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Short Communication

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

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A B S T R A C T

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 a symmetry relation to each other. For an inversion relation, if a tone for a syllable in a certain position is one category (e.g. ping) in the first line, the syllable in the same position in the second line would be in the other category (e.g. ze). For a retrograde relation, the order of tone categories would be reversed in successive lines. After memorizing poems, participants are then informed that the poems were constructed according to a rule and asked to classify new poems as well formed or not, with half of poems instantiating the relevant symmetry.

In Jiang et al. (2012), in order to assess the conscious status of the knowledge acquired, the "structural knowledge attributions" of Dienes and Scott (2005) were used. Specifically, after each classification decision, subjects indicated if the decision was based on a pure guess, intuition (they had some confidence but have no idea why), memory (they recollected or failed to recollect a sequence) or rules. A subject may learn that the lines of poetry are inversions, as shown by their tendency to classify new poetry as well-formed according to this feature, but not be aware that they knew this feature. Such a subject may insist their classification was just a guess, or based on intuition. By contrast, if subjects were aware of the basis of their classification, they could claim they followed memory or a rule. That is, unconscious knowledge of relevant structure prima facie exists when people say they are guessing or using intuition (implicit attributions); conscious knowledge of structure exists when people say they are using rules or recollection (explicit attributions) (see Dienes, 2012, for a review and evaluation of this method).

Exploring the relative difficulty of learning different symmetries is important for evaluating models of implicit learning. Dienes and Longuet-Higgins (2004) discussed how, by contrasting the implicit learning of retrogrades and inversions, researchers could investigate the nature of the memory buffer required for processing structures beyond finite-state (which, by definition, require a buffer; e.g. Chomksy, 1963). A first in-first out buffer, which outputs material in the same order it was inputted, will facilitate detecting inversions, whereas a last in-first out buffer, which outputs material in the reverse order to which it was inputted, will facilitate detecting retrogrades (Christiansen & Chater, 1999; Dienes & Longuet-Higgins, 2004; Kuhn & Dienes, 2008; Uddén et al., 2012). Thus, investigating implicit learning of retrogrades and inversions is theoretically valuable for modelling in terms of constraining the computational properties of the memory buffer involved in the implicit learning of sequences. Whatever the exact architecture of the memory buffer, differences in difficulty between inverses and retrogrades may be explained in terms of the relative memory cost in processing them (compare natural language parsing for which centre embeddings (retrogrades) have been argued to be especially difficult because of memory cost, in syntactic prediction locality theory, Gibson, 1998).

Uddén et al. (2012) demonstrated that Dutch participants performed better on materials instantiating inversions than retrogrades in an artificial grammar learning paradigm involving strings of letters (in which each letter in one section of the string was paired with a corresponding letter in another section; namely, F was paired with L and D with P). Nonetheless, the authors made no claims about the knowledge being of symmetrical structures (i.e., cross-serial dependencies/inversions or centre embeddings/retrogrades) per se, nor of the knowledge being unconscious. Specifically, although the associative chunk strength (ACS) for the grammatical and non-grammatical test strings was controlled, the repetition structures were not controlled, but the authors pointed out, differed between retrogrades and inversions. A repetition pattern is the pattern of letter repeats across a string, e.g. the pattern MTVTX can be represented as 12324 indicating that the second letter is repeated in the fourth position but all other letters are unique (Brooks & Vokey, 1991). Thus, participants may have simply memorized repetition patterns, a strategy for which there is evidence in artificial grammar learning (e.g. Tunney & Altmann, 2001). Participants did not report the symmetry rules in post task report; but perhaps they did not learn symmetry patterns, implicitly or explicitly. Thus, we controlled both chunks and repetition patterns as Jiang et al. (2012) did, to allow more focused interpretations of the content of the acquired knowledge. We also took trial by trial attribution ratings (specifically, those used by e.g. Chen et al., 2011; Dienes, Baddeley, & Jansari, 2012; Dienes & Scott, 2005; Guo et al., 2011; Jiang et al., 2012; Kemeny & Luckacs, 2013; Kiyokawa, Dienes, Tanaka, Yamada, & Crowe, 2012; Mealor & Dienes, 2012; Neil & Higham, 2012; Rebuschat, 2008; Rebuschat, Hamrick, Sachs, Riestenberg, & Ziegler, 2014; Wan, Dienes, & Fu, 2008) to sensitively measure the conscious status of knowledge on the fly.

