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Timo Fischinger

University of Kassel, Germany

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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 on 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 nonmusicians, 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.

Keywords

different cognitive pathways, dual-task performance, professional drummers, rhythm perception and production, sensorimotor synchronization and information processing, timing control

Introduction

Professional drummers have the ability to perform with millisecond precision (see Fischinger, 2009; Fischinger, 2010; Honing & de Haas, 2008). Such peak performances require a large number of complex movements, which have to be executed in the right order and coordinated with the time structure of the music.

Likewise, this seems to be true for nonmusicians, 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 for motor variations and to adapt to expressive (timing) nuances or tempo changes.

Corresponding author:

Timo Fischinger, Dept. of Music, University of Kassel, Germany
Email: timo.fischinger@uni-kassel.de

Since Stevens (1886), a vast number of psychological publications have addressed this issue, mainly focusing on the analysis of synchronization behaviour by using simple tapping paradigms in which people (mostly nonmusicians) have to synchronize their finger taps to auditory beat sequences (see Repp, 2005, for a review) or music (see Dixon & Goebel, 2002; Franek et al., 1987; Snyder & Krumhansl, 2001; Toiviainen & Snyder, 2003). This type of sensorimotor synchronization is considered to be 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 & Wing, 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 such as the occurrence of the negative mean asynchrony (Aschersleben, 2002; 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, 2009). 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, Onishi, & Pöppel, 2004; Repp, 2005).

Studies from neuro-imaging 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 & Covey, 1995). Overall, different distributed stages in both cortical and subcortical brain networks are responsible for movement and timing control.

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 such as “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 in parallel and partly sequentially (see Pribram, 1991). Response

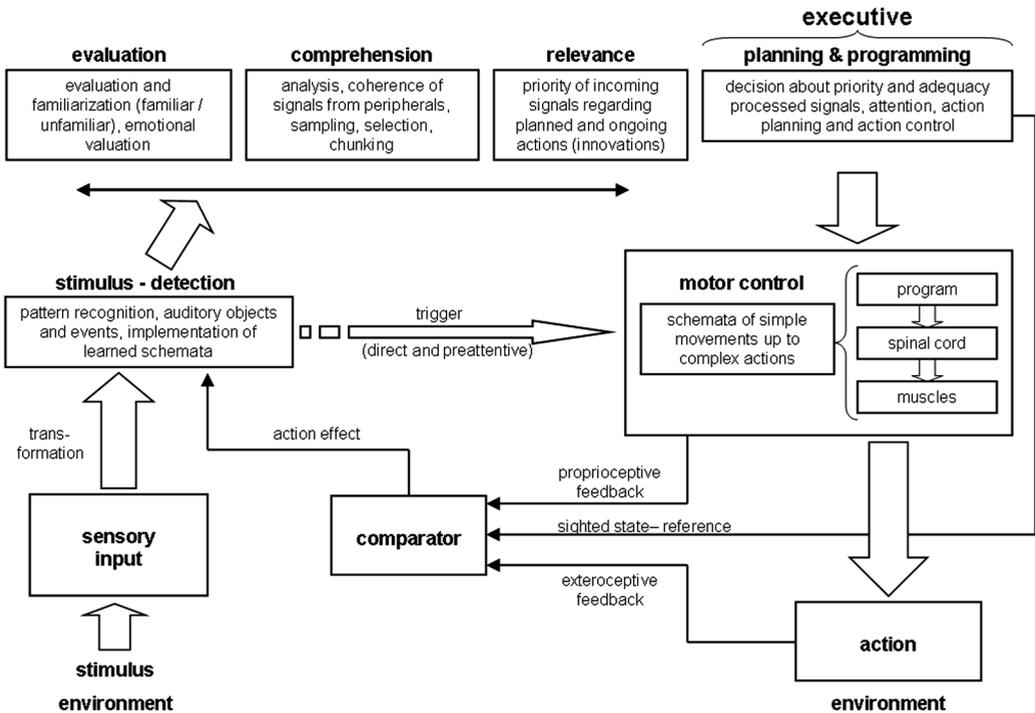


Figure 1. Integrative dual-route model of rhythm perception and production.

programming is administered by a central executive (see Kluwe, 2006). The model also integrates both open-loop processing and 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).

