Proceedings of the 7th Triennial Conference of European Society for the Cognitive Sciences of Music (ESCOM 2009) Jyväskylä, Finland
Jukka Louhivuori, Tuomas Eerola, Suvi Saarikallio, Tommi Himberg, Päivi-Sisko Eerola (Editors)

An integrative dual-route model of rhythm perception and production

Timo Fischinger

Dept. of Music, University of Kassel, Germany

timo.fischinger@uni-kassel.de

ABSTRACT

An integrative dual-route model of rhythm perception and production is proposed here. Furthermore, an empirical study illustrated in the second part of this paper provides evidence of the existence of two different cognitive pathways.

The development of the model is based on fundamental psychological principles of perception, action control and relevant neurobiological findings in rhythm processing and sensorimotor synchronization. Experiments with a dual-task paradigm were used during synchronization tapping to verify the fundamental assumptions of the model. The aim was to examine whether professional drummers show a change in tapping performance when their attention is drawn to another task.

In contrast to other experiments on sensorimotor synchronization with non-musicians, the results show a considerable effect on the tapping performance of timing experts for the concurrent condition with tempi between 100 and 120 bpm. Overall, these results provide further evidence of the existence of both, an automatic and a cognitively-controlled timing procedure, which is also in line with the integrative dual-route model of rhythm perception and production mentioned above.

I. INTRODUCTION

Professional drummers have the ability to perform with millisecond precision (see Fischinger, 2009; Fischinger, submitted; Honing & de Haas, 2008). Such peak performances require a large number of complex movements which have to be executed in right order and coordinated with the time structure of music.

Likewise, this seems to be true for non-musicians, when they simply tap along to music with their feet or fingers. Although this kind of synchronization is rather simple compared to the skilled actions of a drummer, these repetitive movements demand a steady timing control which is crucial to compensate motor variations and to adapt to expressive (timing) nuances or tempo changes.

Since Stevens (1886), a vast number of psychological publications has addressed this issue, mainly focussing on the analysis of synchronization behaviour by using simple tapping paradigms at which people (mostly non-musicians) have to synchronize their finger taps to auditory beat sequences (see Repp, 2005, for a review) or music (see Dixon & Goebl, 2002; Franek et al., 1987; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003). This type of sensorimotor synchronization is considered as one of the most important experimental paradigms in the field of psychomotricity in order to illuminate the underlying processes of action control in view of the coupling of both, perception and action (Repp, 2006; Vorberg, 1996). This kind of anticipatory behaviour (Butz, 2003) is a crucial ability in everyday life and an elementary skill for playing a musical instrument in particular.

Experiments with simple tapping tasks to a metronome already show distinctive features like the occurrence of the negative mean asynchrony (Aschersleben, 2000; Dunlap, 1910; Franek et al., 1994; Johnson, 1898; Mates et al., 1994; Miyake, 1902; Woodrow, 1932). Nonmusicians in particular show this systematic timing error when they have to synchronize their finger taps to a sequence of isochronous beats as precisely as possible. Generally, the taps tend to precede the physical onset of the metronome click during tapping trials. In contrast to musical novices, expert drummers are able to synchronize their taps without, or at least with a very low, negative asynchrony (Fischinger, submitted). Although there have been several attempts to find an explanation for the negative synchronization error, the causes for this phenomenon still remain unclear (Repp, 2005).

However, two essential processes responsible for synchronization have recently been identified, and can be characterized separately: One is the implicit automatic anticipation and the other the explicit processing of temporal information (Miyake, 2004; Repp, 2005).

Studies from neuroimaging have also clarified two distinct systems for automatic and cognitively controlled time measurement which seem to work in both a partly parallel and partly concurrent manner (Lewis & Miall, 2003).

Thaut (2005) argues that strong connections between stages of the auditory pathway and the cerebellum are responsible for a mostly subconscious processing of sensorimotor information. At this subcortical level, the colliculus inferior and the nucleus cochlearis (dorsal) project to the cerebellum while they also receive signals from the cerebellum (Casseday, 1995). Overall, different distributed stages in both cortical and subcortical brain networks are responsible for movement and timing control.

