

PLEASE NOTE:

This is the author's version of the manuscript accepted for publication in *The Quarterly Journal of Experimental Psychology*. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures, may have been subsequently added.

The published version can be found in: Silva, S., Petersson, K.M., & Castro, S. L. (2017). The effects of ordinal load on incidental temporal learning. *Quarterly Journal of Experimental Psychology*, 70(4), 664-674. doi: 10.1080/17470218.2016.1146909

The effects of ordinal load on **incidental** temporal learning

Susana Silva^a, Karl Magnus Petersson^b and São Luís Castro^a

^aCenter for Psychology at University of Porto, Portugal

^bCentre for Biomedical Research (CBMR), University of Algarve, Faro, Portugal

Acknowledgments

This work was supported by Fundação para a Ciência e a Tecnologia under grants PTDC/PSI/66641/2006, PEst-C/PSI/IU0050/2011, PEst-OE/EQB/LA0023/2011, PEst-OE/EQB/LA0023/2013, PTDC/PSI-PCO/110734/2009, UID/BIM/04773/2013 CBMR 1334 and UID/PSI/00050/2013. We are grateful to Fredrik Ullén for the stimulating discussion on a previous version of this manuscript.

Correspondence to São Luís Castro, Faculty of Psychology and Educational Sciences, University of Porto, Rua Alfredo Allen, 4200-135 Porto, Portugal. Telephone: +351 226 079 756 Fax: +351 226 079 725. E-mail: slcastro@fpce.up.pt

Abstract

How can we grasp the temporal structure of events? A few studies have indicated that representations of temporal structure are acquired when [there is an intention to learn](#), but not when learning is [incidental](#). Response-to-stimulus intervals, uncorrelated temporal structures, unpredictable ordinal information and lack of metrical organization have been pointed out as key obstacles to [incidental](#) temporal learning, but the literature includes piecemeal demonstrations of learning under all these circumstances. We suggest that the unacknowledged effects of ordinal load may help reconcile these conflicting findings, ordinal load referring to the cost of identifying the sequence of events (e.g., tones, locations) where a temporal pattern is embedded. In a first experiment, we manipulated ordinal load into simple and complex levels. Participants learned ordinal-simple sequences, despite their uncorrelated temporal structure and lack of metrical organization. They did not learn ordinal-complex sequences, even though there were no response-to-stimulus intervals nor unpredictable ordinal information. In a second experiment, we probed learning of ordinal-complex sequences with strong metrical organization, and again there was no learning. We conclude that ordinal load is a key obstacle to [incidental](#) temporal learning. Further analyses showed that the effect of ordinal load is to mask the expression of temporal knowledge, rather than to prevent learning.

Keywords: temporal structure; sequence learning; [incidental](#) learning; ordinal information; serial recall.

The effects of ordinal load on *incidental* temporal learning

Every sequence of events follows a temporal structure, or rhythm. Series of time intervals between tones in a tune, words in a sentence or gestures in a dance define temporal sequences that are embedded in ordinal information (which tone, word or gesture follows one another). It seems evident that humans learn temporal sequences when they reproduce the rhythm of a song or a dance, showing *temporal learning*. However, *various* research findings (Brandon, Terry, Stevens, & Tillmann, 2012; Buchner & Steffens, 2001; O'Reilly, McCarthy, Capizzi, & Nobre, 2008; Schultz, Stevens, Keller, & Tillmann, 2013; Shin & Ivry, 2002) have indicated that temporal learning is constrained by several factors *when there is no intention to learn and learning is thus incidental*. In some of these studies (Brandon et al, 2012; Buchner & Steffens, 2001; Schultz et al., 2013; Shin & Ivry, 2002), *incidental learning* was coupled with evidence that there was no awareness of what had been learned. Therefore, learning could be classified as *implicit* in a strict sense (Abrahamse, Jiménez, Verwey, & Clegg, 2010; Forkstam & Petersson, 2005; Seger, 1994). In the study of O'Reilly and colleagues (2008), the focus was on incidental learning regardless of awareness. Since all implicit learning is incidental, the viewpoint of constraints arising from incidental learning is common to all studies, and this is the viewpoint we adopt in the present investigation.

A group of early studies (Buchner & Steffens, 2001; O'Reilly et al., 2008; Shin & Ivry, 2002) applied the serial reaction time paradigm (SRT, Nissen & Bullemer, 1987) to *incidental* temporal learning and identified two major constraints. One related to using *response-to-stimulus intervals (RSI)* instead of inter-stimulus intervals (ISI) to define the target temporal sequence. In SRT experiments, participants are repeatedly stimulated with a target temporal sequence and requested to react on-line to each event. Decreases in reaction times across trials indicate that the sequence was learned. When temporal sequences are RSI-

