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Effects of Surrogate Feedback on the Temporal Coordination of Sequential Movements

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by

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Abstract

The human motor system integrates various sources of feedback to increase movement precision. This can be observed, for instance, when lifting an object with the thumb and index finger, where the tactile sensory feedback of the fingertips is being used to control the amount of grip force applied. Other modalities can be used as well (e.g., auditory feedback helps to produce more regular intervals in a tapping task).

In the context of an assistance system for users with sensorimotor deficits, a general question is whether artificially generated sensory feedback can be used as surrogate sensory feedback to enhance movement precision. This thesis examined several aspects of this question by means of a tapping task. Several methods were chosen to evaluate whether the feedback was integrated. Global measures of timing precision (viz., constant and variable error), as well as measurement of the applied force at the tapping movements during the continuation phase were employed.

Furthermore, a well-known model from basic psychological research, the two-level timing model for interresponse intervals by Wing and Kristofferson[1,2], was applied. The two-level timing model distinguishes a central timing structure and the motor implementation processes by partitioning the observed global interresponse interval variance into a central and a peripheral variance component. Recent studies showed that the central timing structure seems to integrate sensory feedback—despite that it was originally assumed as an open loop process. Therefore, it was assessed whether the two-level timing model is also suited to model the influence of surrogate sensory feedback on the timing of movements, and how the variance components are influenced under such circumstances.

Experiment 1 showed that surrogate tactile feedback could be integrated when ap-

[1] Wing, A. M., & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*(1), 5–12.
[2] Wing, A. M., & Kristofferson, A. B. (1973b). The timing of interresponse intervals. *Perception & Psychophysics*, *13*(3), 455–460.

plied on both the finger and the hallux (big toe) with little differences. Experiment 2 extended the findings, showing that the surrogate tactile feedback could compensate for missing sensory reafferences to some extent. However, in both experiments, the estimators of the two-level timing model also showed unexpected behavior, such as an increase of the peripheral variance with target interval. In Experiment 2, it was confirmed that about a third of all trials did not met the model assumptions, which may be the cause for the unexpected behavior. To maintain comparability with a number of studies, the remaining experiments continued to apply the variance decomposition, despite the unmet assumptions.

The remaining three experiments addressed questions which arose during Experiments 1 and 2. Experiment 3 investigated whether the pacing modality could increase the familiarity with the surrogate tactile feedback, if the tapping speed was also given using tactile pacing stimuli instead of audio stimuli. This was not the case. Experiment 4 introduced a systematically varied delay of the surrogate feedback signal in order to manipulate the perceived reliability. The delay manifested in the temporal measures already at the lowest level of delay. Furthermore, the force measures (e.g., amplitudes) indicated that the force regulation was most economic for mid-range values of the delay. Experiment 5 compared the influence of two different modalities (tactile vs. audio) across systematically varied delays. The effects of audio feedback were much more pronounced, on both the temporal and force measures. Furthermore, two different age groups were compared. The older adults generally performed comparable to the younger adults at the temporal measures. The force measures instead showed clear differences between both age groups in general but also regarding the integration of surrogate feedback in particular.

To conclude, the effects found were generally in line with the literature. However, the problematic behavior of the estimators as well as the frequently unmet model assumptions oppose the application of the two-level timing model in this context. For evaluating the effect of surrogate sensory feedback, the global measures of timing precision performed better. Force measures also seemed promising, but require further research to increase understanding prior to application in a practical context.

Zusammenfassung

Bei der Steuerung von Bewegungen verwendet das motorische System verschiedene Arten von Rückmeldungen, um die Präzision zu erhöhen. Dies lässt sich z. B. bei Greif- und Hebe-Bewegungen beobachten, bei denen die taktile Rückmeldung von den Fingerspitzen dazu genutzt wird, die Griffkraft zu regulieren. Dies ist nicht auf gleiche Modalitäten beschränkt – so können z. B. auditive Rückmeldungen dazu genutzt werden, die Variabilität bei einer Tapping-Aufgabe zu senken.

Eine zentrale Fragestellung im Kontext von Assistenzsystemen für Nutzer mit sensomotorischen Defiziten ist, ob künstlich erzeugte sensorische Rückmeldungen ebenfalls dazu genutzt werden können, die Präzision von Bewegungen zu verbessern. In dieser Arbeit wurden verschiedene Aspekte dieser Fragestellung anhand einer Tapping-Aufgabe untersucht. Hierzu wurden mehrere abhängige Variablen genutzt, z. B. globale Maße wie konstanter und variabler Fehler, aber auch Messungen der aufgewandten Kraft bei den Tapping-Bewegungen.

Desweiteren wurde ein bekanntes Modell aus der psychologischen Grundlagenforschung eingesetzt: Das Zwei-Ebenen-Modell (WKM) von Wing und Kristofferson[1,2]. Das WKM teilt die bei rhythmischen Bewegungen gemessene Variabilität in zwei Komponenten auf: Eine zentralnervöse Zeitgeber-Struktur und die motorischen Umsetzung. Neuere Studien zeigen, dass der zentrale Zeitgeber sensorisches Feedback integriert – im Gegensatz zu der ursprünglichen Annahme von Wing und Kristofferson, die den Zeitgeber als offenen Regelkreis annahmen. Daher wurde in dieser Arbeit überprüft, ob sich das WKM eignet, um den Einfluss von künstlichen sensorischen Rückmeldungen auf die Variabilität zu modellieren.

Experiment 1 zeigte, dass künstliche taktile Rückmeldungen sowohl am Zeigefinger

[1]Wing, A. M., & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*(1), 5–12.

[2]Wing, A. M., & Kristofferson, A. B. (1973b). The timing of interresponse intervals. *Perception & Psychophysics*, *13*(3), 455–460.

als auch am großen Zeh integriert werden können, mit lediglich geringen Unterschieden. Experiment 2 erweiterte die Befunde, indem gezeigt wurde, dass taktile Rückmeldungen auch bis zu einem gewissen Grad die endogenen taktilen Rückmelddungen kompensieren können, wenn diese reduziert werden. Jedoch gab es in beiden Experimenten unerwartetes Verhalten der Schätzwerte für zentrale und periphere Varianz. In Experiment 2 wurde bestätigt, dass ca. ein Drittel aller Trials nicht die Modellannahmen erfüllten, was der Grund für das unerwartete Verhalten sein könnte. Um Vergleiche mit anderen Studien zu ermöglichen, wurde das Modell dennoch in den verbleibenden Experimenten angewandt.

