Knut Drewing · Mareike Hennings · Gisa Aschersleben

The contribution of tactile reaference to temporal regularity during bimanual finger tapping

Accepted: 14 June 2001 / Published online: 30 October 2001
© Springer-Verlag 2001

Abstract In a repetitive tapping task, the within-hand variability of intertap intervals is reduced when participants tap with both hands, as opposed to single-handed tapping. This bimanual advantage can be attributed to timer variance (according to the Wing-Kristofferson model). Separate timers have been proposed for each hand whose outputs are then averaged (Helmut & Ivry, 1996, Journal of Experimental Psychology: Human Perception and Performance, 22, 278–293). Alternatively, timing might be based on sensory reaference and the bimanual advantage due to the enhancement of sensory reaferences. This alternative hypothesis was tested in three experiments. In the first experiment, we replicated the bimanual advantage in tapping with two fingers of the same hand compared with single finger taping. In the second experiment, we demonstrated that the bimanual advantage decreased when tactile reaferences from left-hand taps were omitted (by contact-free tapping). In the third experiment, participants tapped bimanually with the index fingers of both hands firmly mechanically coupled. The bimanual advantage was replicated for this condition. Results are consistent with the assumption that the bimanual advantage is due to the sensory reaferences of the second hand. We suggest that our results are best explained by a reformulation of the Wing-Kristofferson model, in which the timer provides action goals in terms of sensory reaferences.

Introduction

An increasing number of studies have demonstrated the important role of sensory reaferences in the timing of movements. An influence of sensory reaferences has even been reported in very simple timing tasks, such as the repetitive tapping of isochronous intervals (e.g., Aschersleben & Prinz, 1995; Aschersleben, Stenneken, Cole, & Prinz, in press; Barratt, Patton, Olsson, & Zucker, 1981; Kellers & Brewster, 1985; Wing, 1977). In the present study, we extend this research by studying the contribution of tactile-kinesthetic reaferences to a coupling phenomenon for repetitive actions: the bimanual advantage. When two hands tap simultaneously, temporal regularity is improved in comparison to unimanual tapping (Helmut & Ivry, 1996).

In the repetitive tapping task (designed by Stevens, 1886) a trial typically consists of two phases: an initial synchronization phase and a subsequent continuation phase. During the synchronization phase participants synchronize simple finger taps on a response key with a metronome. During the continuation phase they continue to produce the previously established intervals without the pacing signal and the intervals between successive tap-onsets (intertap intervals, ITIs) are measured. Tapping in the continuation phase has been modelled by Wing and Kristofferson (1973a, 1973b). According to this model, a central timekeeper provides intervals of the appropriate length and triggers motor commands at the end of each interval. The time that elapses between this trigger and the observable reaction (e.g., the finger tap) is called the motor delay. All involved processes are assumed to be independent of each other. Under these assumptions, the variability of motor delays (here: motor variance) and timer intervals (here: timer variance) can be estimated separately, allowing for the decomposition of the ITI variability into two different components. Moreover, predictions concerning the autocovariance function of the ITI can be deduced (see Vorberg & Wing, 1996, for a detailed description). In the case of unimanual tapping, the predictions of the Wing-Kristofferson model gain broad empirical support in terms of both the predicted autocovariance functions and the general interpretations of the estimates of timer and motor variance (e.g., Ivry & Keele, 1989; Ivry,
Keele, & Diener, 1988; Miedreich, 2000; Wing & Kristofferson, 1973a, 1973b), although the concrete processes reflected in these estimates seem to be slightly different from those assumed originally (Helmuth & Ivy, 1996; Ivy & Hazeltine, 1995).

Extensions of the model have been suggested for multi-limb coordination: the timekeeper is assumed to trigger movements of different limbs either simultaneously or successively in any order the task requires (Vorberg & Hambuch, 1984; Vorberg & Wing, 1996; Wing, 1982; Wing, Church, & Gentner, 1989). In bimanual tapping, the ‘bimanual advantage’ described by Helmuth and Ivy (1996; cf. Franz, Ivy, & Helmuth, 1996; Ivy & Hazeltine, 1999) has challenged these suggested extensions: A decrease of the within-hand variability of ITI during simultaneous bimanual compared with unimanual tapping was fully attributed to a reduction of timer variance, whereas motor variance was not affected. Multi-limb extensions, however, do not differentiate between timing of one and timing of two movements, and thus predict timer variance to be the same in both cases.

