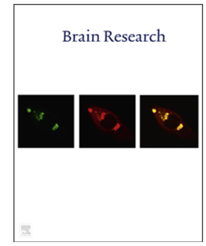
BRAIN RESEARCH 1626 (2015) 66–87

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/brainres



Research Report

Sensorimotor synchronization with tempo-changing auditory sequences: Modeling temporal adaptation and anticipation

M.C. (Marieke) van der Steen[a,*], Nori Jacoby[b], Merle T. Fairhurst[a], Peter E. Keller[a,c]

[a]Max Planck Research Group "Music Cognition and Action Group", Max Planck Institute for Human Cognitive and Brain Sciences, PO Box 500355, 04303 Leipzig, Germany
[b]The Edmond and Lily Safra Center for Brain Sciences, Hebrew University, Jerusalem, Israel and Music Department, Bar Ilan University, Ramat Gan, Israel
[c]The MARCS Institute, University of Western Sydney, Sydney, NSW, Australia

ARTICLE INFO

Article history:
Accepted 31 January 2015
Available online 25 February 2015

Keywords:
Sensorimotor synchronization
Temporal adaptation
Error correction
Temporal anticipation
Predictive internal models
Computational model

ABSTRACT

The current study investigated the human ability to synchronize movements with event sequences containing continuous tempo changes. This capacity is evident, for example, in ensemble musicians who maintain precise interpersonal coordination while modulating the performance tempo for expressive purposes. Here we tested an ADaptation and Anticipation Model (ADAM) that was developed to account for such behavior by combining error correction processes (adaptation) with a predictive temporal extrapolation process (anticipation). While previous computational models of synchronization incorporate error correction, they do not account for prediction during tempo-changing behavior. The fit between behavioral data and computer simulations based on four versions of ADAM was assessed. These versions included a model with adaptation only, one in which adaptation and anticipation act in combination (error correction is applied on the basis of predicted tempo changes), and two models in which adaptation and anticipation were linked in a joint module that corrects for predicted discrepancies between the outcomes of adaptive and anticipatory processes. The behavioral experiment required participants to tap their finger in time with three auditory pacing sequences containing tempo changes that differed in the rate of change and the number of turning points. Behavioral results indicated that sensorimotor synchronization accuracy and precision, while generally high, decreased with increases in the rate of tempo change and number of turning points. Simulations and model-based parameter estimates showed that adaptation mechanisms alone could not fully explain the observed precision of sensorimotor synchronization. Including anticipation in the model increased the precision of simulated sensorimotor

Abbreviations: SMS, sensorimotor synchronization; IOI, inter-onset interval; ITI, inter-tap interval; PT-ratio, prediction/tracking ratio; PT-index, prediction/tracking index; ADAM, ADaptation and Anticipation Model; ANOVA, analysis of variance; bGLS, bounded Generalized Least Squares

*Corresponding author.
E-mail address: steen@cbs.mpg.de (M.C. van der Steen).

http://dx.doi.org/10.1016/j.brainres.2015.01.053
0006-8993/

synchronization and improved the fit of model to behavioral data, especially when adaptation and anticipation mechanisms were linked via a joint module based on the notion of joint internal models. Overall results suggest that adaptation and anticipation mechanisms both play an important role during sensorimotor synchronization with tempo-changing sequences.

This article is part of a Special Issue entitled SI: Prediction and Attention.

1. Introduction

Music making often involves multiple performers collectively producing actions that vary in tempo. This purposeful non-stationarity in tempo, which plays a role in communicating musical expression to an audience, places challenges upon interpersonal coordination. Sometimes the composer specifies the manner in which the tempo should change by using terms such as 'ritardando' (slowing down gradually) and 'accelerando' (speeding up) in the musical notation. However, performers typically introduce additional planned or spontaneous tempo changes to convey their interpretation of a piece (e.g., Keller, 2014; Wing et al., 2014). Furthermore, tempo changes might arise unintentionally as a result of the relation between musical structure and patterns of performance expression (e.g., Repp, 1998, 2008; Repp and Bruttomesso, 2009) and as a result of the dynamic interplay between musicians (Palmer, 1997; Madison and Merker, 2005).