II. DUAL-ROUTE MODEL

Taking into account that there seem to be different cognitive pathways, an *integrative dual-route model of rhythm perception and production* is proposed here (Fig. 1). The model is based on fundamental psychological principles of perception, action control and relevant neurobiological findings regarding rhythm processing and sensorimotor synchronization mentioned above.

According to the „expanded closed-loop model for movement control“ by Schmidt & Lee (1999), it includes different modules on different cognitive levels like “*Stimulus*“ (Input), “*Movement*“ (Output), “*Stimulus identification*“, “*Response selection*“ and “*Response programming*“ (see Schmidt & Lee, 1999, p. 43). Here, the stimulus identification and response selection is illustrated by three different modules (evaluation, comprehension and relevance), which work partly parallel as well as sequential (see Pribram, 1991). Response programming is administrated by a central executive (see Kluwe, 2006). The model also integrates open-loop processing as well as closed-loop circuits, including different feedback components (proprioceptive and exteroceptive feedback loops) and a *„reference of correctness“* (Schmidt & Lee, 1999) as important prerequisites for a tight coupling of perception and action. The main assumption of the model is the differentiation between the "cognitively controlled" and "automatic" pathway (direct and preattentive trigger).

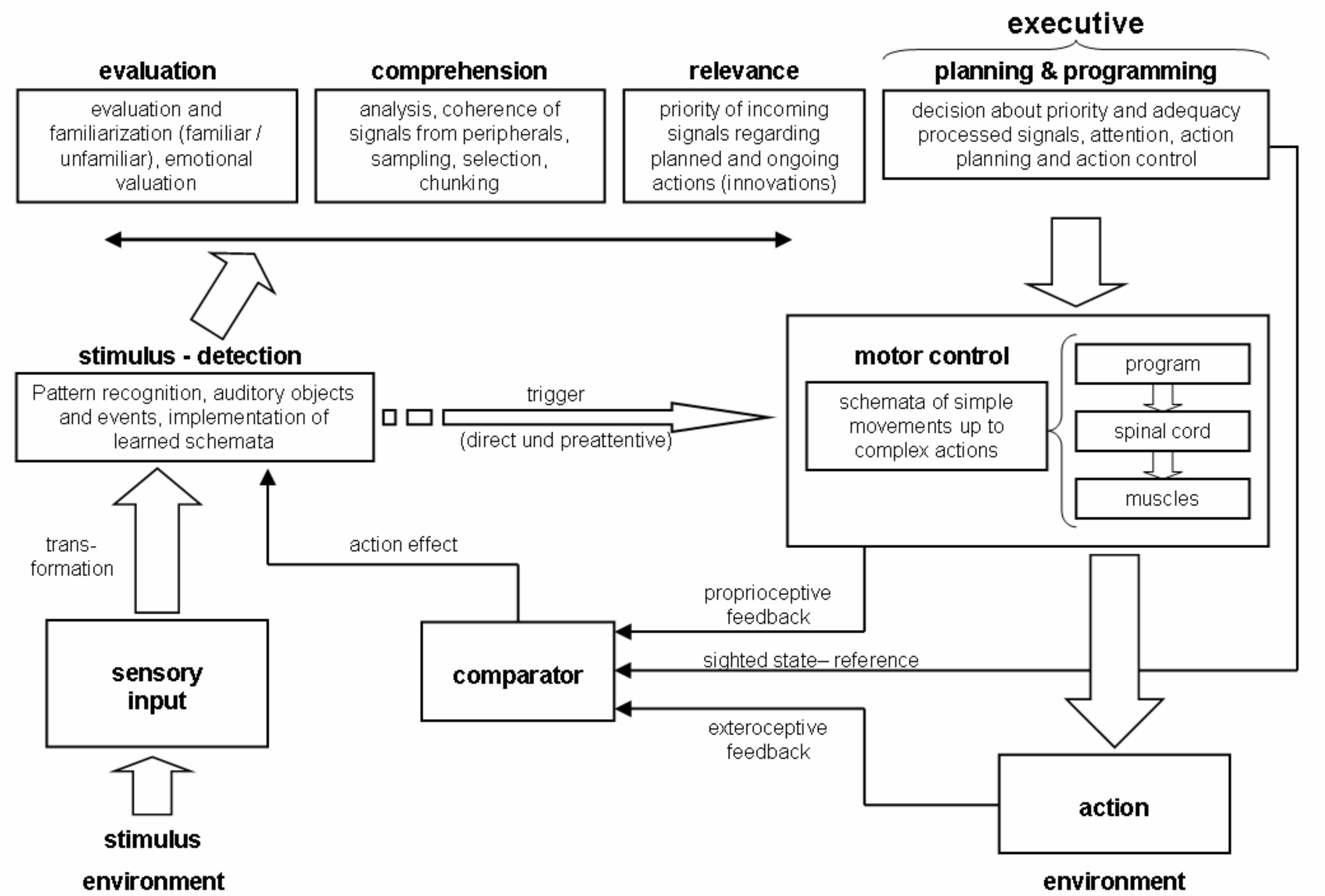

Figure 1. Integrative dual-route model of rhythm perception and production.

III. EXPERIMENT

In the following study on synchronization behaviour of professional drummers (Fischinger, submitted), a dual-task paradigm (Baddeley, 1986) was used during synchronization tapping similar to the experiments of (Miyake, 2004) in order to elucidate the effects of higher brain functions such as attention. The aim was to examine whether expert drummers show a change in tapping performance when they have to draw their attention to another task. Unlike in the study of (Miyake, 2004) it was assumed that timing accuracy of very precise rhythmic action at interstimulus-onset interval (IOI) 600 ms depends on attentional resources of higher brain functions. If these monitoring processes (timing control and correction) are disturbed by an additional task that minimizes the capacity of working memory (e.g., phonological loop), this should result in an increased negative mean asynchrony (NMA), because timing control falls back on the "automatic" pathway.

A. Method

1) Participants. Ten professional drummers volunteered in the experiment (two women; eight men; ages 20-44). All participants were right-handed and had extensive drum training, with a minimum 10 years of instruction.

