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Abstract

Dexterous assistive devices constitute one of the frontiers for hybrid human-machine systems. Manipulating unstable systems requires task-specific anticipatory dynamics. Learning this dynamics is more difficult when tasks, such as carrying liquid or riding a horse, produce unpredictable, irregular patterns of feedback and have hidden dimensions not projected as sensory feedback. We addressed the issue of coordination with complex systems producing irregular behaviour, with the assumption that mutual coordination allows for non-periodic processes to synchronize and in doing so to become regular. Chaos control gives formal expression to this: chaos can be stabilized onto periodic trajectories provided that the structure of the driving input takes into account the causal structure of the controlled system. Can we learn chaos control in a sensorimotor task? Three groups practiced an auditory-motor synchronization task by matching their continuously sonified hand movements to sonified tutors: a sinusoid served as a Non-Interactive Predictable tutor (NI-P), a chaotic system stood for a Non-Interactive Unpredictable tutor (NI-U), and the same system weakly driven by the participant's movement stood for an Interactive Unpredictable tutor (I-U). We found that synchronization, dynamic similarity, and causal interaction increased with practice in I-U. Our findings have implications for current efforts to find more adequate ways of controlling complex adaptive systems.

Introduction

Sensory substitution devices have demonstrated the potential of human-machine interfaces to supplant and qualitatively augment human repertoire of interactions with the world (Bach-y-Rita and Kercel, 2003). Motor substitution technologies are also exciting. Previously, transportation machines such as cars or powered wheelchairs have enabled novel means of engaging with the world within co-evolved urban ecologies. Prosthetic devices could enable another wave of innovation. Cheetah transtibial prostheses allow paraplegic athletes to dominate in certain disciplines. Hybrid systems can lead to societal changes by encouraging the creation of complementary infrastructure. A standing issue with assistive technologies is how to imbue dexterous devices such as artificial hands with fine motor skill (Froese, 2014). For complex adaptive prostheses to unfold their full potential the problem of dynamic control needs to be solved first. Current designs avoid dealing with more natural dynamics and thus limit their potential for smooth control and tighter integration with the rest of the body.

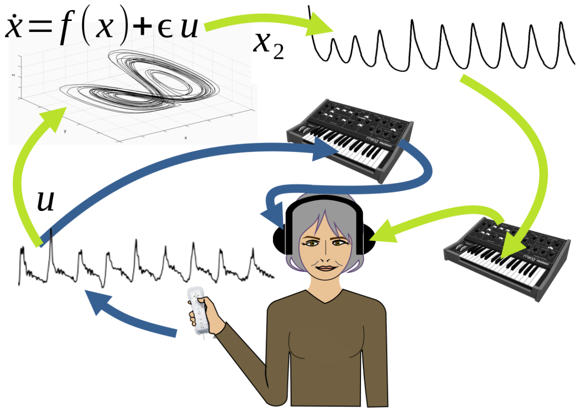

Figure 1: UNpredictable Interactive system with SONnified movement (UNISON). Learner: the transformed sensor state (accelerometer) of a hand-held device ($u = arcsin(s/g)$) was streamed to a computer and sonified by mapping it to the pitch of a pure tone in the right channel (blue arrows). Tutor: a state variable (x_2) of the chaotic Chua oscillator ($\dot{\mathbf{x}} = f(\mathbf{x}, \epsilon u)$) was similarly sonified in the left channel (green arrows) and driven by the hand movement signal u scaled by a coupling gain ϵ. $\epsilon = 0$ made for a non-interactive condition. In a periodic non-interactive condition the tutor was replaced with a sine wave. (Sample trials as video at https://vimeo.com/267437234.)