In sum, the present study presented participants with artificial poems to remember, where successive lines of the poems, for different groups, instantiated either retrogrades or inversions of the sequences of successive Chinese tones. Implicit learning was established using subjective measures of the conscious status of the structural knowledge used by participants (see Dienes, 2012, for the argument that these measures separate different knowledge types in theoretically expected ways). That is, subjects indicated whether the basis of their judgment on each trial was a guess, intuition, memory, or rules. The first aim was to establish whether retrogrades can be implicitly learned at all. The second aim was to establish whether retrogrades or inversions are easier, in order to explore the functional properties required of the memory buffer in implicit learning.

2. Method

2.1. Participants

Ninety-four volunteers (70 females, M = 21.88, SD = 3.76) from East China Normal University took part in the experiment in exchange for credits or 20 RMB. All the participants were native Chinese speakers and none of them reported a history of hearing difficulties. They were randomly allocated to one of four groups, with 25 in the retrograde experimental (trained) group, 22 in the retrograde control (untrained) group, 25 in the inversion experimental (trained) group and 22 in the inversion control (untrained) group.

2.2. Materials

Two grammars were used in this experiment: retrogrades (centre embedding) and inversions (cross-serial dependencies) based on two tone types (ping and ze tones). Specifically, a total of 20 tonal syllables were selected. The tone type of 10 tonal syllables was ping: "can1, chao1, hui1, ju1, shen1, di2, fo2, lai2, ping2, qin2", and the tone type of other 10 tonal syllables was ze: "er3, guo3, mai3, ye3, zhan3, jun4, kan4, tu4, wei4, zou4". Each string consisted of 10 different tonal syllables where the tone types (pings or zes) of the first five tonal syllables predicted the tone types of the following five tonal syllables by forming a retrograde or an inversion (see Figs. 1 and 2).

Two sets of stimuli were developed according to the retrograde and inversion rules. For each rule, 8 grammatical tone type strings were generated, 4 of which served as training strings and 4 as test strings. In addition, for the retrograde rule, 4 ungrammatical tone type strings were created for the test phase by exchanging the tone type of the second element for that of the seventh element of the grammatical test strings, producing violations in the second (and ninth) and fourth (and seventh) positions (see Appendix A). For the inversion rule, 4 ungrammatical tone type strings were created for the test phase by exchanging the tone type of the seventh element for that of the ninth element of the grammatical test strings, producing the same violating positions as for the retrograde rule (see Appendix A). Each training tone type string was shown twelve times with different tonal syllables each time, with 48 training tonal syllable strings in all. Each test tone type string was shown six times with different tonal syllables each time, with 48 test tonal syllable strings in all (e.g., ungrammatical tone type string "ping ze ze ze ping - ping ping ze ping ping" generated tonal syllable strings "lai2 jun4 kan4 zhan3 shen1 - di2 ju1 wei4 can1 hui1", "qin2 er3 wei4 zhan3 fo2 - hui1 ju1 kan4 di2 ping2" and so on.). None of the tonal syllable strings had a clear semantic interpretation.