based, the onset of each target time interval is the subject's response to the previous event and the offset is the next event. In ISI-based temporal sequences, however, the onset of all time intervals is predefined by stimulus presentation. Because the regularity of ISI sequences does not depend on participants' fluctuations in response time, ISI sequences are supposed to facilitate learning (Karabanov & Ullén, 2008; O'Reilly et al., 2008; Ullén & Bengtsson, 2003). The other constraint *is related to* the correlation between temporal and ordinal information, that is, the coupling between time intervals (the learning target) and events (tones, words, spatial locations, etc.) in the sequence. Temporal and ordinal sequences correlate when the target rhythm is embedded in a fixed sequence of events (e.g., a constant tone sequence, as when learning a song). Temporal and ordinal sequences are *uncorrelated* when they have different lengths, or when ordinal information is randomly assigned to the fixed temporal sequence across trials. The latter happens, for instance, when the rhythm of a song is used to sing different melodies. Studies using uncorrelated temporal sequences (Buchner & Steffens, 2001; O'Reilly, McCarthy, Capizzi, & Nobre, 2008; Shin & Ivry, 2002) found that they are typically not learned *in an incidental manner*. For instance, Shin & Ivry (2002) analysed the learning of seven- and eight-element temporal sequences embedded in eight-element ordinal sequences, and found that only eight-element (correlated) temporal sequences were learned. O'Reilly and colleagues (2008) presented a fixed temporal sequence in the context of random ordinal information (uncorrelated) and found no evidence of temporal learning.

Neither ISIs nor correlated temporal sequences seem to be undisputable requirements of *incidental* temporal learning. Salidis (2001) used RSIs to define temporal sequences embedded in constant ordinal information (one single beep) and showed evidence of implicit

learning. Concerning uncorrelated temporal sequences, it was first suggested that they are not learned because temporal representations are dependent on ordinal ones when learning is *incidental* (O'Reilly, McCarthy, Capizzi, & Nobre, 2008). However, Ullén and Bengtsson (2003) provided an alternative explanation. They raised the hypothesis that uncorrelated sequences are learnable, but the *unpredictability* of uncorrelated ordinal information in SRT tasks leads to underestimating acquired temporal knowledge. Because on-line reactions to unpredictable ordinal events tend to be delayed, temporal learning would be less likely to show up in performance. Ullén and colleagues (Karabanov & Ullén, 2008; Ullén & Bengtsson, 2003) addressed this problem asking subjects to reproduce the sequence only after its presentation is complete (serial recall task), and successful implicit learning was seen. In the study of Ullén and Bengtsson (2003), lack of awareness of temporal structures was inferred from verbal reports only, while Karabanov & Ullén (2008) used both verbal reports and the process dissociation procedure (Toth, Reingold, & Jacoby, 1994). Schultz and colleagues (2013) approached the unpredictability problem in a different manner and probed the implicit temporal learning of ISI-based sequences of sound sources (left, right, or both) by means of a stimulus-detection task. This task differs from the SRT traditional multiple-alternative forced-choice task ('press key X for sound source Y'), in that it eliminates the need to define the identity of ordinal information ('press the same key for any sound source') and hence the unpredictability problem. Strengthening the findings of Ullén and colleagues (Karabanov & Ullén, 2008; Ullén & Bengtsson, 2003), *learning of uncorrelated temporal sequences occurred with a stimulus-detection task, and not with a multiple-alternative task.*

A puzzling finding in this scenario was presented by Brandon and colleagues (2012), who did not address the ordinal predictability problem (they used a multiple-alternative task)

but yet elicited implicit temporal learning of uncorrelated, ISI-based sequences in SRT. A novelty introduced in this study was that the temporal stimuli had a strong metrical organization. When time intervals are perceived as multiples or subdivisions of an underlying regular interval (the pulse), pulses tend to be clustered into regular groups, usually containing 2, 3, or 4 pulses each (Fitch, 2013). The *metrical organization* of a temporal sequence is the extent to which the perception of regular pulse groups is facilitated, which depends on the presence (vs. absence) of events and from intensity accents (Essens and Povel 1985; Povel and Essens 1985) at the onset of each pulse-group. One sequence with events and/or accents every 2 or 3 pulses, for instance, is metrically stronger than one without these characteristics. The findings of Brandon et al. (2012) suggested that strength of metrical organization, rather than ordinal unpredictability, might be the key obstacle to implicit temporal learning. However, Schultz et al. (2013) showed shortly after that implicit learning was possible with a level of metrical organization that is null, in the sense that the events were not even aligned to a common pulse.

Since *incidental* temporal learning does not seem to be prevented by either RSIs (Salidis, 2001), uncorrelated temporal sequences (Brandon et al., 2012; Karabanov & Ullén, 2008; Schultz et al., 2013; Ullén & Bengtsson, 2003), ordinal unpredictability (Brandon et al., 2012) or weak metrical organization (Schultz et al., 2013), determining the key constraints that act upon it is an ongoing challenge. The contribution of this paper is to raise and test an alternative explanation of Schultz et al.'s (2013) findings that *may accommodate the remaining findings from the literature* and, thus, indicate a key obstacle to *incidental* temporal learning. We suggest that the multiple-response task in Schultz et al. (2013) impeded learning because the identification of ordinal information (spatial location of sounds) was a demanding process, and not because the information was unpredictable.

Conversely, successful temporal learning may have resulted from subjects responding to easy-to-identify ordinal information (auditory-presented syllables: Brandon et al., 2012; Ullén & Bengtsson, 2003), or from not responding to ordinal information of any sort (Salidis, 2001; Schultz et al., 2013). Humans rely strongly upon vision to localize objects in space, and conscious auditory-based spatial localization is probably an underdeveloped skill that gains prominence only when there are losses in sight (Abel & Shelly Paik, 2004; Röder et al., 1999). In contrast, humans identify syllables every time they engage in oral communication. Increased ordinal-related costs are also expected to arise from sequences with higher ordinal complexity (Janata & Grafton, 2003), that is, with a larger variety of categories (e.g., sequences combining four syllable types, compared to two types only), as well as from non-direct mappings between stimulus space and response device space (e.g., syllables vs. high/low tones mapping into up/down buttons). We refer to the cognitive demands associated with processing ordinal information in a sequence as its *ordinal load*.