2) Materials & Equipment. A custom made application written in C was used for stimulus control and real-time data collection on a standard PC running Linux OS. All word lists for the secondary task were displayed in the center of a monitor screen. Each of these word lists consisted of 5 to 6 different German disyllabic and meaningful words. Words were chosen in such a way that it was difficult to create meaningful associations between them. The MIDI-based program FTAP (Finney, 2001) was used as a subprogram for the tapping task providing a reliable time resolution of 1 millisecond in combination with a SoundblasterLive! 5.1 as a sound card MIDI-interface. A Roland PD-8 Trigger Pad was used as an input device, which was connected to the PC (MIDI-IN) via a Roland TMC-6 Trigger MIDI Converter. Additionally the PC was connected to the sound generator of a Roland HPD-15 HandSonic (MIDI-OUT). Both pacing stimulus and feedback sounds of the taps (Preset: P02 AFRICAN, 07 Log Drum of the Roland HPD-15) were presented binaurally through AKG-Headphones. The basic stimulus material for the pacing signal (log drum sound, low pitch) consisted of three metronome sequences with different tempi: IOI = 400, 500 and 600 ms. Another log drum sound (high pitch) was used as a feedback sound for the taps. All participants were used to performing with click track.

3) Procedure. Participants were required to synchronize their finger taps as precise as possible to a given metronome sequence in blocks of separate trials. The duration of each trial was 1 minute, while five different conditions were varied: In the first condition, participants had to tap without a secondary task. In the second condition, a word list was displayed for 3 seconds at the beginning of a tapping trial so that participants could read the list (at least once) and memorize the words throughout the rest of the trial. In the third, fourth, and fifth conditions, the word lists were presented at different time points during the tapping trials after 30, 35 and 40 seconds as a variation of intervention. At the end of each dual-task trial, participants were asked to recall all of the memorized words. The conditions were presented for all three IOIs, and randomly intermixed with adequate intervals between trials (participants started trials by pressing the enter key on the computer keyboard). Participants attended two one-hour sessions with varying word lists on different days. Each session started with a set of three control trials without dual-task before the block of 15 trials. In addition, a word span test (Haarmann, 2003) was conducted under normal conditions (without tapping task) at the beginning of the first session to evaluate the general word memory skills of the participants, and to adjust the appropriate length of the word lists.