Although 32 tone type strings can be created by using all possible permutations of pings and zes to form a retrograde, we chose 8 grammatical tone type strings according to the following criteria: (1) The first element of the first half was not the inverse of first element of the second half; similarly, the last element of the first half was not the inverse of the last element of the second half, to avoid the tone type string forming an inversion, even a partial inversion. For example, the tone type string "ping

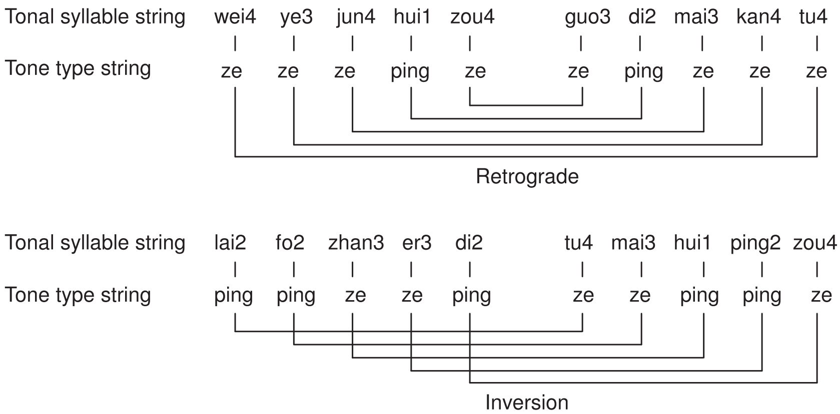

Fig. 1. Examples of grammatical strings of the retrograde and inversion. Each string consists of 10 different tonal syllables. The tone types (pings or zes) of the previous five tonal syllables predict the following five tonal syllables by forming a retrograde or an inversion. (a) For retrograde, if the tone type of the first tonal syllable is ze, then the tone type of the tenth tonal syllable must be ze, and if the tone type of the second tonal syllable is ze, then the tone type of the ninth tonal syllable must be ze, and so on. (b) For inversion, if the tone type of the first tonal syllable is ping, then the tone type of the sixth tonal syllable must be ze, and if the tone type of the second tonal syllable is ping, then the tone type of the seventh tonal syllable must be ze, and so on.

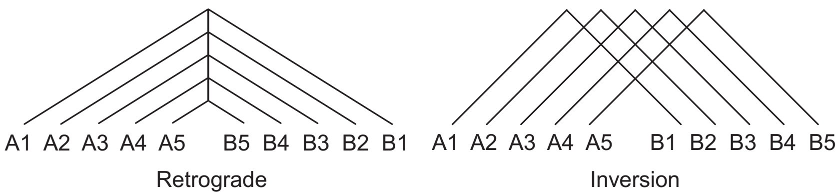

Fig. 2. Retrograde and inversion rules used in this experiment. A and B could be any ping tones or ze tones. (a) For retrograde, any ping tones could go with any other ping tones in an AB pair, and any ze tones could go with any other ze tones in an AB pair. If A1 is ping, then B1 must be ping, and if A2 is ze, then B2 must be ze, and so on. (b) For inversion, any ping tones could go with any other ze tones in an AB pair, and any ze tones could go with any other ping tones in an AB pair. If A1 is ping, then B1 must be ze, and if A2 is ze, then B2 must be ping, and so on.

Table 1
Mean MFF and ACS for grammatical and ungrammatical strings for retrograde and inversion ($M \pm SD$).

Rule	Measure	Tone type		Tones 1–4		Tonal syllable	
		G	UG	G	UG	G	UG
Retrograde	MFF	720.00 ± 0.00	720.00 ± 0.00	360.15 ± 1.48	360.20 ± 1.84	72.26 ± 2.09	72.05 ± 1.71
	GACS	224.75 ± 7.79	233.75 ± 0.00	49.08 ± 4.33	50.84 ± 3.00	2.00 ± 0.69	1.70 ± 0.60
	AACS	36.00 ± 0.00	36.00 ± 0.00	9.16 ± 2.51	9.38 ± 2.89	0.34 ± 0.54	0.50 ± 0.68
Inversion	MFF	720.00 ± 0.00	720.00 ± 0.00	360.77 ± 2.21	360.20 ± 2.16	71.58 ± 2.48	71.95 ± 1.95
	GACS	224.75 ± 0.00	224.75 ± 7.79	48.91 ± 1.98	48.70 ± 2.36	1.67 ± 0.62	1.71 ± 0.67
	AACS	36.00 ± 0.00	36.00 ± 0.00	9.50 ± 2.96	9.31 ± 2.75	0.47 ± 0.58	0.31 ± 0.44

