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Entraining chaotic dynamics: A novel movement sonification paradigm could promote generalization

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ABSTRACT

Tasks encountered in daily living may have instabilities and more dimensions than are sampled by the senses such as when carrying a cup of coffee and only the surface motion and overall momentum are sensed, not the fluid dynamics. Anticipating non-periodic dynamics is difficult but not impossible because mutual coordination allows for chaotic processes to synchronize to each other and become periodic. A chaotic oscillator with random period and amplitude affords being stabilized onto a periodic trajectory by a weak input if the driver incorporates information about the oscillator. We studied synchronization with predictable and unpredictable stimuli where the unpredictable stimuli could be non-interactive or interactive. The latter condition required learning to control a chaotic system. We expected better overall performance with the predictable but more learning and generalization with unpredictable interactive stimuli. Participants practiced an auditory-motor synchronization task by matching their sonified hand movements to sonified tutors: the Non-Interactive Predictable tutor (NI-P) was a sinusoid, the Non-Interactive Unpredictable (NI-U) was a chaotic system, the Interactive Unpredictable (I-U) was the same chaotic system with an added weak input from the participant's movement. Different pre/post-practice stimuli evaluated generalization. Quick improvement was seen in NI-P. Synchronization, dynamic similarity, and causal interaction increased with practice in I-U but not in NI-U. Generalization was seen for few pre-post stimuli in NI-P, none in NI-U, and most stimuli in I-U. Synchronization with novel chaotic dynamics is challenging but mutual interaction enables the behavioral control of such dynamics and the practice of complex motor skills.

1. Introduction

Practicing a musical instrument with an instructor or dancing with a partner are popular methods for improving motor capacities and even for countering the effects of motor disabilities as demonstrated empirically in clinical studies in stroke and Parkinson's disease (Altenmüller, Marco-Pallares, Münte, & Schneider, 2009; Hackney & Earhart, 2010; Patel, 2011; Schneider, Schönle, Altenmüller, & Münte, 2007; Sparks, Helm, & Albert, 1974; Wan, Zheng, Marchina, Norton, & Schlaug, 2014). Coordinated motor behavior can be understood in terms of dynamic patterns formed by coupled oscillatory processes (Kelso, 1995). There is also evidence for neural entrainment to external stimuli (Fujioka, Trainor, Large, & Ross, 2012; Nozaradan, Peretz, Missal, & Mouraux, 2011) and oscillations of neural populations and synchronization among different neural populations may serve as an organizational

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principle within the brain given the noisy intrinsic activity of individual neurons (Buzsáki, 2009; Giraud & Poeppel, 2012; Tass, 1999).

Evidence for neural entrainment is typically confined to paradigms with periodic stimuli such as musical beat and periodic tones. When one steps outside of the laboratory, however, periodic stimuli are the exception rather than the rule. Furthermore, neural oscillations may not be intrinsically periodic but become periodic with the appropriate constraints because the design characteristics of neuronal microcircuits support unstable, high-dimensional, and nonlinear dynamics, rather than self-sustained harmonic oscillations (Laje & Buonomano, 2013; Mauk & Buonomano, 2004). This suggests that humans must have the capacity to interact with nonlinear, non-periodic processes where successful interaction is defined as entrainment or generalized synchronization (Friston & Frith, 2015). The objective of this work is to propose an experimental paradigm for studying some of the constraints involved in synchronization with stimuli that are not intrinsically periodic.

Sensorimotor synchronization with non-periodic stimuli could also be beneficial as a form of motor practice because complex tasks are preferable in the acquisition of motor skills with real-world relevance (Wulf & Shea, 2002). Moving a tool or one's body inside a dynamically unstable task space is an example of such a complex task. Feedforward muscle activation can compensate for destabilizing but anticipated forces such as those encountered while walking, standing, using a screwdriver, or carrying liquid in an open container if the activation is coordinated with the direction and timing of the given diverging force field (Burdet, Osu, Franklin, Milner, & Kawato, 2001; Kuo, 2007; Latash, 1996; Loram & Lakie, 2002; Maus, Lipfert, Gross, Rummel, & Seyfarth, 2010). In these circumstances feedback control would be unfeasible because compensatory activation would arrive too late. For example, pressing against a screw with a screwdriver creates lateral forces that destabilize the tool more quickly than feedback loops can compensate for and, arguably, forward models anticipate the structure of such destabilizing force fields and set task-specific patterns of stiffness to absorb the perturbations (Burdet et al., 2001).

