

RESEARCH ARTICLE

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Memory for Random Time Patterns in Audition, Touch, and Vision

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Abstract—Perception deals with temporal sequences of events, like series of phonemes for audition, dynamic changes in pressure for touch textures, or moving objects for vision. Memory processes are thus needed to make sense of the temporal patterning of sensory information. Recently, we have shown that auditory temporal patterns could be learned rapidly and incidentally with repeated exposure [Kang et al., 2017]. Here, we tested whether rapid incidental learning of temporal patterns was specific to audition, or if it was a more general property of sensory systems. We used a same behavioral task in three modalities: audition, touch, and vision, for stimuli having identical temporal statistics. Participants were presented with sequences of acoustic pulses for audition, motion pulses to the fingertips for touch, or light pulses for vision. Pulses were randomly and irregularly spaced, with all inter-pulse intervals in the sub-second range and all constrained to be longer than the temporal acuity in any modality. This led to pulse sequences with an average inter-pulse interval of 166 ms, a minimum inter-pulse interval of 60 ms, and a total duration of 1.2 s. Results showed that, if a random temporal pattern re-occurred at random times during an experimental block, it was rapidly learned, whatever the sensory modality. Moreover, patterns first learned in the auditory modality displayed transfer of learning to either touch or vision. This suggests that sensory systems may be exquisitely tuned to incidentally learn re-occurring temporal patterns, with possible cross-talk between the senses.

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INTRODUCTION

Audition, touch, and vision sense different parts of the physical world, such as acoustic waves, surface textures, or light patterns. Peripheral sensory receptors in each modality are adapted to best transduce their respective physical input (e.g. Lewicki, 2002). From subsequent neural processes, qualitatively distinct perceptual qualities emerge, such as auditory timbre, tactile texture, or visual color. However, at a more general level of description, all sensory modalities are embedded in time: they all must deal with sequences that contain possibly crucial information in their temporal patterning (O'Regan, 2011). Thus, memory processes applying to temporal sequences would seem beneficial in any sensory modality, and may also have to address similar computational constraints across modalities (Hardy and Buonomano, 2016).

Recently, we documented a rapid form of incidental learning for temporal sequences in the auditory modality (Kang et al., 2017). Adapting a paradigm previously used in audition (Agus et al., 2010) or vision (Gold et al., 2014), we observed fast incidental learning of time patterns made of irregularly spaced audio clicks, with inter-click intervals in the range of tens to hundreds of milliseconds. Learning occurred, in an unsupervised manner, as long as these patterns re-occurred over the course of an experiment. In this recent study, we ensured that the only cues available to learn patterns were in the precise sequence of time interval durations, and not in any other auditory-specific cue. So, the same experimental paradigm may be transposed to other sensory modalities, simply by conveying time intervals not through audio clicks, but rather through modality-adapted events. This is what was done in the present study. Our aim was to investigate whether rapid incidental learning of random time patterns was specific to audition, or if it could be a more general feature of perceptual systems.

On a neural level, for stimuli consisting of time intervals delimited by brief energy pulses, the input time patterns will be reflected in neural spike time patterns in peripheral receptors and also at higher stages of processing, at least

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Abbreviations: ANOVA, analysis of variance; IPI, inter-pulse intervals; RefRP, reference repeated pulses; SNR, signal-to-noise ratio.

for moderate rates of up to a few pulses per second. Temporal patterning of spike trains has been observed in sensory cortices for audition (Lu et al., 2001), touch (Saal et al., 2016), and vision (Gur and Snodderly, 1997). Of course, there are differences in temporal resolution between these modalities. Also, it is a matter of controversy whether spike time patterning is an epiphenomenon of peripheral encoding (Gur and Snodderly, 1997; Salinas et al., 2000) or a true information-bearing code (Cariani, 2001; VanRullen et al., 2005). But at a minimum, the possibility exists to learn temporal patterns of spikes up to the cortical level in all of the three modalities considered here, audition, touch, and vision. Probing the behavioral learning of purely temporal patterns in these modalities would be a first step in investigating the underlying neural mechanisms.