Die verbleibenden drei Experimente befassten sich mit Fragestellungen, die während Experiment 1 und 2 auftauchten. In Experiment 3 wurde untersucht, ob sich die Vertrautheit mit den künstlichen taktilen Rückmeldungen steigern lässt, wenn die Vorgabe der Tapping-Geschwindigkeit nicht durch Töne erfolgt, sondern ebenfalls durch taktile Pulse. Dies war nicht der Fall. Experiment 4 führte eine künstliche, systematisch variierte Verzögerung der künstlichen Rückmeldungen ein. Die Verzögerung war dazu gedacht, die Verlässlichkeit der künstlichen Rückmeldungen zu manipulieren. In den Maßen für zeitliche Präzision hatte dies bereits einen Effekt ab der niedrigsten Verzögerungsstufe. Bei den Kraftmaßen war der Effekt am ausgeprägtesten für mittlere Verzögerungsstufen. Die Verzögerung wurde bei Experiment 5 beibehalten, aber zusätzlich wurde neben den künstlichen taktilen Rückmeldungen auch auditive Rückmeldungen verwendet. Dies führte zu deutlich ausgeprägteren Effekten in sowohl den Zeit- als auch den Kraftmaßen. Außerdem wurden zwei Altersgruppen miteinander verglichen. Ältere Probanden zeigten im Ganzen eine mit den jüngeren Probanden vergleichbare Leistung bei den Maßen für zeitliche Präzision. Bei den Kraftmaßen zeigten sich hingegen klare Unterschiede zwischen beiden Altersgruppen.

Zusammenfassend lässt sich sagen, dass die Befunde der Experimente in dieser Arbeit zur Literatur passen. Jedoch sprechen die häufigen Verletzungen der Modellannahmen sowie das unverwartete Verhalten der Schätzwerte für zentrale und periphere Varianz gegen die Anwendung des WKM um den Einfluß von künstlichem Feedback zu modellieren. Hierzu erwiesen sich die globalen Maße als geeigneter. Die Kraftmaße erschienen ebenfalls vielversprechend, bedürfen allerdings noch weiterer Erforschung vor einer eventuellen praktischen Anwendung.

Contents

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Chapter 1

Introduction

Spatial and temporal coordination of movements is essential for a wide range of everyday tasks (e.g. speaking, handwriting, walking, etc.). These examples all require accurate control of movement sequencing and timing—otherwise, the results would be unpredictable.

A common notion is that for the goal of maximizing movement precision, the human motor system includes all possible sources of information. This includes internal state information (such as proprioceptive cues) as well as sensory signals from multiple modalities that arise from the periphery. These sensory signals can be of two origins: a) the result of environmental influences (e.g., temperature) and b) the signals that arise as consequence of self-generated movements—such as the sensation of pressure on the skin when grasping an object (Miall & Wolpert, 1996).

According to the principle of reafference (von Holst & Mittelstaedt, 1950), another source of information is generated by the motor system itself: While issuing a motor command (efference) to an effector, the motor system generates an efference copy of that signal. While the effector executes the motor command, the resulting sensory input (reafference) is generated and compared afterwards by the motor sytem with the efference copy to determine whether there is any deviation. By means of this theory, von Holst and Mittelstaedt were able to explain how organisms can distinguish between sensory input from the environment (exafferences) and reafferences.

It was later noted by Held (1961) that exafferences and reafferences could not be directly compared to efference copies due to their different types (sensory inflow vs. motor outflow), which led to the proposition of two computational mechanisms: *forward models* and *inverse models* (Schröder-Schetelig, Manoonpong, & Wörgötter, 2010). The latter map sensory consequences to a specific set of motor commands

(Wolpert & Ghahramani, 2000). In contrast, forward models allow the motor system to anticipate the sensory consequences of a movement based on an internal efference copy (Shadmehr, Smith, & Krakauer, 2010, Wolpert, Ghahramani, & Jordan, 1995). This perceptual efference copy in turn serves for tuning and continously updating the motor command during movement execution (Desmurget & Grafton, 2000).

Some movements are simply too fast for sensory feedback to be integrated, such as saccades (which typically take less than 80 ms to execute, while the minimum delay needed for a visual or proprioceptive signal to influence an ongoing movement is about 80–100 ms; Desmurget & Grafton, 2000). In these time-constrained situations, *forward models* allow a decent movement performance without relying on sensory feedback.

In other cases, sensory reafferences are integrated into the planning and execution of movements to increase movement precision. In the process, sensory information is often merged from different modalities (e.g., tactile and visual) to create a unique coherent percept (Andersen, Snyder, Bradley, & Xing, 1997). During integration of sensory reafferences from multiple modalities, cross-modal stimuli can be enhanced when they are coherent, but also depressed when they are incoherent (Ursino, Magosso, & Cuppini, 2011). This means that coherent multimodal stimuli increase the total available information based on sensory reafferences, while incoherent stimuli are filtered from the perception to reduce error.

There are situations where sensory reafferences are either entirely not available or only in a reduced form. For instance, when working in environments which demand thick protective wear. In such situations, one reason that can cause problems is that when lifting an object, the grasping force is regulated based on the fine sensation of pressure on the finger tips (Johansson & Westling, 1987). A nice example are space suits for extravehicular activities. The problem of reduced or even missing sensory reafferences in this context is long known and addressed (Bach-y-Rita, Webster, Tompkins, & Crabb, 1987). Bach-y-Rita et al. proposed to collect the tactile information via sensors and offer them in a transformed manner to the user by means of a tactile display (a matrix of pushrods exerting pressure on the skin) around the waist. The idea of using the body surface as an additional means of conveying information in a human-machine context is even older (more than half a century; Gallace, Tan, & Spence, 2007)—still, much of the fundamental limitations on the human information processing of tactile stimuli are largely unknown (Gallace et al., 2007).

Another example of missing sensory reafferences are injuries. Peripheral sensory dysfunction can be a consequence of, for instance, spinal cord injuries or cerebrovascular diseases (mostly stroke; Sullivan & Hedman, 2008). While the pattern of symptoms in stroke patients is highly variable and depending on the location of the affected brain regions, patients with spinal cord injuries typically suffer from loss of motor function and sensation below the spinal level of the injury (Hoschouer, Basso, & Jakeman, 2010).

In all contexts of the above-mentioned examples, it is desirable to not only support and/or restore the motor function, but the sensory function as well. The following section will describe a few examples of supporting systems to restore motor and sensory functionality of disabled persons.