Next to instability, nonlinearity is another frequent complicating factor in real-world situations. Even something as basic as the movement of the hand is a nonlinear combination of the different possible activations in each segment of the arm and body (Wolpert, Ghahramani, & Flanagan, 2001). Small changes in activations across motor units could result in diverging movement patterns (Latash, 1996; Turvey, 1990) and, consequently, lead to diverging sensory feedback that is difficult to relate back to its cause. Even if control can be simplified by way of linearly separable activations of motor synergies, each synergy still has to deal with these nonlinearities and, importantly, it has to be acquired somehow (Mussa-Ivaldi, Giszter, & Bizzi, 1994). When possible, anticipating the underlying task dynamics is more beneficial than rote learning of sensory feedback. Indeed, generalization seems to be a consequence of learned task dynamics, not of learned patterns of sensory stimulation (Conditt, Gandolfo, & Mussa-Ivaldi, 1997).

Bi-direction coupling is crucial in this context because it allows the learner to go beyond rote learning of the sequence of sensory stimulation, a so-called Markov blanket, and instead explore the structure of external dynamics. The learner can tune her dynamics by producing changes in the stimulus while interacting with it and comparing the expected and actual sensory consequences (Friston & Frith, 2015). Formally this can be understood as updating the parameters of a generative model for priors about motion (Clark, 2015; Friston, 2010; Friston & Ao, 2012). Consequently, practice paradigms involving reciprocal dynamic causation should enable superior learning relative to leader–follower paradigms. Importantly, an acquired generative model can be used in non-interactive mode hence interactive practice could generalize to non-interactive performance.

Next to interaction, stimulus variability in the form of unexpected changes in task conditions is expected to have an important role. Random trial conditions improve retention and generalization (Schmidt & Bjork, 1992; Schmidt & Lee, 2011; Shea & Morgan, 1979; Welsh & Elliott, 2000). Expanding the context of training is an important desirable because motor learning is typically task- and context-specific (Ghahramani, Wolpert, & Jordan, 1996; Hwang, Donchin, Smith, & Shadmehr, 2003; Krakauer, Mazzoni, Ghazizadeh, Ravindran, & Shadmehr, 2006; Krakauer, Pine, Ghilardi, & Ghez, 2000; Shadmehr, 2004). The positive effect of unpredictable practice conditions, called contextual interference, manifests in stronger cerebellar activations in training and weaker in testing compared to blocked practice (Shimizu, Wu, & Knowlton, 2016). Moving from changing conditions across trials to variation within the trials, stimuli with unpredictable trajectories can also be effective (Wu, Miyamoto, Castro, Ölveczky, & Smith, 2014). Next to randomly switching stimulus parameters, fine movement variability of the learner also has a role. Participants who exhibited higher variability of kinematic variables at the early phase of skill acquisition exhibited superior performance post-training (Vegter, Lamoth, De Groot, Veeger, & Van Der Woude, 2014). Variability is found not only in execution but also in motor planning (Churchland, Afshar, & Shenoy, 2006). Its functional role is to expand the set of neural processing constraints encountered during training and prepare the animal for a larger context of potential tasks (Schmidt & Lee, 2011; Seidler, 2004).

1.1. Entrainment with an unpredictable interactive system by movement sonification

The task consisted of synchronizing in time and matching in pitch the continuous sound produced by a hand-held tool with the continuous sound of a stimulus. The stimulus consisted of periodic or non-periodic oscillatory pitch fluctuations. The tool was sonified by mapping its movement to the pitch of a synthesizer heard on one side. The stimulus was a dynamic system sonified in the same way on the other side, see Fig. 1. Furthermore, in an interactive condition the stimulus was weakly driven by the tool movement. Weak was defined as not sufficient to allow entrainment of the stimulus by simulated periodic input with the same amplitude. The benefit of movement sonification is that it capitalizes on capacities for multimodal integration and could provide an effective avenue for augmented feedback in rehabilitation (Hermann, Hunt, & Neuhoff, 2011; Scholz, Rhode, Großbach, Rollnik, & Altenmüller, 2015).

Tracking of a quasi-oscillatory chaotic trajectory with randomly changing period and amplitude is likely to challenge to the limit one's capacities for sensorimotor prediction and synchronization. Because of its unpredictability, achieving a relatively consistent