knowledge of structural regularities (Dienes, 2012; Reber, 1989; for a different view on the knowledge being unconscious, see Shanks, 2005; for a somewhat intermediate position, see Cleeremans, 2006). Such implicit learning plays a major role in different areas of human cognition, including music (e.g. Rohrmeier & Rebuschat, 2012; Rohrmeier, Rebuschat, & Cross, 2011; Tillman, Bharucha, & Bigand, 2000), perceptual-motor skills (e.g. Reed, McLeod, & Dienes, 2010), and language acquisition (e.g. Chen et al., 2011; Guo et al., 2011; Leung & Williams, 2011; Poletiek, 2002; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997; Williams, 2009).

One of the key questions in implicit learning has focused on the contents of the acquired knowledge. Reber (1967) initially claimed that participants' knowledge could take the form of abstract rules, for example rules that distinguished terminal elements (the elements that actually appear in the string) from non-terminal symbols (e.g. classes of such elements, like word classes); and rules that are about nonlocal rather than adjacent elements (Manza & Reber, 1997). However, some have argued that implicit learning in more general domains may merely involve learning of allowable chunks of successive terminals (e.g. Perruchet & Vinter, 1998) or specific sequences of terminals found in learned exemplars (e.g. Brooks & Vokey, 1991; Jamieson & Mewhort, 2009).

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There is good evidence that both chunks and specific encountered patterns are learned in implicit learning paradigms (e.g. Pothos & Bailey, 2000; Scott & Dienes, 2008), but linguists long ago rejected chunking as an explanation of language acquisition (e.g. Chomsky, 1959). They argued that natural language can only be acquired and processed by a mechanism that was able to deal with grammars more complex than finite state (and even finite-state grammars can involve more than chunking) (e.g. Gazdar, Klein, Pullum, & Sag, 1985; Joshi, Vijay-Shanker, & Weir, 1991; Steedman, 2000). In Chomsky's (1959) hierarchy, finite-state grammars, context-free grammars, context-sensitive grammars and general phrase-structure grammars constitute an inclusion hierarchy. That is, each grammar in the hierarchy involves rules with restrictions, the restrictions being lifted as one goes up the hierarchy, so that grammars higher up can produce structures impossible lower down. For instance, with no length restrictions, context-free grammars, unlike finite-state grammars, can generate sentences where the last half is the reverse of the first (e.g., AAB-BAA, cf. Chomsky, 1956). With no length restrictions, context-sensitive grammars, unlike context-free grammars, can generate sentences where the last half is a copy of the first (e.g., AAB-AAB, cf. Chomsky, 1956). Copying and reversing are types of symmetries. Thus, symmetry has a structural complexity beyond finite-state.

The Chomsky hierarchy is just one way of specifying complexity (see e.g., Van den Bos & Poletiek, 2008, 2010, for other measures of complexity in artificial grammar learning). It remains an open issue whether the Chomsky hierarchy happens to measure complexity in a psychologically relevant way, an issue we will be addressing by using symmetries (cf. Dienes & Longuet-Higgins, 2004; Westphal-Fitch, Huber, Gómez, & Fitch, 2012). The grammars above finite-state in the Chomsky hierarchy uniquely produce various symmetries. Symmetry occurs when transformation leaves a structure invariant; a mirror symmetry occurs when the transformation is reflection. For example, in virtue of exhibiting mirror symmetries, musical structures are analogous to certain linguistic structures. A retrograde symmetry in a melody, such as CEB-BEC (Balch, 1981; think of the music score for the first half being reflected in a vertical mirror to obtain the second half), corresponds to centre embedding in natural language (e.g. "The bamboo the panda ate was fresh", cf. Dienes, Kuhn, Guo, & Jones, 2012), and to a context-free grammar in Chomsky's hierarchy (Chomsky, 1959; Fitch & Friederici, 2012; Hopcroft, Motwani, & Ullman, 2000; i.e. a level above finite state).