1.1 Supporting Motor and Sensory Functionality

To allow for the support of motor function, the absence of spasticity (permament contraction of muscles) is a requirement. Spasticity is a common sequelae of spinal cord injury—about 65–78% of patients develop a type of spasticity as a consequence of their injury (Adams & Hicks, 2005)—but can be treated well due to a variety of methods available, including medications (Burchiel & Hsu, 2001) and surgical methods (Barnes & Good, 2013).

A second requirement for the successful applicability of assistive devices is a certain amount of remaining motor function. Which specific motor functions are exactly required depends on the type of assistive device used. For instance, a commonly addressed problem is the restoration of grasping ability by means of a mechanical or electrical orthosis (Eriksson, Sebelius, & Balkenius, 1998; Biddiss & Chau, 2007). This can be achieved in a number of ways. One way is a shoulder-driven orthosis, which permits patiens with weak or lacking wrist extension capability a stable and controlled hand position—in this example, the motion of the hand is driven via bowden cables actuated by the contralateral shoulder muscles (Dittmer, Buchal, MacArthur, et al., 1993; Long & Schutt, 1986).

Options other than mechanically driven orthoses include static orthoses, electrically driven orthoses, or functional electrical stimulation (Mulcahey et al., 2004; Rupp, 2008). Static assistive orthoses can be as simple as a leather loop, which is used as an aid to clamp tools (for example, a fork) to the paralyzed hand.

A good balance between flexibility, abilities, costs, and maintainability is offered by electrically driven orthoses: all components are accessible and the total costs are relatively low compared to functional electrical stimulation variants because no surgical measures are required. Furthermore, the advantages include a possible application as therapeutic device during rehabilitation (Stein, Narendran, McBean, Krebs, & Hughes, 2007).

A problem of existing orthotic and prosthetic devices is the lack of adequate sensory feedback: as of 2014, there are no commercially available sensory feedback systems for prostheses or orthoses (Antfolk et al., 2012; Raspopovic et al., 2014), despite a number of proposed ideas. These ideas include visual, auditory, electrical, tactile and vibrotactile stimulation (Tiwana, Redmond, & Lovell, 2012). Additionally, neuroprosthetics offer a method to directly stimulate remaining functionally intact nerves—a method most successfully applied for auditory sense substitution (Leuthardt, Schalk, Moran, & Ojemann, 2006). It was also shown that via intra-neural interfacing, tactile sensations can be induced at different levels of intensity, thereby offering a potential method to transfer sensory feedback from an orthosis or prosthesis (Rossini et al., 2010).

However, according to Tiwana et al. (2012), tactile and electrical stimulation have been proven to be most effective. Moreover, to really benefit the quality of life of a potential user, the prosthesis or orthosis should not only increase the motor and sensory abilities, but also should be designed with usability in mind (i.e., it should be easy to put on and off, combined with good maintainability, etc.). Therefore, in this case, tactile stimulation is preferably compared to surgical implants.

In the case of orthoses in this context, the applied area often has reduced or even missing sensory functionality. Therefore, a transformation to other, still functioning areas of the body, as proposed by Bach-y-Rita et al. (1987), offers a promising perspective. The transferred feedback should also be meaningful, i.e., it should contribute to the functioning of the motor system. The integration of meaningful feedback is crucial for the usability aspect and is a key criterion, which makes an orthotic or prosthetic aid to an assistance system.

Based on these considerations, the German Federal Ministry of Education and Research funded project *GripAssist* was initiated. The project comprised five small and medium-sized businesses as well as two research institutes. The objective was to develop an assistance system for active support of patients with decreased or diminished hand functionality. The target group suffers from partial or complete motor and/or sensory loss of function, which has to be supported or replaced. In terms of sensory support, many aspects have to be considered, such as whether to use mechanotactile or vibratory feedback (Antfolk et al., 2013).

As already mentioned above, a crucial aspect of movements is timing. Tactile feedback is thought to play an important role in the timing of movements (Aschersleben, Gehrke, & Prinz, 2001). From experiments with patients suffering from polyneuropathy (a disease affecting the peripheral nerves), it is known that the absence of tactile reafferences cause changes in motor behavior. For instance, a deafferented patient (AN) participated in a tapping study by Billon, Semjen, Cole, and Gauthier (1996). AN was able to control movements under visual attention, but lacked proprioceptive and tactile sensibility below the neck. Unlike the control group, he increased the tapping force when his vision was occluded. Additionally, in most conditions, he showed greater timing variability than the control group. Billon et al. concluded that peripheral feedback information appears to be necessary for indicating that a movement-produced effect (tap) occurred in accordance with an anticipated timing scheme and, furthermore, that within this feedback, the proprioceptive and/or tactile feedback modality plays an important role.

Another example can be found in a study by Drewing, Hennings, and Aschersleben (2002), where the participants had to execute repetitive finger tapping movements under various conditions. In earlier studies (Helmuth & Ivry, 1996), a bimanual advantage was found: participants produced less variable interresponse intervals when they tapped with both index fingers simultaneously compared to only one index finger. Drewing et al. suggested that the decrease in variability was due to the additional sensory reafferences present when tapping with both left and right index fingers—but more on that in Section 1.2.3 (and in Chapters 3 and 7).

As already mentioned, influence of tactile feedback on the timing of movements is of great interest in the context of sensorimotor assistance. The next section introduces a framework which models the internal processes of a sequential tapping task and therefore should allow for a precise localization and a better understanding of the influence of tactile feedback on the timing of movements.

1.2 Variability in Motor Timing: The Wing-Kristofferson Model

Typical for human motor actions, there is always a certain amount of variability, with timing being no exception. In the analysis of technical systems, variability is undesired in most cases and engineers will try to get rid of it. In the analysis of humans instead, variability can be used to shed light onto the underlying mental processes. Since these processes cannot be measured directly, one has to infer about such processes for example by using formal models of these mental processes.

There are a number of theories trying to explain the origins of the variability of timing in motor behavior (Schöner, 2002; Repp, 2005). This section introduces the origins, idea and basic concepts of one of the more important models, the two-level timing model by Wing and Kristofferson (1973a).

1.2.1 History

More than a century ago, Stevens (1886) found that there was a certain degree of variability in the timing of repetitive movements. He analyzed responses from participants instructed to tap a lever at a fixed pace. The pace was initially given by a metronome. The metronome was halted and the participant had to continue pushing the lever at the same pace—the synchronization-continuation paradigm was born.