Experiment

In the following study on the synchronization behaviour of professional drummers (Fischinger, 2009), a dual-task paradigm (Baddeley, 1986) was used during synchronization tapping, similar to the experiments of Miyake et al. (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 et al. (2004), it was assumed that timing accuracy of very precise rhythmic action at interstimulus-onset interval (IOI) 600 ms depends on the attentional resources of the 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.

Method

Participants. Ten professional drummers volunteered for 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.

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 centre 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.

Procedure. Participants were required to synchronize their finger taps as precisely 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 et al., 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.

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 et al., 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).

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.

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).

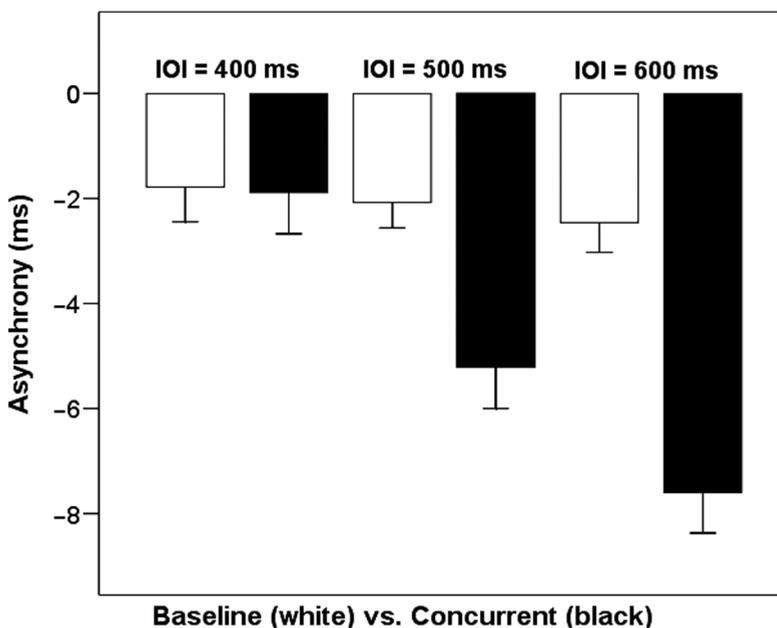


Figure 2. Means and between-trials standard errors of the mean asynchronies in the tapping task at three different IOIs (400, 500 and 600 ms) under the two tested conditions Baseline and Concurrent.

Table 1. 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
<i>t</i> test	$p = 0.9$	$p < 0.001$	$p < 0.001$
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 ($p = 0.9$). 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 calculations 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).

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, 2009) showed that in contrast to other experiments on SMS with nonmusicians (Miyake et al., 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 the attentional resources of the 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 centres, 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 such as professional drummers make use of cognitively controlled monitoring processes that depend on attentional resources.

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Un modelo integrador de doble vía de la percepción del ritmo y la producción

Se propone un modelo de doble vía integrador de la percepción del ritmo y la producción. Además, un estudio empírico ilustrado en la segunda parte de este texto proporciona evidencias sobre la existencia de dos senderos cognitivos diferentes. El desarrollo del modelo se basa en los principios psicológicos fundamentales de percepción, control de la acción, y sobre hallazgos neurobiológicos relevantes sobre el procesamiento del ritmo y la sincronización senso-motora. Se utilizaron experimentos con un paradigma de tarea dual durante la sincronización para verificar las hipótesis fundamentales del modelo. El objetivo era examinar si bateristas profesionales muestran un cambio en el rendimiento de la interpretación cuando su atención se dirige a otra tarea. En contraste con otros experimentos sobre sincronización senso-motora en no músicos, los resultados muestran un considerable efecto sobre el rendimiento en la interpretación de los especialistas en tiempo para la condición concurrente con *tempi* entre 100 y 120 pulsos por minuto. En general, estos resultados proporcionan claras evidencias de la existencia tanto de un procedimiento automático como de un procedimiento de tiempo controlado cognitivamente, que está también en consonancia con el modelo integrador de doble vía de la percepción del ritmo y la producción mencionado anteriormente.