In this paper, we test the hypothesis that ordinal load has an effect on *incidental* temporal learning (Experiment 1) and we investigate if and how metrical organization modulates this hypothesized effect (Experiment 2).

Experiment 1

In this experiment, we used a serial recall task to compare the learning of a fixed temporal sequence in two different groups. In one group, the ordinal information in the temporal sequence was highly complex, comprising four categories and a non-direct stimulus-response mapping: four vowels mapped into left, right, up and down arrow keys (*complex ordinal load*). In the other group, the ordinal information was less complex, comprising two categories and a direct stimulus-response mapping: high and low tones map

into up and down response keys (*simple ordinal load*). Because our focus was on the constraints that act upon *incidental* temporal learning, we compared *incidental* with *intentional* learners within each level of ordinal load. To that purpose, we manipulated the instruction as Karabanov and Ullén (2008) did. We asked *incidental* learners to recall ordinal information, and *intentional* learners to recall both ordinal and temporal information. Temporal learning was defined as an improvement in temporal performance during the serial recall task. We predicted that *incidental* learners under simple ordinal load would show learning, whereas those under complex load would not.

Our paradigm incorporates two features that are obstacles to *incidental* temporal learning according to previous literature (uncorrelated temporal structures and weak metrical organization), and two features that facilitate learning from the same viewpoint (ISI-based sequences and the elimination of unpredictable ordinal information by using serial recall). If ordinal load is a key obstacle to *incidental* temporal learning, we expect learning to occur in the simple load *incidental* group despite the obstacles, and not to occur in the complex load *incidental* group despite the facilitating features.

A second goal of this experiment was to better define the effects of ordinal load when temporal learning does not occur. There may be two types of effects. Either complex ordinal load prevents the acquisition of temporal knowledge and representations of the temporal sequence are not acquired (*blocking effect*), or complex ordinal load merely impedes the expression of temporal knowledge (*masking effect*). In order to test for masking effects, we asked subjects to reproduce the temporal sequence without ordinal information (*non-loaded performance*) after all serial recall trials had been completed, and we compared the non-loaded performance with the loaded one in the last trials of serial recall. Masking effects relate to the expression of temporal knowledge, and thus they were based on the combination

of two indices: absence of temporal learning in serial recall (loaded performance), and increased accuracy in the non-loaded performance compared to the loaded one. In our paradigm, the default expectation for non-loaded performance was that accuracy would decrease, since non-loaded performance would be delayed relative to stimulus presentation. Therefore, increased accuracy should be clear evidence of masking effects, but decreased accuracy would not necessarily indicate that there was blocking instead of masking. In this sense, our question was limited to whether or not there was evidence of masking effects.

Method

Participants

Sixty-four graduate and undergraduate college students (58 women, mean age \pm SD = 22 \pm 5) took part in the experiment. They were assigned to one of four groups (n = 16 per group), so that age, sex and level of musical training were matched across groups (2 subjects with training beyond the elementary school *curricula* in each group). Groups were formed according to type of learning (*incidental* vs. *intentional*) and ordinal load (simple vs. complex) in a factorial 2 x 2 plan.

Stimuli

Sequences with complex ordinal load (Figure 1) were made from four spoken vowels ([E, i, O, u] in SAMPA transcription). The vowels were articulated by a female speaker instructed to keep a constant pitch (F0 ~200 Hz). Vowel length was normalized to 250 ms. Fifty different sequences were generated by combining the four vowels into 9-element strings by random generation. Sequences with simple ordinal load were built with two tones (250 ms length), one high (F0 = 493 Hz) and one low (F0 = 261 Hz). The pitch interval between tones

corresponded to a major seventh, which is a dissonant interval and maximized the contrast. Tones were generated from audio samples of pizzicato violin sounds. We derived the ordinal combinations from the sequences with complex ordinal load. First, we replaced two of the four vowels ([i] and [O]) by [E] and [u]. Then, we assigned high and low tones to [E] and [u] respectively. All sequences embedded the same rhythm, which was the rhythm used in Karabanov and Ullén (2008). This target temporal structure displayed a weak metrical organization (wM), since the onset of sounds (at pulses 1-2-4-6-8-9-10-11-13) did not align with the onset of regular pulse-groups. Aligned onsets would be either at pulses 1-3-5-7-9-11-13 (double meter, every 2 pulses), 1-4-7-10 (triple, 3 pulses) or 1-5-9 (quadruple, 4). The temporal structure that we used combined cues to double and to triple meter and thus it did not provide clear cues to the perception of high-level isochrony.

Insert Figure 1 about here, please

Procedure

In the first phase of the experiment, participants did the serial recall task. They reproduced each sequence with ordinal load (loaded performance) immediately after listening to it (50 sequences in all). **Incidental** learners were asked to reproduce the order of vowels (non-attended temporal structure), while **intentional** learners were asked to reproduce the order and the sequence of time intervals between elements (attended temporal structure). The arrow keys on the computer keyboard were used as a response device (Figure 1). Vowels (complex

ordinal load) were assigned to the four different keys and tones (simple ordinal load) to the up/down keys. In a second phase, subjects were asked to tap, on a single computer key (non-loaded performance, Figure 1), 10 rhythms like the ones perceived in the previous 50 trials.