Stevens made several important observations at his experiments. For example, although the interresponse intervals produced by the participants were variable to some extent, the participants nevertheless were able to reproduce the pace quite exactly. It was found that the subsequent interval always seemed to compensate its predecessors deviation from the target interval, described by Stevens as "constant zig-zag" (Vorberg & Wing, 1996).

Another important observation was that the interresponse interval length variability increased with the target interval length (i.e., the longer the target intervals, the higher the variability of the length of produced intervals). Taking these findings into account led Stevens to speculations about an underlying structure composed of two distinct levels of control in timing.

Nearly a century later, Wing and Kristofferson (1973a) proposed their model based on these assumptions. In contrast to Stevens, however, they postulated that there was no active error correction—instead, the two timing components were assumed to be statistically independent of each other. This in combination with the negative correlation of successive lags was deemed to be sufficient to abandon the need for an active error correction (Vorberg & Wing, 1996).

The idea of the original model is depicted in Figure 1.1. The production of sequential tapping movements results in a number of interresponse intervals $I_n \ldots I_x$. An assumed central structure, the "timekeeper", generates intervals $T_n \ldots T_x$ for the intended movement onsets. It is assumed that there exists a certain delay between the timekeeper-generated intervals and the observed movement onsets, the so-called "motor delay" M, which is thought to represent peripheral motor implementation (Repp, 2005). Hence, each observable interresponse interval I_n is essentially the sum of a timekeeper generated interval T_n and a motor delay M_{n+1}, subtracted by the previous motor delay M_n.

Thus, the model basically comprises a partition of the observed variances into two components. It has assumptions and requirements, which have to be met, otherwise the partitioning is not justified. For instance, one of the important assumptions is that both components, the timekeeper as well as the motor delay, are assumed to be inherently variable and independent of each other.

As mentioned above, the movements (i.e., the interresponse intervals) can be observed directly, but not the motor delay nor the timekeeper intervals. Instead, if the assumptions and requirements are met, they can be estimated based on the interresponse intervals, as described in the following section.

1.2.2 Estimator Definition

The estimation of specific values from underlying mental processes offers several benefits. First of all, since it is impossible to directly "look up" how the cognitive system works by dissection, one has to build a theoretical model and test hypotheses to gain an understanding about the cognitive architecture. Estimators like those described below offer this possibility, which is one of the most important aspects.

Furthermore, they can also be used for diagnostic purposes. For instance, neurological disorders can be studied by means of these estimators, which can offer new perspectives about function and disfunction of covered processes (Duchek, Balota, & Ferraro, 1994; Harrington, Haaland, & Hermanowitz, 1998). In the context of this

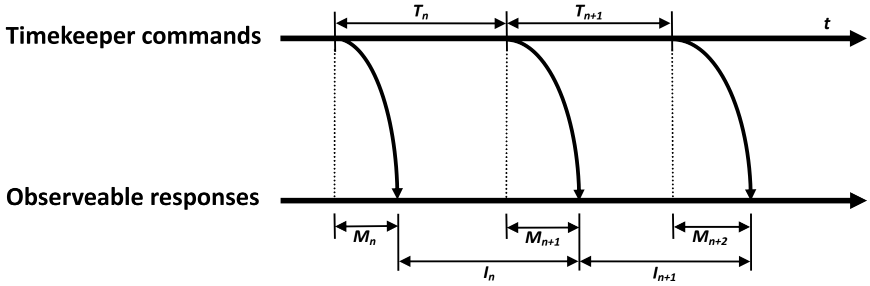


Figure 1.1: Underlying idea of the Wing-Kristofferson model: responses I generated by a central timekeeper T can only be observed through the movements with which they are associated after delays M that arise during the execution of each movement (Vorberg & Wing, 1996).

thesis, the estimators will be used to examine the influence of surrogate tactile feedback on the temporal coordination of sequential movements as well as the process level, at which timing is affected.

The suggested approach by Wing and Kristofferson (1973b) essentially uses the autocovariance function to partition the interresponse interval variability into two components, the variance of the central timekeeper σ_T^2 and the variance of the peripheral motor delay variance σ_M^2. Under certain assumptions (described below), it is possible to assess the variability of both components separately. This section covers the estimation of these two metrics as presented by Vorberg and Wing (1996).

The basic idea of the Wing-Kristofferson model (Wing & Kristofferson, 1973a), as already mentionend and shown in Fig. 1.1, is described in Equation (1.1). The length of an interresponse interval I_n, as stated above, is defined as the sum of the interval produced by both the central timekeeper T_n and the motor delay M_{n+1} of the next interval, minus the motor delay of the current interval M_n.

$$I_n = T_n + M_{n+1} - M_n \qquad n = 1, N \tag{1.1}$$

The variance of the central timekeeper is assumed to linearly increase with target interval duration. This assumption is based on earlier experiments of variability with multiple target interval durations, such as that by Stevens (1886). Vorberg and Wing also note that the finding of linearity in the increase of the central variance is consistent with a timekeeper that waits until a predetermined count of neural events is attained.

Vorberg and Wing assumed independence between the timekeeper and motor subsystems, which is a critical assumption also applied in all analyses within this thesis. As a consequence, all intervals and motor delays are mutually uncorrelated, i.e. $cov(T_m, M_n) = 0$ for $m = n = 0$ and $cov(T_m, T_n) = cov(M_m, M_n) = 0$ for $m \neq n$. The covariance between any two intervals j steps apart can be acquired by inserting Equation (1.1) in $cov(I_n, I_{n+j})$:

$$\begin{aligned} cov(I_n, I_{n+j}) = cov(T_n, T_{n+j}) + cov(M_{n+1}, M_{n+j+1}) - cov(M_{n+1}, M_{n+j}) \\ - cov(M_n, M_{n+j+1}) + cov(M_n, M_{n+j}) \end{aligned} \tag{1.2}$$

Wing and Kristofferson (1973a) assumed that the variances of the motor delay and the timekeeper-generated intervals remain constant within a trial, i.e., $var(T_n) = \sigma_T^2$ and $var(M_n) = \sigma_M^2$ for all n in I_n. Furthermore, the covariance of a variable with itself is defined as the variance. Therefore, the following interdependencies between variances are expected at responses j steps apart and can be described as:

for $j = 0$:

$$\begin{aligned} var(I_n) &= cov(T_n, T_n) + cov(M_{n+1}, M_{n+1}) + cov(M_{n+j}, M_{n+j}) \\ &= var(T_n) + var(M_n) + var(M_n) \\ &= \sigma_T^2 + 2\sigma_M^2 \end{aligned} \tag{1.3a}$$

for $j = 1$:

$$\begin{aligned} cov(I_n, I_{n+1}) &= -cov(M_{n+1}, M_{n+1}) \\ &= -var(M_{n+1}) \\ &= -\sigma_M^2 \end{aligned} \tag{1.3b}$$

for $j > 1$:

$$cov(I_n, I_{n+j}) = 0 \tag{1.3c}$$

Another critical assumption is stationarity. In the context of time-series analyses, weak-sense stationarity means that the covariance between two adjacent interval responses I_{n+j} and I_{n+j+1} does not depend on n, but only on j, i.e., not where the intervals are located within the sequence $\{I_n\}$ but how many steps they are apart within the sequence.