An obvious question then arises: if learning of time patterns were to be observed in all modalities, would it be the result of canonical computational principles, or rather reflect mechanisms specific to each modality of entry? The question overlaps with broader issues in time research, such as whether the psychological and neural representations of time are modal or amodal (Ivry and Schlerf, 2008; van Wassenhove, 2009; Grondin, 2014). Several studies have approached the issue by inducing perceptual learning for a time interval in one modality, and then test for transfer of learning in another modality. A variety of results have been found, often with asymmetric transfer characteristics across modalities (e.g. Nagarajan et al., 1998; Lapid et al., 2009; Bratzke et al., 2012; Pasinski et al., 2015). As summarized by Pasinski et al. (2015), these results may reflect differences in task demands. Using a variant of the time-interval discrimination task, they found a behavioral advantage of the auditory modality over the visual modality, but similar expectancy-related and memory-related EEG responses across the two modalities (Pasinski et al., 2015), consistent with a combination of modality-specific mechanisms for the encoding of time intervals followed by modality-general memory processes (see also Merchant et al., 2008).

It is yet unclear whether such a conclusion would hold beyond interval discrimination tasks, for instance for the learning of more complex temporal patterns. There are behavioral demonstrations of rapid learning for complex sequences in audition, touch, and vision separately (Gold et al., 2014; Bale et al., 2017; Kang et al., 2017), but not all stimuli in these studies were purely temporal patterns. Sequence learning has been compared across modalities (Handel and Buffardi, 1968; Manning et al., 1975; Conway and Christiansen, 2006), but again combining timing-cues with a variety of modality-specific cues such as sound frequency or spatial location, which may impact results in unsuspected ways (e.g. Grahn, 2012). Perceptual learning of purely-temporal rhythmic sequences has been compared between audition and vision (Patel et al., 2005; Grahn, 2012; Barakat et al., 2015), but rhythmic sequences may recruit additional, beat-based mechanism for sequence learning (e.g. Pasinski et al., 2015). In one example using comparable stimuli across modalities, which were aperiodic and differing only by timing characteristic, Nazzaro and Nazzaro (1970) had participants learn

auditory or visual Morse code “words”. They found faster learning in the auditory modality. This finding echoed early suggestions of an advantage of audition over vision for the motor reproduction of temporal rhythms (Fraisse, 1948), and also classic findings of a greater temporal acuity for audition compared to touch or vision for single-interval discrimination (Goodfellow, 1934). Interestingly however, when the discriminability between elements was equated for auditory and visual Morse code, the auditory advantage vanished (Hansen and Cottrell, 2013). Note also that the Morse code task involved explicit learning, which could recruit different mechanisms than incidental learning (e.g. Chen and Zhou, 2014). In summary, while there is ample evidence for behavioral sequence learning in audition, vision, and touch, less is known about the learning of purely temporal complex patterns. In particular, a detailed comparison of the learning of aperiodic temporal patterns in all three modalities, with the same participants and procedure, is lacking.

In the present set of experiments, we adapted the auditory paradigm of Kang et al. (2017) to the tactile and visual domain. A full description of the task will be provided in the Methods, but, briefly, we used random temporal patterns made of irregular time intervals delineated by brief energy bursts. The energy bursts were audio clicks for audition, tangential motion pulses applied to the fingertips for touch, and light flashes for vision. The task as explained to participants was to discriminate two types of stimuli: either a fully random pulse sequence (pulses, P), or a pulse sequence of the total same duration but made from the seamless repeat of two identical half-duration sequences (repeated pulses, RP). The two conditions are illustrated in Fig. 1. In addition, without instructing participants, we also introduced a third type of stimulus: reference repeated pulses (RefRP), which were constructed exactly as RPs but re-occurred over randomly selected trials interspersed throughout the course of an experimental block. Thus, participants were exposed to the exact same pattern of inter-pulse intervals (IPI) for several trials for RefRP, whereas the IPI patterns comprising P or RP stimuli were unique to one trial. An advantage in performance for RefRP over RP, that is, for re-occurring patterns over novel patterns, is the measure used to estimate perceptual learning (Agus et al., 2010; Agus and Pressnitzer, 2013; Luo et al., 2013; Gold et al., 2014; Andriillon et al., 2015; Kang et al., 2017).

Importantly, for the present study we ensured that the encoding of temporal patterns was not limited by temporal acuity in any of the three modalities tested (Goodfellow, 1934). A pre-test served to adjust the minimum IPI required for all modalities. The IPI distribution statistics was then fixed across modalities. A similar approach had been taken by Marks (Marks, 1987), who collected perceptual similarity judgments for temporal sequences in audition, touch, and vision, with identical supra-thresholds IPIs. He concluded that, in such a setting, the perceptual dimensions underlying similarity judgments were common to all three modalities (Marks, 1987). We followed the same logic but aimed to probe perceptual learning rather than perceptual similarity. Our stimuli therefore had identical statistical properties in all modalities

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