Analysis

Following Karabanov and Ullén (2008), we measured the accuracy of temporal performance by means of an error measure, referred to as the *mean relative error*. The mean relative error of a sequence is the average deviation of the intervals produced by the subject in that sequence relative to the target intervals. Each of the 8 target intervals was subtracted from the produced one, and the absolute value of the difference was divided by the target interval. The obtained value reflected the fraction of the target interval that was added or subtracted during performance (e.g., a value of 0.5 indicates that participants added or subtracted 50% of the original duration). One value of mean relative error was obtained for the performance of each subject at each sequence (average of intervals' deviations). The error in temporal performance was averaged over each sequence of 10 trials of the serial recall task (loaded performance), defining average values for 5 blocks. The error in the last block of serial recall (10 trials) was compared with the non-loaded performance (10 trials).

We tested whether temporal performance reflected learning during serial recall (changes in loaded performance across blocks), and whether there were masking effects (improved non-loaded performance compared to the last block of serial recall). We first transformed the data, such that subject-level error values for each serial recall block were recomputed as proportions of block 1 (learning test), and values for non-loaded performance as proportions of block 5 from serial recall (masking test). Note, however, that Figures 2 and 3 display the non-transformed values. Both the learning test and the masking test were based

on mixed ANOVAs with Ordinal Load Complexity (simple vs. complex) and Instruction (*incidental vs. intentional*) as between-subject factors. The within-subjects factor in the learning test was Block (1-5), and linear contrasts were probed. In the masking test, the within-subjects factor was Performance Type (last block of loaded performance vs. non-loaded performance). Since we were interested in determining whether and how the incidental group responded to ordinal load complexity, we carried out planned comparisons, and the effects of Block (learning) and Performance Type (masking) were tested in each of the four groups (simple load incidental, simple load intentional, complex load incidental, complex load intentional). Given the small sample size ($n = 16$) and deviations from normality, we cross-checked the results with nonparametric alternatives that tested learning in each of the four groups (Friedman's two-way analysis of variance by ranks for block effects and Wilcoxon signed-rank test for comparisons between loaded and non-loaded performance).

In order to validate the two levels of ordinal complexity (simple vs. complex), we analysed subjects' accuracy in reproducing the random ordinal information. Accuracy was measured with the similarity score provided by the Needleman-Wunsch algorithm (Needleman & Wunsch, 1970) as implemented in Matlab (www.mathworks.com). The score qualifies the global alignment between two sequences, in our case, the alignment between the target ordinal sequences and the ones produced by participants. Higher scores indicate increased similarity, hence increased response accuracy. A two-way ANOVA with Ordinal Load Complexity (simple vs. complex) and Instruction (*incidental vs. intentional*) as factors was used to test whether sequences with simple load generated increased ordinal accuracy, regardless of instruction.

Statistical analysis was carried out with IBM SPSS Statistics, v. 22. A critical p level of .05 was adopted.

Results

Ordinal accuracy

The two-way ANOVA showed a significant main effect of Ordinal Load Complexity ($F(1,60) = 36.42, MSE = 8.01, p < .001$), no effects of Instruction and no interaction. The average Needleman-Wunsch similarity score was higher in the simple load condition (mean \pm standard deviation: 15.25 ± 2.73) than in complex load ($10.98 \pm 2.85; t(32) = 6.11, p < .001$), thus validating the difference between the two levels of ordinal complexity.

Temporal learning

There was a significant Block effect (Figure 2) on the overall performance error ($F(4,240) = 3.78, MSE = 0.042, p = .005$, linear contrast: $F(1,60) = 10.02, MSE = 0.051, p = .002$) and a marginal Block x Ordinal Load Complexity interaction ($F(4,240) = 2.10, MSE = 0.042, p = .082$). Performance error decreased in the simple load incidental group ($F(4,60) = 3.42, MSE = 0.025, p = .014$; linear contrast: $F(1,15) = 5.18, MSE = 0.038, p = .038$) as well as in the simple load intentional one ($F(4,60) = 5.47, MSE = 0.025, p = .001$; linear contrast: $F(1,15) = 14.35, MSE = 0.026, p = .002$), and none of the two complex load groups decreased the error across blocks ($p > .28$). The same pattern of results was provided by non-parametric tests.

Loaded vs. Non-loaded performance

Performance Type had a significant effect on error ($F(1,60) = 16.33, MSE = 0.393, p < .001$), and interacted with Ordinal Load Complexity ($F(1,60) = 13.47, MSE = 0.393, p = .001$) as

well as with Instruction ($F(1,60) = 6.25$, $MSE = 0.393$, $p = .015$). Load removal after serial recall improved the performance of *incidental* learners dealing with complex ordinal information (masking effect; non-loaded vs. loaded performance: $t(15) = -4.02$, $p = .001$, see Figure 3), while it increased the error in the other three groups (complex *intentional*: $t(15) = 2.04$, $p = .059$; simple *incidental*: $t(15) = 2.54$, $p = .023$; simple *intentional*: $t(15) = 3.82$, $p = .002$). Non-parametric tests showed the same pattern of results (performance improvements in *incidental* learners with complex ordinal information).