According to Vorberg and Wing (1996), a sequence that fulfills this assumption can conveniently be summarized in terms of its autocovariance function γ, which is defined as:

$$\gamma_I(j) = cov(I_n, I_{n+j}) \tag{1.4}$$

With a tapping sequence that fulfills the two above-mentioned assumption of stationarity and the covariance structure as defined in Equation (1.2), Equation (1.3) can be rewritten as:

$$\gamma_I(j) = \begin{cases} \sigma_T^2 + 2\sigma_M^2 & \text{if } j = 0 \\ -\sigma_M^2 & \text{if } j = 0 \\ 0 & \text{if } j > 1 \end{cases} \tag{1.5}$$

The autocorrelation function ρ, defined as $\rho_I(j) = \gamma_I(1)/\gamma_I(0)$, is essentially a scaled version of the covariance. Like the covariance $\gamma_I(j)$, it should reflect the proposed linear dependence between two interresponse intervals j steps apart in a sequence (Vorberg & Wing, 1996).

Therefore, this function will be used to evaluate the validity of the estimation in the following experiments. According to Vorberg and Wing, the model indicates that successive intervals will generally be negatively correlated, while intervals more than 2 steps apart have a theoretical correlation of zero. For ρ_I by (1.5):

$$\rho_I(j) = \begin{cases} -1/[2 + \sigma_T^2/\sigma_M^2] & \text{if } j = 1 \\ 0 & \text{if } j > 1 \end{cases} \tag{1.6}$$

Vorberg and Wing conclude from Equation (1.6) that if the model holds, the autocorrelation for successive intervals is bounded by:

$$-1/2 \leq \rho_I(1) \leq 0 \tag{1.7}$$

In all of the following experiments (except for Experiment 1), there will be a subsection in the results dedicated to the evaluation of model fit based on Equation (1.7). Tapping sequences where $\rho_I(1) \leq 0$ and $\rho_I(1) \geq -1/2$ will be regarded as fitting to the model assumptions. There are a number of ways to cope with non-fitting sequences (cf. Section 4.2.3 on page 72, where different strategies to cope with tapping sequences violating this criterion will be compared by their effects on the analyses).

The value of $\rho_I(1)$ allows for determination of the source of variability. If $\rho_I(1)$ is closer to zero than -0.5, the central variance is much greater than the peripheral variance. Instead, if most of the measured variability can be attributed to the motor system ($\sigma_M^2 > \sigma_T^2$), $\rho_I(1)$ will be more close to -0.5 (Vorberg & Wing, 1996).

Given a sequence of responses $\{I_n\}$, the actual estimators for the central variance $\hat{\sigma}_T^2$ and the peripheral variance $\hat{\sigma}_M^2$, as used for the analysis in the following experiments, can be derived by Equation (1.5) as follows:

$$\hat{\sigma}_M^2 = -\gamma_I(1) \tag{1.8a}$$

$$\hat{\sigma}_T^2 = \gamma_I(0) + 2\gamma_I(1) \tag{1.8b}$$

Thus, given a series of S particular sequences of length N which contain the inter-response intervals $\{i_{n,s}; n = 1, N; s = 1, S\}$, this means

$$\hat{\sigma}_M^2 = -\left(\sum_{n=1}^{N-1} \frac{(i_{n,s} - \hat{\mu}_{.,s})(i_{n+1,s} - \hat{\mu}_{.,s})}{(N-1)}\right) \tag{1.9a}$$

and

$$\hat{\sigma}_T^2 = \sum_{n=1}^{N} \frac{(i_{n,s} - \hat{\mu}_{.,s})^2}{(N-1)} + 2\left(\sum_{n=1}^{N-1} \frac{(i_{n,s} - \hat{\mu}_{.,s})(i_{n+1,s} - \hat{\mu}_{.,s})}{(N-1)}\right), \tag{1.9b}$$

where

$$\hat{\mu}_{.,s} = \sum_{n=1}^{N} \frac{i_{n,s}}{N}.$$

1.2.3 Influence of Tactile Feedback

Wing and Kristofferson (1973b) originally assumed the process of continuation tapping to be a serial, open loop process (i.e., the movement planning and execution does not consider feedback, for example efference copies or sensory reafferences). However, this assumption was challenged later. For instance, when participants had to use both hands for the tapping task. In such tasks, a bimanual advantage (viz., tapping with both hands leading to a lower variability) is often found (Drewing et al., 2002).

In the earlier mentioned study by Helmuth and Ivry (1996), participants had to tap with the left, right and both index fingers together. Tapping with both hands led to a lower total variance of the interresponse interval length compared to unimanual tapping. Helmuth and Ivry also applied the analysis of Wing and Kristofferson (1973b), which led to a lower central variance in the bimanual condition, while the motor variance remained unaffected. However, Helmuth and Ivry attributed the lower central variance to an interaction of multiple effector-specific timers, referring to this advantage as the *bidigital advantage*.

Instead, Drewing et al. (2002) as well as Drewing and Aschersleben (2003) introduced the notion that the bimanual advantage (reduced central variability) is unlikely due to effector-specific timers (as suggested by Helmuth and Ivry), but instead a result of the additional sensory reafferences. In their studies, the authors employed multiple variants of the bimanual tapping task with varying sensory feedback for one hand. Conditions included audio-feedback and a condition where one hand tapped contact-free, thus generating no tactile reafference. Drewing and Aschersleben postulated that the timer in the two-level timing model does not control motion onsets of the participants movements but rather their expected sensory reafferences. Hence, they termed it the *sensory-goals model* (Figure 1.2). Thus, the model has an identical mathematical structure (described in the previous section), but a different interpretation—it suggests that the timer plans intervals between the sensory movement consequences and makes the time until the sensory consequences available to the motor system (Drewing, 2013). According to Drewing, this time is used by the motor system as control signal for movement endpoint control, which fits the notion of the initially mentioned *forward-models*.