4) Analysis. The experimental data of the synchronization tasks consisted of the collected MIDI data with the IOIs of the pacing signal and respective inter-response intervals (IRIs) of the taps. Asynchronies were computed as the temporal difference (in ms) between the MIDI onset of the pacing signal and the MIDI onset of the recorded taps. When the tap onset preceded the onset of the pacing signal, asynchronies were defined as negative, while they were positive when the tap onset followed the pacing signal. Asynchronies were extracted from the MIDI output files into a spreadsheet program using another custom made program written in C, and sorted according to the conditions Baseline and Concurrent. The data analysis for the Baseline condition started with the first 30 taps in each of the trials which had no concurrent task. This was also done for the Concurrent condition, in which the word lists were displayed at the beginning of a trial. For trials with word list presentations at different time points, 30 taps before and after the list was displayed were taken into account. Thus, a total number of 480 datasets (consisting of 30 taps x 24 conditions x 2 sessions x 10 participants = 14.400 taps) were generated for the two conditions. Means and standard deviations of asynchronies were calculated per trial and condition. All following statistical analyses were carried out using SPSS 14.0 and G*Power 3.0 (Faul, 2007). The analysis of the secondary task was done by calculating the mean values for all correct responses of the word memory task (for each participant).

B. Results

In contrast to other experiments on SMS with nonmusicians (see Miyake et al., 2004), it was shown that participants were able to synchronize their taps with a very low NMA under normal conditions (Baseline) at all three tapping tempi, while they performed with increased variability and a significantly increased NMA at IOIs = 500 and 600 ms when they had to concentrate on a secondary word memory task while synchronizing (Concurrent).

Figure 2 shows the mean asynchronies (in ms) for the tapping tasks at three different IOIs (400, 500 and 600 ms) under the two tested conditions, Baseline and Concurrent. Mean asynchronies at IOI = 400 ms are almost the same for the two conditions, whereas the means at IOI = 500 and 600 ms indicate clear differences.

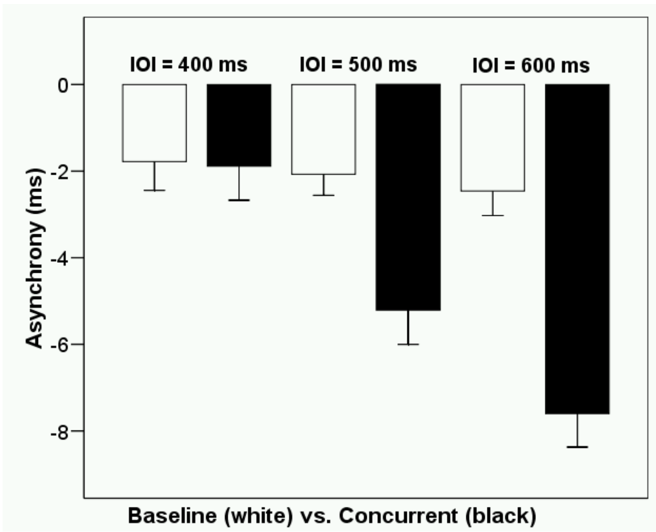

Figure 2. Means and between-trials standard errors of the mean asynchronies in the tapping task at three different IOIs (400, 500 and 600 ms) under the two tested conditions Baseline and Concurrent.

Table 1 displays the means of the asynchronies with standard deviations in the different tapping conditions of the experiment. Table 1 also shows the differences between the Baseline and Concurrent conditions (BC-Diff) among all trials (N = 80, per condition and IOI) plus corresponding effect sizes for dependent samples (Cohen, 1988).