Discussion

Our hypothesis stated that ordinal load is a key obstacle to *incidental* temporal learning. On the one hand, we found support for the hypothesis by demonstrating that a complex ordinal load obstructs learning even if the obstacles of RSIs and unpredictable ordinal information are removed. On the other hand, we showed that a simple ordinal load allows learning to take place when the obstacles of uncorrelated temporal sequences and weak metrical organization are present. It was also our goal to find out whether ordinal load blocks learning, not allowing the acquisition of temporal representations, or if it merely masks learning, preventing temporal knowledge from showing up during the serial recall task. We saw that when the complex load was removed (non-loaded performance) temporal performance improved in the *incidental* group. This suggests that the temporal knowledge exhibited under complex load does not reflect entirely the acquired knowledge and, thus, that there are at least some masking effects.

Since the effects of metrical organization on *incidental* temporal learning have only recently been the topic of investigation (Brandon et al., 2012; Schultz et al., 2013), we focused on these effects in a second experiment. We now removed the obstacle of weak

metrical organization from the complex load condition and examined whether *incidental* temporal learning took place.

Insert Figure 2 about here, please

Insert Figure 3 about here, please

Experiment 2

Meter perception is a fundamental cognitive process (Honing, 2012) that is active early in human life (Hannon & Johnson, 2005; Trehub & Hannon, 2009; Winkler, Háden, Ladinig, Sziller, & Honing, 2009). Metrical organization facilitates the synchronization with the pulse (Patel, Iversen, Chen, & Repp, 2005) and the long-term, explicit, encoding of temporal structures (Fitch & Rosenfeld, 2007). The dynamic attending theory (Jones & Boltz, 1989) and subsequent approaches based on the concept of resonance (Large & Snyder, 2009) suggested that temporal events matching to a strong metrical grid might facilitate implicit temporal learning (Schultz et al., 2013). Schultz et al. (2013) did not find an effect of metrical organization on implicit temporal learning, but they raised the question of whether encode-and-retrieval tasks might be more sensitive to metrical organization than on-line tasks such as SRT.

In experiment 1, we saw that a weak metrical organization does not obstruct *incidental* temporal learning, provided that the ordinal load is simple. However, a full comparison of ordinal load and metrical organization as determinants of *incidental* temporal learning is not complete until we analyse learning under a complex load and a favourable (strong) metrical organization. A weak meter does not seem to eliminate the benefits of a simple ordinal load, but will strong meter override the obstacles of complex load? Based on Schultz et al.'s (2013) hypothesis that strong meter may benefit encode-and-retrieval tasks, we tested whether a strong metrical organization counteracts the obstacle of complex load in the encode-and-retrieval context of serial recall.

Experiment 1 presented a complex ordinal load without the obstacles of RSIs and unpredictable ordinal information, and no learning was observed. Experiment 2 *compares* this condition with a new one, in which a third hypothetical obstacle to *incidental* temporal learning *is* removed, namely weak metrical organization. We tested whether learning was also absent under strong meter, which would provide further evidence that ordinal load is a key obstacle to the *incidental* acquisition of temporal structure.

Method

Participants

Thirty-two participants were assigned to strong meter (complex ordinal load, see Figure 1) groups (*incidental* = 16; *intentional* = 16), adding to the 32 subjects who took part in the complex ordinal load condition of experiment 1 (now representing weak meter, also *incidental* and *intentional* groups). Participants in the strong meter group were selected so as to match the age, sex and musical training distributions in the weak meter (complex load) groups of experiment 1.

Stimuli

A new temporal sequence was created, with a stronger metrical organization than the weak meter (wM) sequence used in experiment 1 (Figure 1). This *strong meter* (sM) condition contained the same variety of time intervals as the wM sequence (4 two-pulse-length sounds [2], 4 one-pulse-length [1], 1 final pulse of undetermined length [x]). However, intervals were arranged in different ways (1-1-2-2-2-1-1-2-x in sM; 1-2-2-2-1-1-1-2-x in wM), such that sound onsets were heard every two (and four) pulses (pulse length = 375 ms). To strengthen the perception of a 4-pulse regularity, intensity accents (increases in loudness) were placed at the first of every four-pulse group. The structure of sound onsets (1-2-3-5-7-9-10-11-13) **allowed the perception of** either a two-pulse meter (onsets at 1, 3, 5, 7, 9, 11) or a four-pulse meter (onsets at 1, 5, 9, 13) across the whole sequence, although the intensity accents reinforced the 4-pulse regularity (1-2-3-5-7-9-10-11-13). The C-score for rating temporal pattern complexity (Povel & Essens, 1985; Shmulevich & Povel, 2000) was larger in wM than in sM (14 vs. 0 in double meter; 6 vs. 0 in quadruple meter), showing that participants exposed to sM had greater opportunity to perceive a high-level isochrony than those exposed to wM.

Procedure

The procedures were similar to those in experiment 1. In loaded performance, all participants used four keys, mapped into four vowels (Figure 1).

Analysis

The analyses were similar to those in experiment 1. The factor Ordinal Load Complexity was replaced by Metrical Organization, with two levels: wM (weak meter) and sM (strong meter).

Results

Temporal learning

There were no block effects on the overall performance error ($p > .71$). None of the four groups showed evidence of temporal learning (Figure 2), and the same went for non-parametric tests.