Note. G = grammatical, UG = ungrammatical; MFF = mean feature frequency, GACS = global associative chunk strength, AACS = anchor associative chunk strength.

ze ping ping ze - ze ping ping ze ping" was excluded. (2) The sequence of tone types in the first half could not be the same as in the second half. For example, "ping ze ze ze ping - ping ze ze ze ping" was excluded, because it might be easily detected. Similarly, the criterion of choosing 8 grammatical tone type strings for the inversion rule was same as that of retrograde.

For the materials for both retrograde and inversion strings, we controlled both repetition structure and chunks. None of the test strings had the same repetition structures, in terms of being a succession of tone types, as any of the training strings. Furthermore, none of the test grammatical strings had the same repetition structures, in terms of tones 1–4, as any of the training strings. With respect to tonal syllables, because each string consisted of 10 different tonal syllables, the repetition structure of tonal syllable strings was the same for all retrogrades and non-retrogrades and inversions and non-inversions.

Furthermore, mean feature frequency (MFF), global associative chunk strength (GACS) and anchor associative chunk strength (AACS) were counterbalanced between grammatical and ungrammatical test tone type strings, $ps > .05$ (see Table 1) (see Knowlton & Squire, 1994: GACS is the average frequency with which each chunk in a test string appeared in training strings; AACS is the average frequency with which each chunk at the beginning and end of a test string appeared at the beginning and end of training strings). Grammatical and ungrammatical strings were also balanced along the same dimensions in terms of chunks of tonal syllables and also separately for tones 1–4 rather than tone types (see Table 1).

The 20 tonal syllables, each lasting for 450 ms, were created by Chinese pronunciation software (Xunfei interphonic, cf. Jiang et al., 2012). For each tonal syllable string, a 600 ms interval was interposed between the fifth and sixth tonal syllables to create a perceptual gap between the first half of the tonal syllable string and its retrograde or inversion in the final half (cf. Mueller et al., 2010). Thus, each tonal syllable string lasted for 5100 ms.

2.3. Procedure

There were two phases: training phase and test phase. Only the two experimental groups received the training phase; all the participants received the test phase (cf. Dienes & Altmann, 2003; Jiang et al., 2012).

2.3.1. Training phase

Participants in the experimental groups were asked to listen to 144 tonal syllable strings in all, which consisted of 48 grammatical tonal syllable strings presented three times in a different random order for each participant. In each trial, a warning tone was presented for 500 ms, followed by a 5100 ms tonal syllable string and a 5000 ms blank. Participants were instructed to listen to each tonal syllable string carefully and silently repeat it during the 5000 ms delay before the next trial. The training phase lasted about 30 min.

2.3.2. Test phase

During the test phase, participants were informed that the tonal syllable strings that they heard in the training phase were generated using a specific rule and were asked to listen to 48 new tonal syllable strings presented in a random order. For each tonal syllable string, they were asked to judge whether the given string was grammatical and attribute their decision basis to four categories (guess, intuition, memory and rule). As defined to participants, "Guess" indicated that the judgment was based on nothing at all, it could just as well be based on a toss of a coin; "Intuition" indicated that the judgment was based on a hunch or feeling that could not be explicated further, i.e. there was confidence in the judgment but the person had no idea why the judgment was right; "Memory" indicated that the judgment was based on a recollection; "Rule" indicated that the judgment was based on a rule that could be stated if asked.