There is also evidence of the influence of tactile feedback on the central timing component in other tasks than tapping. Recently, Studenka, Zelaznik, and Balasub-

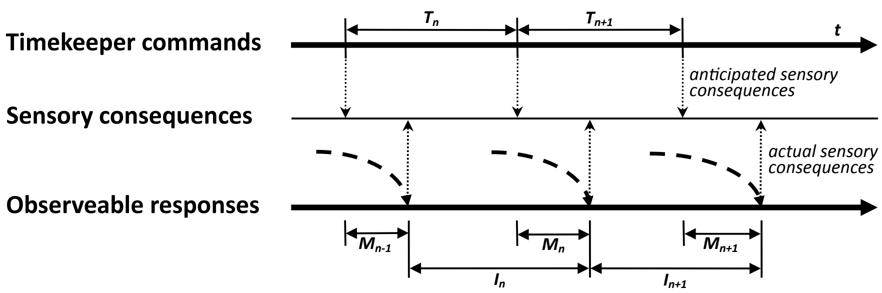


Figure 1.2: Idea of the sensory-goals model: a central timekeeper T generates intervals for anticipated sensory consequences. The actual responses I deviate from these by the motor errors M (Drewing & Aschersleben, 2003).

ramaniam (2012) introducing discrete tactile feedback into a smooth circle drawing task and applied Wing-Kristofferson anaylsis explained above. Studenka et al. concluded that event-based timing is more centrally represented and may be more flexible than the original open-loop concepts, i.e., are influenced by tactile feedback.

The adaption of the two-level timing model suggested by Drewing and Aschersleben (2003) furthermore implies the incorporation of multiple sensory signals, such as audio and tactile signals, which are then combined into a single timing goal by means of a weighted average. This would fit to the concept proposed by Ernst and Banks (2002), that sensory reafferences from different modalities are integrated into a common perceptional construct, with the proportions of the modalities weighted according to their estimated reliability (in terms of low variability). Furthermore, it would be comparable to the multimodal sensory integration described by Ursino et al. (2011). The adaption of the two-level timing model in terms of anticipated sensory consequences would finally fit to the notion of the ideomotor principle (Koch, Keller, & Prinz, 2004).

1.3 Force Control

Apart from the timing of movements, the aspects of force regulation have also been studied several times in combination with tapping tasks. In three experiments, Keele, Ivry, and Pokorny (1987) examined the relation between force control and timing by correlating the variability of force amplitudes measured during tapping tasks to the estimates of central and peripheral variance computed as in Equations (1.8a) and (1.8b). Keele et al. expected a correlation with the peripheral level. Instead, they found that the force control correlated more highly with the central variance.

Due to ambigous data, Keele et al. were not able to determine a clear relation between the two variance estimators and force variability, concluding instead that "force and time appear to have a modest interaction in both peripheral and central stages of motor production."

Newer studies also point out an interdependence between force and timing production in tapping tasks (Inui, Ichihara, Minami, & Matsui, 1998; Sternad, Dean, & Newell, 2000). Therefore, the exerted force during the tapping movements could also be of interest in evaluating the impact of surrogate tactile feedback.

1.4 Study Aims

From both a theoretical and an applied perspective, it is of general interest to see how and at which level certain parameters of the surrogate feedback signal affect the variability of timed motor behavior. For this reason, this thesis is aimed at an evaluation of several aspects of surrogate tactile feedback regarding their effects on central and peripheral variance as well as on the overall timing performance.

One aspect is the effect of the application site of the surrogate tactile feedback. Hence, in **Experiment 1**, the feedback will be applied on two sites (hand and foot) and the effects will be compared.

Another aspect of interest is whether surrogate tactile feedback can serve as replacement if endogenous tactile reafferences are missing. **Experiment 2** introduces a new tapping device, which reduces the tactile reafferences (by requiring contact-free tapping) and a new version of the surrogate tactile feedback to examine this question.

In both experiments, the estimator for the peripheral variance did not behave as expected based on the model predictions. Therefore, the remaining three experiments tested the following aspects:

Tactile Pacing Within Experiment 3, it will be examined whether the tactile feedback has a greater effect when it is used for conveying the tapping speed. Also, only contact-free tapping will be employed in this experiment.

Artificial Delay The tactile stimulators used in the first two experiments differed among others in the activation delay, which could have influenced the results. Experiment 4 was therefore designed to investigate the effect of systematically varied delay on the effects of the surrogate tactile feedback.

Modality and Age Since audio feedback is mostly used in tapping studies with surrogate feedback, Experiment 5 will compare both feedback modalities. Additionally, the effects of both surrogate feedback modalities will be tested across two age groups.

These aims shall be reached by applying an experimental paradigm from basic psychological research, the two-level timing model described above. It will be tested where and how the surrogate tactile feedback influences the central and peripheral processes assumed by (Wing & Kristofferson, 1973a) resp. their successors (Drewing et al., 2002).

One of the main aims of this work is to test whether the two-level timing model is suited to model the influence of surrogate tactile feedback on timing behavior. From a theoretical perspective, this is interesting because it could confirm the bimanual experiments by Drewing et al. (2002), Drewing and Aschersleben (2003) and Drewing (2013) in an unimanual tapping paradigm. Another aim is to test whether the two-level timing model is suited for applied contexts, for instance to test the effectivity of surrogate tactile feedback.

Aside from the sophisticated variability decomposition, typical basic measures of timing performance will also be analyzed. These include the constant error, which means the deviation of the produced intervals from the target intervals, and the variable error, that is, the unpartitioned variance of the interresponse intervals. Again, from both a theoretical and an applied perspective, it is of great interest to see if and to what extent surrogate tactile feedback exerts an influence on these behavioral measures.

Furthermore, the effect of surrogate feedback on contact force of the tapping movements will be measured and analyzed. The force characteristics (amplitude and momentum) could offer an additional window to investigate the underlying mental processes and therefore supplement the evaluation of the effects of additional sensory reafffereces.

The remainder of this thesis is structured as follows: in Chapter 2, the general method is initially explained. This comprises the tests, tasks, materials and analysis methods used in all of the following experiments. Chapters 3–7 report the experiments adressing the specific study aims of this thesis, followed by a general discussion in Chapter 8.

Chapter 2

General Method

This chapter will introduce the common underlying methodological issues of all experiments. The basic task remains the same throughout all experiments: adapt to a given pace and reproduce it as precisely as possible, using movements of the index finger.