Loaded vs. Non-loaded performance

There were no effects of Performance Type ($p > .88$) on error, but Performance Type interacted with Instruction ($F(1,60) = 17.70$, $MSE = 0.224$, $p < .001$). Similar to incidental learners under weak metrical organization (cf. Experiment 1), incidental learners under strong metrical organization showed less error in the non-loaded performance than in the loaded one ($t(15) = -2.87$, $p = .012$). Intentional learners, who marginally increased performance error in weak meter (cf. Experiment 1), showed no differences between loaded and non-loaded performances ($p > .18$) in strong meter. Non-parametric tests replicated the results in each of the four groups.

Discussion

We tested whether a strong metrical organization reduces the detrimental effects of complex ordinal load on temporal learning, and to that we compared weak and strong meters embedded in complex load. There was no evidence of learning for strong meter, just as there had been no evidence of learning for weak meter. Moreover, incidental learners of the strong

meter sequence showed less error in the non-loaded performance than in the loaded one, paralleling *incidental* learners of weak meter. These results strengthen our hypothesis that ordinal load is a key obstacle to *incidental* temporal learning, and that it masks learning, rather than preventing it.

General discussion

We raised the possibility that ordinal load is an obstacle to *incidental* temporal learning that has remained unacknowledged, and may help to reconcile mixed findings concerning the detrimental effects of RSIs, uncorrelated temporal sequences, ordinal unpredictability or weak metrical organization. We started to test this hypothesis (Experiment 1) by examining the serial recall of temporal structures under simple and complex ordinal loads, both under the obstacles of uncorrelated temporal sequences and weak metrical organization, and both free from the obstacles of RSIs and ordinal unpredictability. Learning was defined as increasing performance accuracy during a serial recall task. In the simple load condition, learning survived the two obstacles. In the complex load condition, *there was no evidence of learning*, although the other two obstacles were removed. In a second experiment, we freed the complex load from a third obstacle — weak metrical organization — and again there was no evidence of learning. Our study was the first to demonstrate the effects of ordinal load on incidental temporal learning, and we have found *partial* evidence that ordinal load overrides other factors whose effects on *incidental* temporal learning have been stressed by the literature.

Our evidence is partial because we did not perform an exhaustive test. This would require, on the one hand, using correlated temporal sequences (*removing* the fourth obstacle) in the complex load condition and, on the other, adding the obstacles of RSIs and ordinal

unpredictability to the simple load condition. Given that RSIs and ordinal unpredictability have been used under simple loads in the studies of Salidis (2001) and Brandon et al. (2012) respectively, and that successful implicit learning was seen in both (see introduction), our prediction is that incidental learning would be preserved in these circumstances.

Our definition of ordinal load complexity is clearly distinct from that of ordinal unpredictability, as approached by Ullén and Bengtsson (2003) and further explored by Schultz et al. (2013). Ordinal unpredictability is locked to the specifics of SRT and taps into the uncertainty about the identity of the upcoming ordinal event. In a serial recall task like the one we used there is no “upcoming event”, since the whole sequence has already been heard by the time a response is given. Rather, what might change is the type of ordinal information to identify (syllables, spatial locations, etc.), the variety of ordinal elements, or the mapping between stimulus space and response space. Concerning the type of ordinal information, we hypothesized that the study of Schultz et al. (2013) showed no evidence of temporal learning because identifying sound sources was a demanding process (complex ordinal load), and not necessarily because of ordinal unpredictability. Conversely, we hypothesized that Brandon et al.’s study favoured temporal learning because identifying syllables was not a demanding process (simple ordinal load), and not because of meter strength. The variety of ordinal elements may have also played a role in previous studies. Both Salidis (2001) and Schultz et al. (2013) found evidence of temporal learning when the number of options was equal to one.

In our study, we manipulated the variety of ordinal elements (2 against 4) and the mapping between stimulus space and response space (transparent, or compatible, for the tones in simple load; incompatible for the vowels in complex load), but we did not disentangle the effects of these two variables. Which of these should we expect to have a greater impact on temporal learning? As we mentioned above, the literature on temporal

sequence learning is consistent with effects arising from the variety of ordinal elements (Salidis, 2001; Schultz et al., 2013). The study of Brandon et al. (2012) is also consistent with this possibility, since the authors used only three different elements instead of four, as we did in our complex load condition. Nevertheless, the effects of incompatible mappings on the response times to random ordinal information are known since long (Fitts & Seeger, 1953). The effects of incompatible mappings seem to be strong enough to modulate the effects of the variety of elements, such that the latter are larger when mappings are incompatible (e.g., Kornblum, Hasbroucq, & Osman, 1990). Therefore, our predictions are mixed, and a challenge to future studies is to clarify the components of ordinal load complexity.

In all cases of learning failure, *incidental* temporal learning was associated to a masking effect of ordinal load (improved non-loaded performance compared to loaded), while *intentional* learning was not. On the one hand, this indicates that the obstacle to *incidental* temporal learning we are dealing with is not totally related to acquiring temporal knowledge, but rather with expressing this knowledge under a complex load. This may have practical implications, for example, in music or dance teaching, suggesting that the timing of movements may be temporarily suspended from practice to allow the focus on the ordinal component (as in the serial recall task) and still be available at a later point (as in the non-loaded performance). On the other hand, the contrast between the two groups indicates that one same variable (ordinal load complexity) had different effects on incidental and intentional learners. According to Stadler (1997), this might be a reason to admit that the incidental group learned *implicitly*, while the intentional one learned *explicitly*, thus circumventing the problem of obtaining reliable measures of awareness (Abrahamse et al., 2010; Cleeremans, Destrebecqz & Boyer, 1998; Frensch & Runger, 2003) to support the explicit/implicit distinction.