Table 1. Means of the asynchronies in ms (with standard deviations), BC-Diffs (difference between Baseline and Concurrent conditions), t-tests for paired samples on the mean values of the asynchrony among trials and effect sizes for the different IOIs (400, 500 and 600 ms).

	Tempo		
	IOI = 400ms	**IOI = 500ms**	**IOI = 600ms**
Baseline	-1.77 (5.94)	-2.07 (4.37)	-2.45 (5.06)
Concurrent	-1.88 (7.03)	-5.2 (7.1)	-7.59 (6.93)
BC-Diff	-0.11	-3.13	-5.14
t-test	p = 0.90	*p* < 0.001	*p* = < 0.001
Effect size	0.01	0.48	0.75

A series of t-tests for paired samples using the mean values of the NMA revealed a significant main effect for the Concurrent condition with IOI = 500 and 600 ms ($p < 0.001$), whereas the means of the trials with IOI = 400 ms did not differ significantly ($p = 0.90$). The SDs show higher values for the Concurrent condition than for the Baseline condition at all IOIs, which indicates that the drummers' performance was more variable under dual-task conditions. Furthermore, the calculation of the effect sizes show that the main effect for the Concurrent condition largely depends on tempo and the length of IOIs respectively: There is a large effect for the Concurrent condition at IOI = 600 ms (ES = 0.75), a medium effect at IOI = 500 ms (ES = 0.48), and only a very small effect at IOI = 400 ms (ES = 0.01). No significant differences between Baseline and control trials were observed. The average of the correct response rate for the (secondary) word memory task for all participants and trials was 85 % (4.2 words, SD = 0.46).

IV. CONCLUSION

The proposed dual-route model integrates significant mechanisms of sensorimotor synchronization, which are based on a tight coupling of perception and action as an essential requirement for timing control. In particular, two distinct systems for automatic and cognitively-controlled mechanisms are illustrated here. They seem to work in both a partly parallel and partly concurrent manner at different distributed stages, guaranteeing a robust but flexible and adaptive motion control which is crucial when playing a musical instrument.

The results of a study on the tapping behaviour of professional drummers (Fischinger, submitted) showed that in contrast to other experiments on SMS with nonmusicians (Miyake, 2004), participants were able to synchronize their taps with a very low NMA under normal conditions (Baseline), while they performed with increased variability and a significantly increased NMA at IOIs = 500 and 600 ms when they had to concentrate on a secondary word memory task while synchronizing (Concurrent).

Such an effect provides further evidence of the existence of two different cognitive pathways mentioned above. It can be concluded that timing accuracy of very precise rhythmic action depends on both expertise and attentional resources of higher brain functions. If these monitoring processes (timing control and correction) are disturbed by an additional task that minimizes working memory capacity, timing control falls back on a secondary processing pathway that is driven by an "automatic" system.

Furthermore, the NMA could be the result of different delay times of two distinct, but simultaneously acting, cognitive pathways. That is, fast information processing at low (subcortical) levels provides close links between sensory peripherals and motor centers, while sensorimotor information processing at higher levels requires attention and working memory resources.

According to this, the tendency to tap ahead of the pacing signal (the NMA) seems to be a kind of preattentive automatic timing behaviour, which is typically true for the tapping performance of untrained participants. In contrast, trained experts like professional drummers make use of cognitively controlled monitoring processes that depend on attentional resources.

ACKNOWLEDGMENT

I would like to thank Herbert Bruhn (University of Flensburg) and Manfred Nusseck (Max Planck Institute for Biological Cybernetics Tübingen).

REFERENCES

Aschersleben, G. & Prinz, W. (1995). Synchronization actions with events: The role of sensory information. *Perception & Psychophysics*, *57*, 3, 305–317.

Baddeley, A. D. (1986). *Working memory*. New York: Oxford University Press.

Butz, M. V. (2003). *Anticipatory behavior in adaptive learning systems. Foundations, theories, and systems.* Heidelberg: Springer.