One of the underlying factors that contribute to successful interpersonal coordination is the timing of one's actions with an external stimulus (e.g., the tones produced by a fellow musician) (Repp, 2005). Humans have the ability to synchronize their movements successfully even with complex timing sequences that contain tempo changes (Repp, 2002a; Rankin et al., 2009; Pecenka and Keller, 2011). Synchronizing actions with tempo-changing sequences is not only important in the music domain. In sports and daily life, people are required to synchronize their movements with sequential events at different rates and to handle rate changes, in order to fulfill task requirements successfully. An example is the Olympic rowing team that in the heat of the moment is instructed by the coxswain to speed up the pace in order to overtake a competing team. A daily life example occurs if you change pace while walking through the city together with a friend who suddenly speeds up in order to be able to cross the street before the light at the pedestrian crossing turns red. The current study investigates how people synchronize their movements with different types of ongoing tempo changes. Our main goal is to identify and gain a better understanding of the mechanisms that underlie this extraordinary form of sensorimotor synchronization skill.

Individuals' sensorimotor synchronization (SMS) abilities and the underlying mechanisms are often investigated by means of paced finger-tapping tasks (Michon, 1967; Repp, 2005). During such tasks, participants are asked to tap with their finger in time with the events (e.g., tones) of computer-controlled pacing sequences. The instruction is typically to synchronize finger taps as accurately and precisely as possible with the stimulus sequence. The mean asynchrony between finger taps and stimulus events can be used as an inverse measure of SMS accuracy, and the variability (i.e., standard deviation) of the asynchronies can serve an inverse measure of SMS precision. The pacing sequences are often isochronous series of tones, but sometimes timing perturbations (lengthened or shortened inter-onset intervals) are added. These perturbations can vary in terms of whether they are predictable or unpredictable and whether they are local (i.e., affecting one single event or interval) or global (i.e., affecting every event).

It has been hypothesized that in order to successfully time movements relative to external events, humans employ mechanisms that enable adaptation (reactive error correction) and anticipation (tempo-change prediction) (e.g., Keller, 2008; van der Steen and Keller, 2013). Temporal adaptation processes have been studied extensively in the tradition of information-processing approaches to SMS. According to the information-processing theory, the timing of simple movements is determined by an internal timekeeping process that generates pulses that, in turn, trigger motor responses (e.g., taps) (Wing and Kristofferson, 1973). The timekeeper outputs intervals of a particular duration (i.e., period) that may or may not change during synchronization. Variability in movement timing arises due to variance in this central timekeeper, and also as a result of variable transmission delays in the peripheral motor system (e.g., Vorberg and Wing, 1996).

Adaptation mechanisms reduce the effects of timing variability and therefore contribute to successful SMS (e.g., Mates, 1994a, 1994b; Vorberg and Wing, 1996). Two types of adaptation mechanisms – phase and period correction – have been distinguished (Mates, 1994a, 1994b; Vorberg and Wing, 1996; Semjen et al., 1998). Both error correction processes modify the timing of the next tap based on a proportion of the asynchrony, the timing error between a tap and stimulus event (Fig. 1). Phase correction is an automatic and local adjustment of the interval generated by the internal timekeeper, leaving the interval setting of this timekeeper unaffected (Repp, 2001a, 2002b) (Fig. 1A). Period correction on the other hand changes the interval setting of the timekeeper that drives the motor activity (Fig. 1B). This change in timekeeper setting persists until period correction is applied again (Repp, 2001b). Period correction requires the conscious perception of a tempo change in the stimulus sequence (Repp and Keller, 2004). Without these adaptation mechanisms, movement timing variability accumulates from movement cycle to movement cycle. This leads to increasingly large asynchronies, phase drift and eventually the loss of synchronization (Vorberg and Wing, 1996).

In addition to the adaptation mechanisms, it has been suggested that anticipation mechanisms contribute to successful