Admitting that incidental and intentional learners recruited implicit and explicit memory systems, one may question whether our results support a dual-system view (Reber & Squire, 1994; Sanchez & Reber, 2013) or a single-system view (Cleeremans & Jiménez, 2002; Shanks & Perruchet, 2002). Single-system views predict that fostering or hindering explicit knowledge respectively increases or decreases the amount of implicit learning (Jiménez, Vaquero & Lupiáñez, 2006; Sanchez & Reber, 2013). In our study, incidental and intentional (implicit and explicit) learners were similar in their *inability* to express temporal learning under a complex ordinal load, as well as in their *ability* to do it under simple load. Thus, the same strategic factor (ordinal load complexity) that controlled the expression of explicit knowledge controlled the expression of implicit knowledge too (Jiménez et al., 2006). This speaks in favour of a single (implicit-explicit) memory system, possibly showing different outputs depending on the means used for probing acquired knowledge (Jamieson & Mewhort, 2009). A different, though more speculative approach might be based on the fact that temporal learning was combined with explicit learning in the two groups of our study. Both incidental (implicit) and intentional (explicit) learners were given explicit instructions to reproduce the random ordinal information. Thus, while the incidental group may have combined implicit (temporal structure) with explicit learning (ordinal information), the intentional group acquired the two types of information explicitly. A possible reasoning is that a parallel (dual)-system architecture should not generate interference between ordinal and temporal information in the incidental (implicit) group, and that a single-system architecture should. Our findings highlighted a form of interference in the incidental (implicit) group, since ordinal load complexity determined temporal learning. This viewpoint also seems to support a single-system view.

Conclusion

The literature is mixed concerning the circumstances that foster and hinder incidental temporal learning. We found evidence that the complexity of the ordinal load is as key determinant of temporal learning, and that it may help reconcile previous findings.

References

- Abel, S. M., & Shelly Paik, J. E. (2004). The benefit of practice for sound localization without sight. *Applied Acoustics*, 65(3), 229–241. doi:10.1016/j.apacoust.2003.10.003
- Abrahamse, E. L., Jiménez, L., Verwey, W. B., & Clegg, B. A. (2010). Representing serial action and perception. *Psychonomic Bulletin & Review*, 17(5), 603–623. <http://doi.org/10.3758/PBR.17.5.603>
- Brandon, M., Terry, J., Stevens, C. J., & Tillmann, B. (2012). Implicit learning of temporal structures conforming to a metrical framework. *Frontiers in Psychology*, 3. doi: 10.3389/fpsyg.2012.00294
- Buchner, A., & Steffens, M. C. (2001). Simultaneous learning of different regularities in sequence learning tasks: limits and characteristics. *Psychological Research*, 65(2), 71–80. doi:10.1007/s004260000052
- Cleeremans, A., & Jiménez, L. (2002). Implicit learning and consciousness: A graded, dynamic perspective. In R. M. French and A. Cleeremans (Eds.), *Implicit learning and consciousness: An empirical, computational and philosophical consensus in the making* (pp. 1–40). Hove, UK: Psychology Press.
- Fitch, W. T. (2013). Rhythmic cognition in humans and animals: distinguishing meter and pulse perception. *Frontiers in Systems Neuroscience*, 7. doi:10.3389/fnsys.2013.00068
- Fitch, W. T., & Rosenfeld, A. J. (2007). Perception and production of syncopated rhythms. *Music Perception: An Interdisciplinary Journal*, 25(1), 43–58. doi:10.1525/mp.2007.25.1.43

- Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, 46(3), 199–210. <http://doi.org/10.1037/h0062827>
- Forkstam, C., & Petersson, K. M. (2005). Towards an explicit account of implicit learning. *Current Opinion in Neurology*, 18(4).
- Frensch, P. A., & R nger, D. (2003). Implicit learning. *Current Directions in Psychological Science*, 12(1), 13–18. doi: 10.1111/1467-8721.01213
- Hannon, E. E., & Johnson, S. P. (2005). Infants use meter to categorize rhythms and melodies: Implications for musical structure learning. *Cognitive Psychology*, 50(4), 354–377. doi:10.1016/j.cogpsych.2004.09.003
- Honing, H. (2012). Without it no music: beat induction as a fundamental musical trait. *Annals of the New York Academy of Sciences*, 1252(1), 85–91. doi:10.1111/j.1749-6632.2011.06402.x
- Jamieson, R. K., & Mewhort, D. J. K. (2009). Applying an exemplar model to the artificial-grammar task: Inferring grammaticality from similarity. *The Quarterly Journal of Experimental Psychology*, 62(3), 550–575. <http://doi.org/10.1080/17470210802055749>
- Janata, P., & Grafton, S. T. (2003). Swinging in the brain: shared neural substrates for behaviors related to sequencing and music. *Nature Neuroscience*, 6(7), 682–687. doi: 10.1038/nn1081
- Jim nez, L., Vaquero, J. M, M., & Lupi  ez, J. (2006). Qualitative differences between implicit and explicit sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32(3), 475–490. <http://doi.org/10.1037/0278-7393.32.3.475>
- Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, 96(3), 459–491. doi:10.1037/0033-295X.96.3.459