Un modello integrativo dual-route di percezione e produzione del ritmo

È qui proposto un modello integrativo dual-route di percezione e produzione del ritmo. Inoltre, uno studio empirico illustrato nella seconda parte di questo saggio dimostra l'esistenza di due diversi percorsi cognitivi. Lo sviluppo del modello si basa sui principi psicologici fondamentali della percezione, dell'azione, del controllo e sui risultati significativi in campo neuro-biologico relativi all'elaborazione del ritmo e alla sincronizzazione moto-sensoriale. Sono stati realizzati esperimenti con l'utilizzo di paradigmi dual-task durante l'atto di sincronizzazione per verificare

gli assunti fondamentali del modello. L'obiettivo era di esaminare se l'attività di sincronizzazione da parte di percussionisti professionisti cambiasse nel caso in cui la loro attenzione venisse rivolta a un'altro compito. In contrasto con altri esperimenti sulla sincronizzazione moto-sensoriale con non-musicisti, i risultati mostrano un effetto rilevante sulla presa del tempo nei professionisti con la presenza concomitante di tempi tra i 100 e i 120 bpm. In particolare, i risultati offrono nuovi elementi che dimostrano l'esistenza di procedure di presa del tempo sia automatiche sia razionalmente controllate. Ciò è, peraltro, in linea con il modello integrativo dual-route di percezione e produzione del tempo sopra menzionato.

Un modèle intégratif à double accès de la perception et de la production rythmique

On propose ici un modèle intégratif à double accès de la perception et de la production rythmique. En outre, une étude empirique illustrée dans la seconde partie de l'article, fournit les preuves de l'existence de deux voies cognitives différentes. Le développement du modèle est basé sur des principes fondamentaux en psychologie de perception et du contrôle de l'action, et sur les données neurobiologiques pertinentes sur le traitement du rythme et la synchronisation sensori-motrice. Des expériences avec un paradigme 'double-tâche' ont été réalisées lors d'une activité de synchronisation de frappes (tapping) pour vérifier les hypothèses fondamentales du modèle. Le but était d'étudier si oui ou non les batteurs (percussionnistes) professionnels montrent un changement dans leur performance de frappes quand leur attention est détournée vers une autre tâche. A la différence d'autres expériences sur la synchronisation sensorimotrice avec des sujets non-musiciens, les résultats montrent un effet considérable sur la performance des spécialistes du rythme avec la condition simultanée d'un tempo entre 100 et 120 bpm (battements par minute). Dans l'ensemble, ces résultats fournissent des preuves supplémentaires de l'existence d'un processus rythmique automatique aussi bien que d'un processus rythmique cognitivement contrôlé, ce qui est également conforme au modèle intégratif à double accès de la perception et de la production rythmique mentionné plus haut.

Ein integratives Zwei-Wege-Modell der Rhythmuswahrnehmung und -verarbeitung

Es soll ein integratives Zwei-Wege-Modell der Rhythmusverarbeitung vorgestellt werden. Darüber hinaus wird im zweiten Teil des Beitrags eine empirische Studie vorgestellt, welche die Existenz zweier unterschiedlicher kognitiver Prozesswege nahelegt. Die Entwicklung des Modells basiert auf grundlegenden psychologischen Prinzipien der Wahrnehmung, Handlungstheorie sowie kognitionspsychologischen und relevanten neurophysiologischen Erkenntnissen zu Fragen der Rhythmusverarbeitung und sensomotorischen Synchronisationsprozessen. Die Aussagekraft des Modells wird überdies durch die Ergebnisse einer empirischen Studie gestützt, die das Ziel hatte, das Timing-Verhalten von professionellen Schlagzeugern mithilfe von Synchronisationsexperimenten mit Doppelaufgabenparadigma zu untersuchen indem überprüft wurde, ob sich das Tappingverhalten ändert, wenn die Aufmerksamkeit beim Tapping auf eine weitere Aufgabe gelenkt wird. Im Gegensatz zu bisherigen Synchronisationsexperimenten mit Nicht-Musikern zeigen die Ergebnisse der Studie für die Concurrent-Bedingung bei Tempi zwischen 100 und 120 bpm einen erheblichen Effekt an. Ganz im Sinne des obengenannten integrativen Zwei-Wege-Modells liefern die Ergebnisse mithin weitere Hinweise auf das Vorhandensein eher automatisiert ablaufender Timing-Prozesse auf der einen, und eher kognitiv kontrollierten Prozeduren auf der anderen Seite.