People can acquire retrograde structures in at least one domain (natural language) and even other animals may be able to: Starlings might (Gentner, Fenn, Margoliash, & Nusbaum, 2006; but contrast e.g. Swaddle & Ruff, 2004); baboons might (Rey, Perruchet, & Fagot, 2012). However pigeons appear not to learn retrograde symmetries at all (Huber et al., 1999). So the structure is not consistently easy for any implicit learning mechanism. In situations that may be explicit, people have learned mirror retrogrades of sequences under lab conditions, when they were guided by staged-inputting (Conway, Ellefson, & Christiansen, 2003; Lai & Poletiek, 2011), salient perceptual cues (Mueller, Bahlmann, & Friederici, 2010), or intentional learning (Lai & Poletiek, 2011; Mueller et al., 2010). Distinctively *implicit* learning of retrograde structures still needs to be demonstrated (cf. Dienes & Longuet-Higgins, 2004, for suggestive evidence; see also Uddén, Ingvar, Hagoort, & Petersson, 2012, discussed below; and see Rohrmeier, Fu, & Dienes, 2012, for evidence of implicit learning of another type of context-free grammar). In the most convincing evidence to date, Tanaka and Watanabe (in press) showed learning of the retrograde structure on an SRT task, where participants did not report the retrograde nature of the stimuli in post task free report.

Another type of symmetry is an inversion, where the elements of a sequence preserve their order but each element is transformed (e.g. to an opposite) (Dienes & Longuet-Higgins, 2004; Jiang et al., 2012; Kuhn & Dienes, 2005). The inversion can be obtained by placing a mirror horizontally below a music score. The inversion corresponds to cross-serial dependencies in some natural languages, where a sequence of nouns is followed by a sequence of verbs in corresponding order (e.g., "Aad heft Jantje de lerares de knikkers laten helpen opruimen" in Dutch, literal: "Aad has Jantje the teacher the marbles let help collect up", gloss: "Aad let Jantje help the teacher collect up the marbles", cf. Christiansen & Chater, 1999); both inversions and cross-serial dependencies can be generated by a mildly context-sensitive grammar (Fitch & Friederici, 2012; Hopcroft et al., 2000; i.e. a level just above context free but not fully context sensitive, a term introduced by Joshi et al., 1991, to unite abstractly many formalisms emerging to describe natural language, e.g. Gazdar, 1988; Steedman, 2000). Kuhn and Dienes(2005) showed that participants learnt to like tunes instantiating a musical inversion, though they could not as sensitively classify the same tunes as rule governed or not. Thus, people can implicitly learn more than chunks of adjacent elements, and perhaps even acquire inversions per se (though Kuhn & Dienes, 2008, found a Simple Recurrent Network could learn the same material by learning a fixed length long distance association, a simpler structure than an inversion per se; cf. also Desmet, Poulin-Charronnat, Lalitte, & Perruchet, 2009, who raised possible confounds, albeit not ones that removed the learning effect of inversions when statistically controlled). Jiang et al. (2012) found that, controlling both chunks and repetition patterns (and the possible confounds raised by Desmet et al.), people could implicitly learn to discriminate nonlocal tonal inversions from non-inversions in artificial Chinese poetry. Jiang et al. thus provide a paradigm where highly controlled apparent implicit learning of symmetries can be found.

The first aim of the present study was to investigate the implicit learning of retrograde structures using the Jiang et al. (2012) artificial Chinese poetry paradigm. The poetry they used is tonal. Chinese is a tonal language that uses four tones to signal different meanings; for example, the syllable "ma" pronounced in tone 1 means "mother", but "horse" when in tone 3. Tone 1, tone 2, tone 3, and tone 4 indicate flat, rising, falling–rising and falling phonetic characteristics in pitch respectively. Tone 1 and tone 2 are categorized into ping (level) tones, while tone 3 and tone 4 are categorized into ze (oblique) tones for the purposes of Chinese poetry. By virtue of the rising and falling intonation in words, Chinese is figuratively depicted as "the small waves adding on the large waves" (Chao, 1933), where each tone superimposes on the overall intonation pattern of a sentence. Tones are closely intertwined with meanings to achieve a musical and esthetic effect. In Jiang et al.'s paradigm, participants are asked to memorize artificial poems, constructed so that the Chinese tones in successive lines bear