3. Results

3.1. Proportion of correct responses

The proportion of correct response was calculated by $\frac{N_C+0.5}{N+1}$ (N_C being the number of correct responses; and N the total number of responses), the correction corresponding to a Bayesian prior of chance performance worth just one observation, useful when some participants have low N for some conditions (as used in e.g. Dienes & Scott, 2005; cf. Baguley, 2012, p. 83).

For the retrograde groups, the classification performance of experimental and control groups were 0.52 ($SD = 0.06$) and 0.49 ($SD = 0.05$), respectively. Participants in the experimental group performed significantly better than the control group, $t(45) = 2.31$, $p < .05$, $d = 0.67$, with sequential Bonferroni correction. For the inversion groups, the classification performance of experimental and control groups were 0.56 ($SD = 0.05$) and 0.50 ($SD = 0.06$), respectively. Participants in the experimental group performed significantly better than the control group, $t(45) = 3.84$, $p < .001$, $d = 1.12$, with sequential Bonferroni correction, see Fig. 3.

For the control groups, the classification performance of retrograde and inversion groups were not significantly different, $t(42) = 0.68$, $p > .05$, but for the experimental groups, the difference was significant, $t(48) = 2.37$, $p = .022$, $d = 0.67$, and remained significant after Bonferroni correction, see Fig. 3. Learning the inversion was easier than learning the retrograde.

3.2. Unconscious structural knowledge of tonal retrograde and inversion

The implicit nature of the knowledge can be assessed by the "structural knowledge attributions" of Dienes and Scott (2005). Specifically, after each classification decision, subjects indicated if the decision was based on a pure guess, intuition (they have some confidence but have no idea why), rule, or memory. A subject may learn that the lines of poetry are inversions, as shown by their tendency to classify new poetry as well-formed according to this feature, but not be aware that they know this feature. Such a subject may insist their classification was just a guess, or based on intuition. By contrast, if subjects were aware of the basis of their classification, they could claim they followed memory or a rule. That is, unconscious knowledge of relevant structure prima facie exists when people say they are guessing or using intuition (implicit attributions); conscious knowledge of structure when people say they are using rule or recollection (explicit attributions) (see Dienes, 2012, for a review and evaluation of this method).

According to the practice of Dienes and Scott (2005), guess and intuition attributions were combined as indicators of unconscious structural knowledge (implicit attributions), and memory and rule attributions were combined as indicators of conscious structural knowledge (explicit attributions). The response proportions of each attribution for retrograde and inversion are shown in Table 2. Because only four participants chose the memory category and none of the participants chose the rule category, we only analyzed the performance of implicit attributions rather than performance of explicit attributions.The proportion of correct response for implicit attributions was calculated by the formula $\frac{N_C+0.5}{N+1}$ (N_C being the number of correct responses when the participants chose implicit attributions; and N the total number of implicit attributions). For retrogrades, the classification performance of implicit attributions for experimental and control groups were 0.52 ($SD = 0.06$)

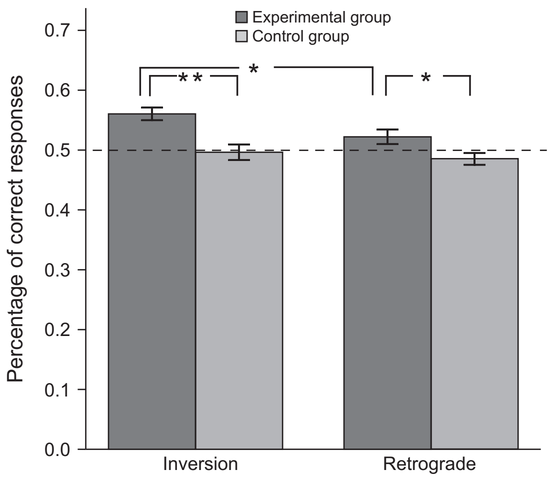

Fig. 3. Percentage of correct responses for the four groups on overall performance (*$p < .05$, **$p < .01$). Error bars indicate standard error of the mean.