2.1 Terminology

Generally, the task will be referred to as tapping task or *tapping*. The sensor housing for the movement recording is called *tapbox* or *tapping device*. The combination of a downward movement of the left index finger, contact on a surface (of course, in case of contact-free tapping, this part is missing) and upward movement again is referred to as *tapping-movement*.

The classical tapping experiments require participants to tap onto solid surfaces. However, in this work, the solid surface was a force sensitive key, made of spring steel. Hence, next to *classical tapping*, it may be referred to as *force tapping*. Experiments 2 and 3 make use of another device that enabled recording of tapping movements without surface contact (Drewing et al., 2002), which is why the conditions employing this device are being referred to as *contact-free* tapping.

An interval between the onset of a surface contact and a successive surface contact is called inter-tap-interval (ITI). The ITI thus incorporates the respective durations of a tap, following upward movement and downward movement. In case of contact-free tapping, there are no surface contacts—in this case, an ITI is defined as the onset of a photoelectric sensor measuring the presence of the index finger in the region close to the lower turning point of the tapping movement and the successive onset.

2.2 Task and Procedure

The main experimental task consisted of a tapping task within the synchronization-continuation paradigm. This specific motor task was invented by Stevens (1886). In this study, Stevens asked his participants to synchronize their finger tapping movements to the speed of a metronome. The metronome was then stopped while the participants had to proceed with their tapping movements as precisely as possible.

The task thus consists of two parts, the synchronization and the continuation phase (Figure 2.1). The synchronization phase comprised 15 pacing stimuli. With one exception, these were tones (1000 Hz sine with a duration of 50 ms). In the continuation phase, 45 taps were counted, beginning with the first tap after the last pacing stimuli and ending with the 46th tap (Figure 2.1).

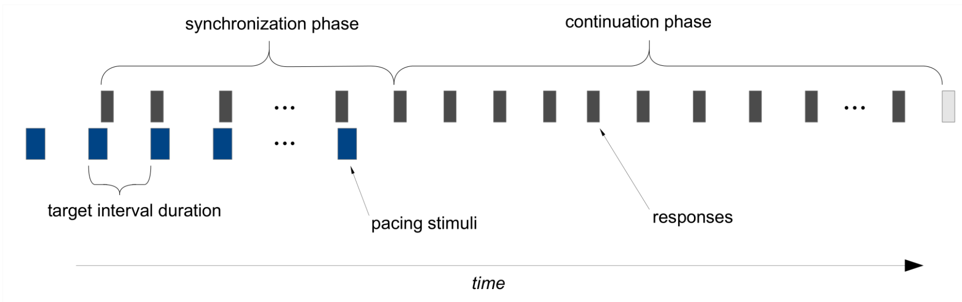


Figure 2.1: Schematic depiction of a tapping trial, showing the definition of both synchronization and continuation phase as well as interval length definition. The actual counts were 15 pacing stimuli and 45 continuation taps.

The participants were instructed to synchronize their finger movements as precisely as possible and to continue as seamlessly as possible. Furthermore, they were instructed to use only their finger joints, while the rest of the fingers had to rest on the ramp around the tapbox. The experimenter controlled for this and reminded participants if necessary. As some participants tend to close their eyes during the continuation phase, the end of a trial was signaled by a different tone (750 Hz with a duration of 50 ms).

Each experiment required the participants to tap at two different speeds. These were predetermined by the target intervals of 250 ms and 500 ms, which corresponds to a frequency of 4 Hz resp. 2 Hz. The shorter interval was chosen to employ a challenging speed. The minimum frequency for ITIs is around 150–200 ms (Repp, 2005), thus

250 ms should still be comfortable. The longer interval was chosen because it is twice as long as the first one and lies within a range of many tapping studies (Repp, 2005), hence, allowing better comparability between this and other studies.

To be able to control for learning effects, the whole factorial combination in each experiment (a block) was repeated four times. Each measure was thereby collected at four different points in time. With the exception of Experiment 5, all blocks were collected subsequently, with a short pause (about 1–2 minutes) between them. The fifth experiment, in contrast, was designed to be conducted on two seperate days.

After the last block, a questionnaire collecting demographic information as well as the amount of musical experience had to be answered by the participants. Previous to the main task, there were a number of pretests, which will be introduced in the following subsection.

2.2.1 Pretests

The pretests were conducted for several reasons, at first hand to gather information about the homogeneity of the sample population. They ensured a certain level of tactile sensibility as well as hand agility. Experiments 1 and 5 employ between-subject factors; therefore, the pretests were also used to compare both subject groups.

As mentioned in the introduction, the tactile sense seems to be incorporated by the motor system to improve timing precision (Drewing & Aschersleben, 2003). According to the authors, multiple sources of haptic information (in this case, left and right index finger tips) are used for increasing the precision of the internal timekeeper.

To determine the actual sensibility of the participants skin, two pretests were conducted: the Semmes-Weinstein monofilament test and the two point discrimination test. The reason for conducting both tests are twofold. First, the tests can be used to indicate whether a participant was suited for the experiment (i.e., no deviation from "normal" levels of tactile perception). Second, the test results could also be employed as covariates to further clarify the actual dependent measurements—however, due to the relatively homogenous results, this was not pursued further.

Touch Pressure Threshold

Used by neurophysiologists to assess "within normal limits" sensory function and by clinicians to detect abnormal sensibility and detection threshholds (Bell-Krotoski, 2011), the touch-pressure threshold test using nylon monofilaments developed by Sidney Weinstein and Josephine Semmes is a viable option to objectively assess tactile sensitivity (Weinstein, 1993). It was used throughout this thesis as measure of touch-pressure threshold, with the exception of Experiment 1—because of delivery problems, the test was not yet available when testing had already commenced.

The test involves the use of a set of nylon monofilaments of defined length (38 mm) and a range of different diameters (Figure 2.2). Each of the nylon monofilaments is marked with a three-digit number (Figure 2.3). These numbers indicate the exerted force as representation of the logarithmic function to the base 10 in tenths of milligrams (Dellon, Mackinnon, & Brandt, 1993). The nylon monofilaments are steadily being held against the test site, with increasing pressure, until the nylon monofilament bends. The nylon fiber material maintains its characteristics for a long time, so that the level of actual exerted pressure remains stable and reliable. Wear can be detected easily, because a worn fiber won't go back in a straight shape but stay bent. Also, the elastic properties of the material dampens the inevitable vibrations of the examiner's hand (Bell-Krotoski, 2011).