Our contribution is to test natural control principles, namely controlling a complex tool and becoming dynamically integrated with such a tool (for full details see Dotov and Froese, in prep). Some daunting control problems with a non-linear task space can be dealt with if the requirement for linear control is replaced with the possibility for mutual dynamic synchronization. Consequently, dynamically transcending the natural-artificial divide seems to be a logical

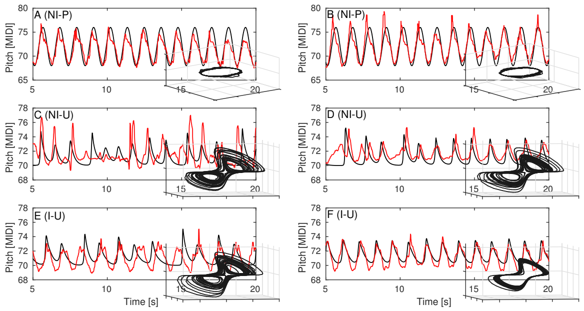

Figure 2: Sample data from the tutor (black) and learner (red) shown for each practice group, NI-P (A-B), NI-U (C-D), and I-U (E-F), and a low-scoring (left: A, C, E) and better-scoring trial (right: B, D, F), along with the respective phase spaces of the tutor.

way for advancing complex systems for enhanced human mobility. Similar principles may apply to human interaction with complex adaptive systems more generally.

Here mutual synchronization serves as a theoretical model for successful interaction. Work on social interaction in minimal virtual reality showed that movement complexity and dyadic synchronization take on different roles, the latter relating to task success (Zapata-Fonseca et al., 2016).

Experiment

Participants ($N = 48$) were assigned randomly to practice auditory-motor synchronization with a tutor in one of three modes. The objective was to synchronize with and match its continuously changing pitch, with a performance score returned after each trial. The task and apparatus are described in Figure 1 with sample trajectories in Figure 2. Generalization was evaluated with pre/post-practice stimuli different from practice. Simulated control scenarios allowed us to set ϵ in I-U so as to avoid trivial control by a periodic signal but enable mutual synchronization with a similar, bidirectionally coupled dynamic system.

Cross-correlation, a measure of phase-locking between two signals, served as performance variable. Linear and non-linear (logistic) regressions tested for improvement in practice trials. As expected, the trivial condition of synchronizing with a sinusoidal signal (NI-P) led to quick improvement and early peak. Participants made no progress in the difficult condition NI-P with random cycle intervals and amplitudes. In contrast, in I-U which used the same tutor as in NI-P but in interactive mode steady improvement was observed. That the tutor became more periodic with trials implies that improvement in synchronization in I-U was associated with stabilization of the tutor.

Evidence for chaos control in I-U was also based on measures of dynamic causal interaction such as delay of coordination (τ, the time-shift of maximal cross-correlation) and transfer entropy (TE, with significance test for causality based on surrogate distributions computed from block-shuffled trials). TE increased with practice only in I-U, and this was equally so in both ways of the dyad (tutor→learner and learner→tutor).

τ was positive in I-U, suggestive of lagged and reactive coordination with the tutor, but decreased with higher-scoring trials in I-U and was statistically not-different from zero for the highest-scoring trials. The maximal Lyapunov exponent, a parameter of chaotic (in)stability, decreased in the tutor (less chaotic) and increased (more chaotic) in the learner with better scoring trials, the two tending to convergence.

With respect to generalization of practice to untrained but dynamically similar stimuli, benefit in most stimuli was observed in I-U, followed by NI-P, with no benefit in NI-U.

Discussion

Often it is not practical or possible to control complex systems with a strong driving signal. Rigid control architectures are unsuitable and often counterproductive. Control techniques can take advantage of the system's internal dynamics in order to harness rather than suppress its flexibility for the generation of adaptive behaviour. We demonstrate that humans can learn to stabilize a chaotic system by entraining with it if they are interactively coupled, an instance of chaos control. In doing so they tend to become slightly more chaotic with practice.

Large scale socio-economic systems such as agricultural and financial systems are also complex and adaptive, requiring subtle and interactive intervention. The control philosophy espoused here could be applicable in principle but only to the extent that they possess consistent inherent dynamics, hence calling for other approaches to first improve our understanding of their dynamics.

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