Interpersonal sensorimotor contingencies: Information-theoretic relevance of subjective experience

Dari Trendafilov[1], Tong-Hun Hwang[2], Gerd Schmitz[2], Alfred O. Effenberg[2], and Daniel Polani[1]

[1]Adaptive Systems Research Group, University of Hertfordshire, Hatfield, UK
[2]Institute of Sports Science, Leibniz University, Hannover, Germany
{d.trendafilov,d.polani}@herts.ac.uk, effenberg@sportwiss.uni-hannover.de

Introduction

Interpersonal synergies are higher-order control systems formed by coupling movement of two (or more) actors. Many different approaches have been utilised for the characterisation of social couplings, such as autocorrelation, cross-correlation (Box and Jenkins (1970)), transfer entropy (Barnett et al. (2009)), Granger causality (Granger (1969)), and their potential has been demonstrated in many applications. Simultaneous hyper-scanning of several brains have recently opened a new field (Babiloni et al. (2006); Astolfi et al. (2010); Schippers et al. (2010); Anders et al. (2011); Dumas et al. (2010)). A key challenge is to design a suitable procedure that allows synchrony and turn-taking to spontaneously take place. Traditional interactive paradigms mainly consist of non-contingent social stimuli that do not allow true social interaction (Redcay et al. (2010)). Imitation is typically used in an interpersonal context with the aim to contribute identifying neurodynamic signatures of human interactions and detect, for example, different patterns of synchrony and movement abnormalities (Grossberg and Seidman (2006)), providing insights about autistic spectrum disorder. A neuromarker of social coordination (known as phi complex) was detected over the right centroparietal area in the 9.2-11.5 Hz range (Tognoli et al. (2007)). However, apparent interpersonal coordination could be merely incidental rather than reflecting true coordination – people may appear to coordinate their movements because they simultaneously execute similar motor programs, mediated by shared motor representations (Garrod and Pickering (2009); Sebanz et al. (2006)).

Experiment

Our study explored the emergence of social coupling within a dyad performing a collaborative task on an iPad, dubbed as the Tetherball game (see Figure1). The Tetherball paradigm was designed for investigating interpersonal coordination and implements a two-player dynamic interactive game. With rhythmic tilt movements the players had to accelerate a shackled ball and maintain it moving on a target path. The visual feedback consists of a ball, a center anchor, and a target circle, while the controllers are fixed on both sides of the tablet. The ball is connected to the center anchor with an invisible rubber band, which has elastic force strong enough to pull the ball to the center anchor when the tablet is flat. Players had to coordinately tilt the tablet using their index fingers in order to move the ball. The tablet movement is restricted to 2-DOF and each controller is responsible for tilting along one axis only. The goal is to keep rolling the ball on the target circle. Visual feedback was overlaid with different types of auditory effects. The experiment comprised of one baseline and three control conditions based on the type of auditory information. Finger movement of both players was recorded from inertial sensors embedded in the tablet at 60Hz. A self-report questionnaire assessed subjective user experience. The level of coordination was estimated by applying information-theoretic functionals on the motion data of both players. Subsequent analysis correlated these objective measures to self-reported subjective user experience, which included, among others, the following questions:

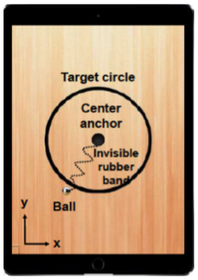

Figure 1: Visual display of the Tetherball game prototype, consisting of the ball, the anchor, and the target.

- Q1: 'How much did you feel your movement helps the collaborator's performance?'
- Q2: 'How much did you feel the collaborator's movement helps your performance?'
- Q3: 'How did you experience the collaboration with you partner?'
- Q4: 'How efficiently did you feel that you managed to do the task?'

Discussion

To assess the level of coordination between the players we applied various information-theoretic measures on the x and y axis of the acceleration data representing the finger movements of the two players. More precisely, we computed the mutual information and the transfer entropy using a continuous KSG estimator (Lizier (2014)), and the directed information using a discrete method (Permuter et al. (2011)). The measures were evaluated on three consecutive 15 sec long sections of each trial, discarding the initial 8 sec when the ball was not rolling. The maximal value of the three was selected as representative coefficient for the specific trial.

Using the maximal value of the two players provided by the subjective ratings for Q1, Q2, Q3, and Q4 we computed the correlation between the subjective and the information-theoretic measures over all 15 trials per pair from each group combined. The overall results (over all 15 trials) show significant correlation between the subjective ratings and the mutual information for Q1 ($\rho = -.32, p = .05$), Q3 ($\rho =$ .35, p=.04), and Q4 ($\rho = .46, p = .004$), the transfer entropy for Q3 ($\rho = .24, p = .04$) and Q4 ($\rho = .29, p = .02$), and the directed information for Q3 ($\rho = .33, p = .05$) and Q4 ($\rho = .52, p = .001$). Different measures provide slightly different levels of correlation, however demonstrate consistent trends with each other. The correlation for Q3 and Q4 is positive, as expected. For Q1 mutual information provided negative correlation, which resonates well with the question, since the better the pair is performing the lower the need for help is anticipated.

The temporal development of the correlation for mutual information and transfer entropy is shown in Figure 2 in which the first data point in every chart corresponds to the overall level (including all 15 trials) and every subsequent value is computed by discarding initial trials one by one, and arriving at the final point, which corresponds only to the last trial. This reveals the evolution of the correlation levels over time and reflects the influence more recent trials have on the subjective rating, which is collected only at the very end. The trajectories reveal steady trends, slightly increasing over time, as expected.

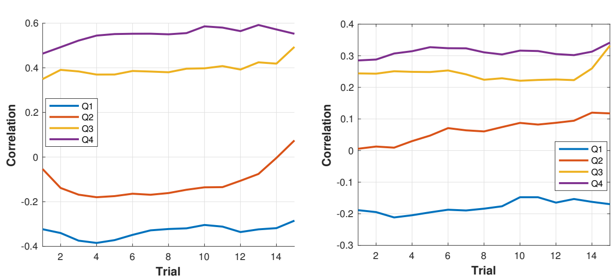

Figure 2: Temporal development of the correlation between the subjective ratings of Q1, Q2, Q3, and Q4 and the estimated mutual information (left) and transfer entropy (right).

This particular study provides a proof-of-concept example for the relevance of the proposed information-theoretic measures for assessing the level of coordination within a dyad and for predicting subjective user experience data. The paper demonstrates how task-independent universal measures could enhance the evaluation of studies and could provide theoretical underpinnings for the characterisation of interpersonal sensorimotor contingencies.

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