Table 2
Response proportions of each attribution for the four groups ($M \pm SD$).

Rule	Group	Implicit attribution		Explicit attribution	
		Guess	Intuition	Memory	Rule
Retrograde	Experimental	0.34 ± 0.27	0.66 ± 0.27	0.00 ± 0.01	0.00 ± 0.00
	Control	0.40 ± 0.27	0.60 ± 0.27	0.00 ± 0.00	0.00 ± 0.00
Inversion	Experimental	0.23 ± 0.23	0.77 ± 0.23	0.00 ± 0.01	0.00 ± 0.00
	Control	0.60 ± 0.34	0.39 ± 0.34	0.01 ± 0.02	0.00 ± 0.00

Note. Only four participants chose memory (two in retrograde experimental group, one in inversion experimental group and one in inversion control group, in ten trials in all); none of the participants chose rule.

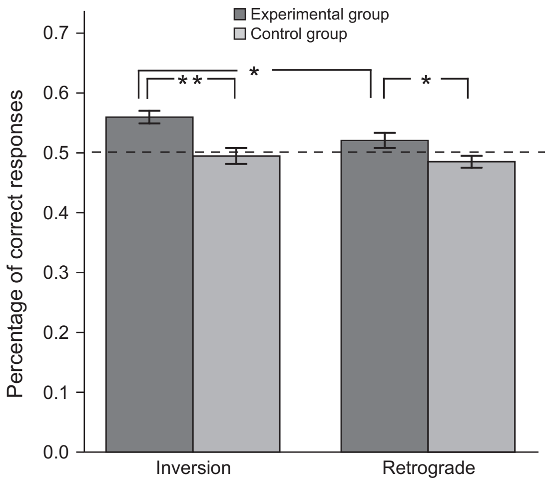

Fig. 4. Percentage of correct responses for the four groups on performance of implicit attributions (*$p < .05$, **$p < .01$). Error bars indicate standard error of the mean.

and 0.49 ($SD = 0.05$), respectively. Implicit knowledge for the experimental group differed significantly from the control group, $t(45) = 2.17$, $p < .05$, $d = 0.63$, indicating unconscious structural knowledge of the tonal retrograde. For inversions, the classification performance of implicit attributions for experimental and control groups were 0.56 ($SD = 0.05$) and 0.49 ($SD = 0.06$), respectively. Implicit knowledge for the experimental group differed significantly from the control group, $t(45) = 3.87$, $p < .001$, $d = 1.13$, indicating unconscious structural knowledge of the tonal inversion.

For the control groups, the classification performance of implicit attributions for retrogrades and inversions was not significantly different, $t(42) = 0.57$, $p > .05$, but for the experimental groups, the difference was significant, $t(48) = 2.37$, $p = .022$, $d = 0.67$, see Fig. 4, indicating implicit learning was easier for inversions than retrogrades.

4. Discussion

The aim of the present study was to investigate the implicit learning of Chinese tonal retrogrades (centre embedding) and inversions (cross-serial dependencies). We provided clear evidence that people can acquire unconscious structural knowledge of retrogrades and inversions. Crucially we also showed that implicit learning was easier for inversions than retrogrades. The results coincide with those of previous studies arguing that people can go beyond learning chunks and repetition patterns and implicitly learn to detect patterns instantiating symmetries, i.e. nonlocal patterns produced by recursive rules (Dienes & Longuet-Higgins, 2004; Jiang et al., 2012; Kuhn & Dienes, 2005; Uddén et al., 2012). We provided evidence for the knowledge being unconscious by taking trial by trial attributions for the basis of the judgments. Almost all attributions were guess or intuition, i.e. claims by the participant that either the judgment had no basis or else they had no idea what it was. Dienes (2012) reviewed evidence that such attributions, at least in the case of the finite state grammars typically used in the implicit learning literature, separate qualitatively different types of knowledge, types that differ in theoretically expected ways. For example, implicit attributions are more resistant to concurrent executive-demanding secondary tasks than explicit attributions. Thus, the attributions have evidential support as a means for measuring the conscious status of knowledge.