Casseday, J. H. & Covey, E. (1995). Mechanisms for analysis of auditory temporal patterns in the brainstem of echolocating bats. In E. Covey, H. L. Hawkins & R. F. Port (Eds.), *Neural Representations of Temporal Patterns* (pp. 25–52). New York: Plenum Press.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Dixon, S. & Goebl, W. (2002). Pinpointing the beat: tapping to expressive performances. *7th International Conference on Music Perception and Cognition*, Sydney, (pp. 1-24).

Dunlap, K. (1910). Reactions on rhythmic stimuli, with attempt to synchronize. *Psychological Review*, *17*, 399–416.

Faul, F., Erdfelder, E., Lang, A.-G. & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191.

Finney, S. A. (2001). FTAP: A linux-based program for tapping and music experiment. *Behaviour Research Methods, Instruments, and Computers*, *33*, 65–72.

Fischinger, T. (2009, in press). High-precision timing control: The secrets of expert drumming. In: Bader, R., Neuhaus, C. & Morgenstern, U. (Eds.) *Studies in Systematic Musicology - Festschrift in honor of Albrecht Schneider*. Frankfurt a. M.: Peter Lang.

Fischinger, T. (submitted). Timing precision in synchronization tapping: A dual-task study with professional drummers. *Music Perception.*

Franek, M., Radil, R., Indra, M.&Lansky, P. (1987). Following complex rhythmical acoustical patterns by tapping. *International Journal of Psychophysiology, 5,* 187–192.

Haarmann, H. J., Davelaar, E. J. & Usher, M. (2003). Individual differences in semantic short-term memory capacity and reading comprehension. *Journal of Memory and Language*, *48*, 320–345.

Honing, H. & de Haas, W. B. (2008). Swing once more: Relating timing and tempo in expert jazz drumming. *Music Perception, 25,* 5, 471-476.

Johnson, W. S. (1898). Researches in practice and habit. *Studies from the Yale Psychology Laboratory, 6*, 51–105.

Kluwe, R. H. (2006). Exekutive Funktionen. In J. Funke & P. A. Frensch (Eds.), *Handbuch der Allgemeinen Psychologie - Kognition*, (Vol. 5, pp. 547–555). Göttingen: Hogrefe.

Lewis, P. A. & Miall, R. C. (2003). Distinct systems for automatic and cognitively controlled time measurement: Evidence from neuroimaging. *Current Opinion in Neurobiology*, *13*, 250–255.

Mates, J., Müller, U., Radil, T. & Pöppel, E. (1994). Temporal integration in sensorimotor synchronization. *Journal of Cognitive Neuroscience, 6*, 332–340.

Miyake, I. (1902). Researches on rhythmic action. *Studies from the Yale Psychology Laboratory, 10,* 1-48.

Miyake, Y., Onishi, Y. & Pöppel, E. (2004). Two types of anticipation in synchronization tapping. *Acta Neurobiologiae Experimentalis, 64,* 415-426.

Pribram, K. H. (1991). *Brain and Perception: Holonomy and Structure in Figural Processing.* Hillsdale: Erlbaum.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12,* 969-992.

Repp, B. H. (2006). Musical synchronization. In E. Altenmüller, M. Wiesendanger & J. Kesselring (Eds.), *Music, motor control and the brain* (pp. 55-76). Oxford: University Press.

Schmidt, R. A. & Lee, T. D. (1999). *Motor control and learning. A behavioral emphasis.* Champaign: Human Kinetics.

Snyder, J. & Krumhansl, C. L. (2001). Tapping to ragtime: Cues to pulse finding. *Music Perception, 18,* 4, 455-489.

Stevens, L. T. (1886). On the time-sense. *Mind, 11,* 393-404.

Thaut, M. H. (2005). *Rhythm, music, and the brain: Scientific foundations and clinical applications.* New York: Routledge.

Toiviainen, P. & Snyder, J. S. (2003). Tapping to Bach: Resonance-based modeling of pulse. *Music Perception, 21*, 1, 43-80.

Vorberg, D. & Wing, A. (1996). Modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action.*, Vol. 3 (pp. 179-262). Dordrecht: Kluwer.

Woodrow, H. (1932). The effect of rate of sequence upon the accuracy of synchronization. *Journal of Experimental Psychology, 15,* 357-379.