- Karabanov, A., & Ullen, F. (2008). Implicit and explicit learning of temporal sequences studied with the process dissociation procedure. *Journal of Neurophysiology*, 100(2), 733–739. doi:10.1152/jn.01303.2007
- Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility--A model and taxonomy. *Psychological Review*, 97(2), 253–270. <http://doi.org/10.1037/0033-295X.97.2.253>
- Large, E. W., & Snyder, J. S. (2009). Pulse and meter as neural resonance. *Annals of the New York Academy of Sciences*, 1169(1), 46–57. doi:10.1111/j.1749-6632.2009.04550.x
- Needleman, S. B., & Wunsch, C. D. (1970). A general method applicable to the search for similarities in the amino acid sequence of two proteins. *Journal of Molecular Biology*, 48(3), 443–453. doi:10.1016/0022-2836(70)90057-4
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19(1), 1–32. doi:10.1016/0010-0285(87)90002-8
- O'Reilly, J. X., McCarthy, K. J., Capizzi, M., & Nobre, A. C. (2008). Acquisition of the temporal and ordinal structure of movement sequences in implicit learning. *Journal of Neurophysiology*, 99(5), 2731–2735. doi:10.1152/jn.01141.2007
- Patel, A., Iversen, J., Chen, Y., & Repp, B. (2005). The influence of metricality and modality on synchronization with a beat. *Experimental Brain Research*, 163(2), 226–238. doi:10.1007/s00221-004-2159-8
- Povel, D.-J., & Essens, P. (1985). Perception of temporal patterns. *Music Perception: An Interdisciplinary Journal*, 2(4), 411–440. doi:10.2307/40285311
- Reber, P. J., & Squire, L. R. (1994). Parallel brain systems for learning with and without awareness. *Learning & Memory (Cold Spring Harbor, N.Y.)*, 1(4), 217–229.

- Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, F., Hillyard, S. A., & Neville, H. J. (1999). Improved auditory spatial tuning in blind humans. *Nature*, 400(6740), 162–166. doi: 10.1038/22106
- Sanchez, D. J., & Reber, P. J. (2013). Explicit pre-training instruction does not improve implicit perceptual-motor sequence learning. *Cognition*, 126(3), 341–351. doi: 10.1016/j.cognition.2012.11.006
- Schultz, B. G., Stevens, C. J., Keller, P. E., & Tillmann, B. (2013). The implicit learning of metrical and nonmetrical temporal patterns. *The Quarterly Journal of Experimental Psychology*, 66(2), 360–380. doi:10.1080/17470218.2012.712146
- Seger, C. A. (1994). Implicit learning. *Psychological Bulletin*, 115(2), 163–196. doi: 10.1037/0033-2909.115.2.163
- Shanks, D. R., & Perruchet, P. (2002). Dissociation between priming and recognition in the expression of sequential knowledge. *Psychonomic Bulletin and Review*, 9(2), 362–367.
- Shin, J. C., & Ivry, R. B. (2002). Concurrent learning of temporal and spatial sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(3), 445–457. doi:10.1037/0278-7393.28.3.445
- Shmulevich, I., & Povel, D.-J. (2000). Measures of temporal pattern complexity. *Journal of New Music Research*, 29(1), 61–69. doi:10.1076/0929-8215(200003)29:01;1-P;FT061
- Stadler, M. A. (1997). Distinguishing implicit and explicit learning. *Psychonomic Bulletin & Review*, 4(1), 56-62. doi: 10.3758/BF03210774
- Toth, J. P., Reingold, E. M., & Jacoby, L. L. (1994). Toward a redefinition of implicit memory: Process dissociations following elaborative processing and self-generation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20(2), 290–303. <http://doi.org/10.1037/0278-7393.20.2.290>

Trehub, S. E., & Hannon, E. E. (2009). Conventional rhythms enhance infants' and adults' perception of musical patterns. *Cortex*, 45(1), 110–118. doi:10.1016/j.cortex.

2008.05.012

Ullén, F., & Bengtsson, S. L. (2003). Independent processing of the temporal and ordinal structure of movement sequences. *Journal of Neurophysiology*, 90(6), 3725–3735.

doi:10.1152/jn.00458.2003

Winkler, I., Háden, G. P., Ladinig, O., Sziller, I., & Honing, H. (2009). Newborn infants detect the beat in music. *Proceedings of the National Academy of Sciences*, 106(7),

2468–2471. doi:10.1073/pnas.0809035106

Figure Captions

Figure 1. Stimulus sequences and tasks. In experiment 1, a temporal sequence with weak meter (wM; vertical lines represent pulses and Xs represent events) and a complex ordinal load (4 different vowels) was compared with the same wM sequence under a simple load (H = high tone; L = low tone). In experiment 2, we compared the wM of experiment 1 with a sequence with strong metrical organization (sM), both with complex load. Simple and complex loads used different response devices in loaded performance. Non-loaded performance used a single response key, and was requested after participants completed all serial recall trials.

Figure 2. Temporal performance (error) in the five 10-trial blocks of serial recall. Temporal learning occurred only in the simple load groups (ns = non-significant). Non-transformed values are plotted (see text).

Figure 3. Loaded (last 10-trial block of serial recall) and Non-loaded (10 trials in a single key) performance according to levels of Ordinal Load Complexity and Instruction. Non-loaded performance was more accurate than the loaded one (masking effect, signed with an asterisk) in the complex load implicit groups. Non-transformed values are plotted (see text).