Helmuth and Ivy (1996) assume that the bimanual advantage originates from multiple effector-specific timers. During bimanual tapping two timers run in parallel, one for each hand. Due to a response bottleneck, the two timers cannot trigger their corresponding motor commands independently of each other, but the outputs of the involved timers are integrated. This integration is thought to be some kind of temporal averaging. Simple statistics predict that two timers, when their outputs are averaged, produce more regular intervals than a single timer. However, the notion of effector-specific timers is contradictory to some other studies, which conclude that an integrated representation underlies the timing of both hands (Klapp, Nelson, & Jagacinski, 1998; Peters, 1981; Wing et al., 1989).

An alternative explanation for the bimanual advantage has been suggested by Drewing and Aschersleben (Reduced timing variability during bimanual coupling: a role for sensory information, manuscript submitted). They assume that the timing of movements is based on sensory information (see also Aschersleben & Prinz, 1995; Aschersleben et al., in press) and that timing becomes more precise as more sensory information becomes available (Aschersleben, Gehrke & Prinz, 2001; Gehrke, 1996; Mates & Aschersleben, 2000; Mates, Radil, & Pöppel, 1992). During bimanual tapping, the additional hand provides additional tactile-kinesthetic reaferences, increasing the available amount of sensory information and resulting in the bimanual advantage. For example, the timekeeper might use the extra sensory reaferences for better adjustment of timing processes, or by the consideration of additional sensory reaferences in advance. First evidence in favor of this explanation stems from the variation of the availability of additional feedback tones given for each tap (Drewing & Aschersleben, submitted). Timer variance decreased both in unimanual and in bimanual tapping when feedback tones were given, supporting the assertion that more precise timing results from an increasing amount of sensory information. Another experiment, which produced a reduction in the right hand’s timer variance as a result of feedback tones given for the left hand’s taps, demonstrated the integration of sensory reaferences of both hands in timing. These results support the assumption that the bimanual advantage is – at least partly – due to the additional hand’s sensory reaferences.

The present experiments were designed to test this alternative explanation for the bimanual advantage further with regard to tactile-kinesthetic reaferences. In the first experiment, tactile-kinesthetic reaferences were manipulated within one hand, by asking participants to tap with either one or two fingers of their right hand. This experiment is designed to examine whether the involvement of different limbs is necessary for the bimanual (or in this case more accurately “bidigital”) advantage. In the second experiment, the availability of tactile reaferences was varied in two-handed tapping. With one hand tapping on a metal plate the additional hand tapped either contact-free (without tactile reaferences) or on a metal plate (with tactile reaferences). Finally, in the third experiment the temporal differences between the tactile-kinesthetic reaferences of both hands were reduced by placing a firm mechanical coupling between the two fingers.

**Experiment 1**

Our sensory explanation of the bimanual advantage predicts that any enhancement of sensory information will lead to improved timing. This prediction was tested in this experiment by varying tactile-kinesthetic reaferences within one limb. Participants tapped with their right hand, either with the index finger only (unidigital), or with both the index and the middle finger simultaneously (bidigital). We expected a reduction of timer variance during bidigital tapping. Helmuth and Ivy (1996) would have to extend their model to finger-specific timers to predict such a bidigital advantage.

**Methods**

**Participants**

Twelve healthy participants, mostly students, were tested (mean age 24.6 years; 3 males and 9 females; 10 right-handed, 2 ambidextrous).

**Apparatus**

Participants were seated at a table in front of a wooden response board in a sound-absorbing room. Their elbows and palms rested comfortably on the board. Participants tapped on metal touch-sensitive plates fixed to the boards (spaced 10 mm apart). A personal computer collected responses (temporal resolution of 1 ms) and controlled auditory stimuli. Stimuli were presented binaurally through headphones (audio-technica ATH-A5) via a D/A converter card (Data Translation Card DT2821) and an