The retrograde and inversion rules in the present study take the form of what Marcus (2001) calls "operations over variables". That is, an inversion or a retrograde is an operation that applies to a vector, and can in principle apply to a vector of any length (Dienes & Longuet-Higgins, 2004). We used stimuli of fixed length, so people may not have learnt the inversion or symmetry per se (especially given the low level of learning for retrogrades). For example, for the inversion, people may have learnt an association between corresponding positions in successive lines (Kuhn & Dienes, 2008). For the retrograde, people may have just learned to associate a specific position in one line (e.g. the 4th) with a specific position in the next line (e.g. the 7th). Such knowledge would enable accurate classification if the position which was learnt was one of the positions we altered as violations (i.e., the 2nd, 4th, 7th and 9th positions, but not otherwise). Thus, such long distance associations could explain the advantage of learning inversions over retrogrades (because in inversions, but not retrogrades, the associations occur at the same fixed distance for all positions), without people having actually learnt the symmetries per se. Nevertheless, the learning we have demonstrated still goes beyond what has been shown in artificial grammar learning before (but see especially Remillard, 2010, for learning long distance contingencies in the SRT task). In order to show that people have learnt the symmetries per se, the next step would be to show people can generalize their knowledge to poems with different length lines. It would also be important to show that retrograde performance can be increased to a more impressive level, for example by repeating the training phase, to increase confidence it was the retrograde that was learnt and not a structure that happened to correlate with it in the current materials (Dulany, 1962).

If people have learnt the symmetries per se, then they found the grammar higher in the Chomsky's hierarchy (inversions, mildly context sensitive) easier than the grammar lower down (retrogrades, context free). The hierarchy is just a way of classifying grammars formally, though it is meant as a useful measure of complexity (Fitch & Friederici, 2012); our results tentatively suggest the measure is not psychologically realistic. Dienes and Longuet-Higgins (2004) pointed that a first in-first out buffer would facilitate detecting inversion rather than retrograde. Working memory appears in general to be first in-first out (backward span is harder than forward span). The actual buffer used need not be strictly either first in-first out, or last in-first out; for example the buffer in a Simple Recurrent Network (SRN) is computationally flexible with its exact properties constructed according to the error landscape it is trained in. Nonetheless, a given memory system may function more like a first in-first out or last in-first out buffer, or find it easier to be trained to act like one of those rather than the other. In this sense, our results suggest that functionally the memory buffer used in implicit learning is more like a first in-first out buffer than a last in-first out buffer, which is consistent with Uddén et al. (2012) in this respect.

The exact architecture of the memory buffer involved in implicit learning, however, is an open question. Kuhn and Dienes (2008) have investigated the nature of the buffer involved in implicit learning of nonlocal dependencies by modelling with the SRN (cf. e.g. Carting, 2008, for SRN modelling of learning phrase-structure grammars). In as yet unpublished work we have found that the SRN can learn the two structures and it replicates the advantage of inversions over retrogrades (Li, 2013). Thus, functionally the SRN acts, or finds it easier to be trained to act, more like a first in-first out buffer than a last in-first out buffer. An even more flexible type of memory (such as the random access memory of a desktop computer) can act as a first in-first out buffer or a last in-first out buffer with equal facility, so it cannot by its architectural properties explain an advantage of inverses over retrogrades. Future research is needed to determine whether the SRN-type buffer really matches the computational properties of the buffer used in implicit learning (cf. Cleeremans, 1993; Jones & Mclaren, 2009; see also French, Addyman, & Mareschal, 2011, for why the SRN-type buffer needs to be changed in some learning contexts).

It is not clear whether prior expectations of structure instantiating inversions versus retrogrades could over-ride the effect of the type of buffer the system uses. Backward span is harder than forward span in standard working memory tasks even when people fully expect to perform the task (e.g. Robinson, Mervis, & Robinson, 2003). Nonetheless, Chinese Tang poetry uses an inversion and not retrograde relation between tone classes, knowledgeour participants were likely exposed to as children. That prior knowledge was not sufficient for them to perform well in the untrained control groups. But there is evidence that implicit learning is sensitive to prior knowledge (e.g. Chen et al., 2011; Leung & Williams, 2011; Ziori & Dienes, 2008), and knowledge of Tang poetry may have biased the implicit learning mechanism to be sensitive to pick up inversions rather than retrogrades. Future research should investigate the role of prior knowledge in the relative ease of inversions versus retrogrades.

The symmetries were defined over non-terminal symbols, i.e. over the ping-ze classes of tones (tones being the terminals). However, we cannot be sure based on the data presented here that people induced the rules over those classes or rather learnt specific associations between the constituent tones. The classes constitute likely prior knowledge for participants. Jiang (2012) used an arbitrary classification of the four tones into two categories and found no learning of the inversion rule. Thus, the use of ping-ze classes appears an important contribution to learning, a claim we plan to explore further with experiments and modelling.

In our materials we used a correspondence between same elements for retrogrades (ping was mapped to ping) and a correspondence between different elements for inversions (ping was mapped to ze). Thus, the rules differed not only in instantiating centre embeddings versus cross-serial dependencies, but also in terms of how corresponding elements were mapped (i.e. as same versus different). However, the extra difference in mapping different rather than same elements should make the inverse more difficult than the retrograde; yet the results showed that inverses were learnt more easily than retrogrades (compare Dowling, 1972, who found the same for explicit judgments in music). In music, transposes (i.e. copies of intervals) are considerably easier to detect than inverses (Krumhansl, Sandell, & Sergeant, 1987), although both instantiate a cross-serial dependency structure. Indeed, there is evidence that people have a general facility for detecting sameness, at the level of well-used perceptual categories (e.g. Endress, Dehaene-Lambertz, & Mehler, 2007). As we found cross-serial dependencies to be easier than centre embeddings, in spite of the former using a mapping between different elements, our claim for their relative ease of learning stands. Future research could use a copy rather than an inversion to instantiate a cross-serial dependency (so ping would map to ping and ze to ze); or an inverse retrograde (a retrograde where pings are transformed to zes and vice versa) for a centre embedding, to test our claim further.

To conclude, controlling both chunks and repetition patterns, we showed that people could implicitly learn Chinese tonal retrogrades and inversions, abstract nonlocal rules. The results suggest that the buffer used in implicit learning functions more like a first in-first out buffer than a last in-first out buffer. Together with Jiang et al. (2012), we provide a paradigm where the nature of the memory buffer in implicit learning can be explored.

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Appendix A.

Tone type strings of the retrograde and inversion.

Sort	Retrograde	Inversion
1	p p p z p - p z p p p	p p p z p - z z z p z
1	p z p p p - p p p z p	p z p p p - z p z z z
1	z z z p z - z p z z z	z z z p z - p p p z p
1	z p z z z - z z z p z	z p z z z - p z p p p
2	p p z z p - p z z p p	p p z z p - z z p p z
2	p z z p p - p p z z p	p z z p p - z p p z z
2	z z p p z - z p p z z	z z p p z - p p z z p
2	z p p z z - z z p p z	z p p z z - p z z p p
3	p z z z p - p p z p p	p p z z p - z p p z z
3	p p z p p - p z z z p	p z z p p - z z p p z
3	z p p p z - z z p z z	z z p p z - p z z p p
3	z z p z z - z p p p z	z p p z z - p p z z p

Note. p = ping, z = ze; 1 = grammatical tone type strings in the training phase, 2 = grammatical tone type strings in the test phase, and 3 = ungrammatical tone type strings in the test phase.

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