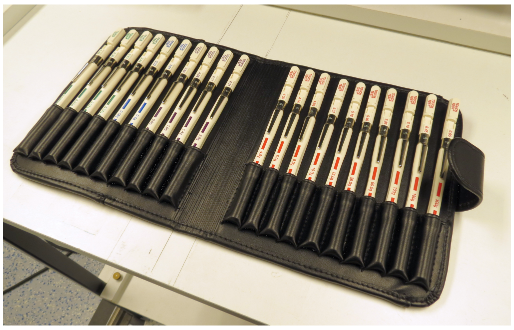


Figure 2.2: Full 20-piece set of Touch Test® monofilaments.

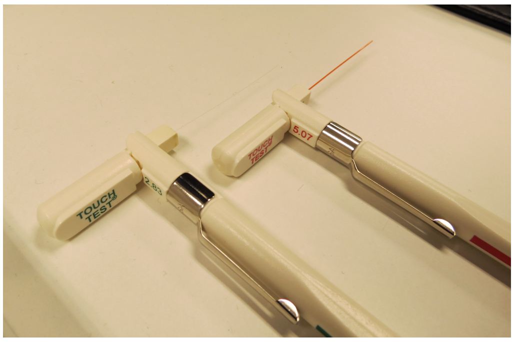


Figure 2.3: Frequently encountered monofilaments (2.83 and 5.07).

The test was introduced to the participants with a demonstration using a thick monofilament, also to ensure participants that the monofilaments do not hurt. The test then commences with the thinnest monofilament and progresses to monofilaments of increasing diameter, until the participant can identify the touch. The monofilaments are always applied perpendicular to the skin, with an approaching duration of 1 to 1.5 seconds, a pressure duration of about 1 to 1.5 seconds, and a lifting duration of also 1 to 1.5 seconds. When a filament has not been recognized by the participant, it will be tested again for a maximum of three repetitions before switching to the next monofilament size.

For the purpose of this thesis, a full hand or foot screening was not necessary. Thus, the tested spots were the center of the right fingertip, since this finger was used for the tapping movements. The left finger tip was used as control measurement. Additionally, the center of the left big toe was tested, because the surrogate tactile feedback was applied at this location. For the index finger tests, the forearm was laid onto a towel while sitting on a table. The toe test was conducted while the participant sat, the leg extended and the foot resting on a swivel chair. After the demonstration phase using a single monofilament, the eyes were occluded.

Two-point Discrimination

Threshold tests like the Semmes-Weinstein monofilament test do not measure end-organ innervation density. Hence, they alone are not sufficient to allow for the conclusion of "normal function". To gain a better representation of the participants sensibility, the two-print discrimination test was employed. This test was invented by Weber (1835) and is a classic test of sensibility used by hand surgeons over several decades (Bell-Krotoski, 2011).

The two-point discrimination test was conducted using a testing device with several pairs of rounded tip points (Figure 2.4). The distance between the tip points varies among the different pairs in steps of 1 mm. The tips were applied to the finger tips, while the participant's hand rested on a towel. The participant then had to respond whether she or he recognized one or two tips. Additionally, the testing instrument possesses a single rounded tip used for catch trials.

Similar to the Semmes-Weinstein monofilaments, this test was also conducted on both index finger tips and the left big toe. The posture remained the same (seated, hand testing on a table, foot testing on a swivel chair) and the eyes were also occluded. The testing commenced with short distances (2 mm). The distance was then increased stepwise, until the participant reported feeling two tips. As the standard staircase testing procedure (Cornsweet, 1962) requires, the direction then changed and it was tested downwards, starting from a large distance (5 mm wider than the distance of the last trial), shrinking until the participant reported feeling only one tip. This procedure

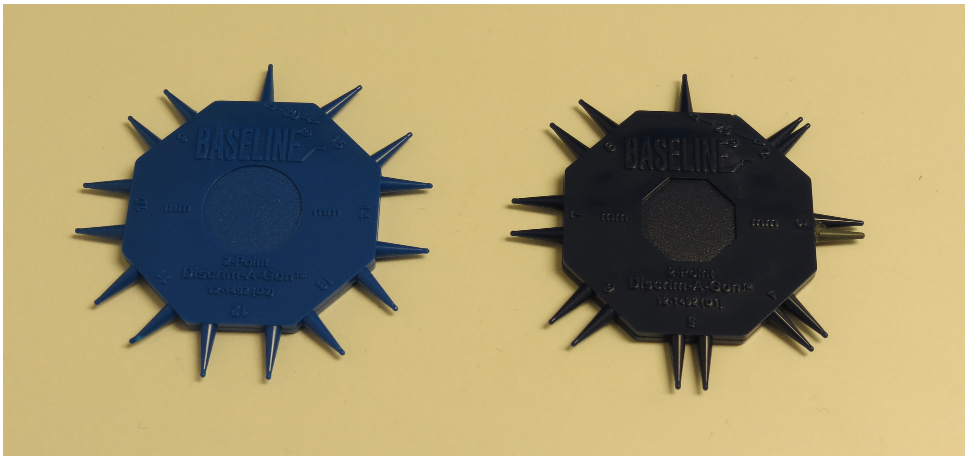


Figure 2.4: Baseline® 2-point Discrim-A-Gon used for the assessment of the finger innervation density. With these two, a range of 1 mm to 25 mm can be tested.

was repeated twice, the mean of all trials was used as definitive result. Experimenters also introduced random catch trials using the single tip during all phases.

A downside of this test is the hand-held related force variability, since the tip points are stiff and do not possess dampening capabilities like the monofilaments. This limitation can be best overcome by using the same instrument and, of course, the same experimenter. Thus, in combination with the Semmes-Weinstein monofilament test, the use of the two-point discrimination test leads to a comprehensive picture of the participants tactile sensibility.

Finger Opposition Test

As a general measure of the general motor coordination ability, the Finger Opposition Test was conducted as a pretest to the actual experiment. It is a frequently used diagnostic tool in clinical assessment of fine motor abilities (Stich & Baune, 2011, Larkin & Cermak, 2002).

The task basically requires the participant to oppose the tip of the long fingers of the right hand with the thumb of the right hand. A variant of the task as found in many neuroimaging studies concerning motor skill acquisition (Ungerleider, 1995, Korman et al., 2007) was used. The sequence started with the little finger, followed by the index finger, ring finger, and middle finger (Figure 2.5 on page 35). This sequence had to be executed as many times as possible within 30 seconds. The sequence was explained to the participants until they were able to consecutively complete three correct sequences.

A Logitech C920 webcam facing at the right hand was used to record the 30 seconds for the purpose of counting. The number of correctly completed sequences was counted, as well as the number of incorrect sequences.

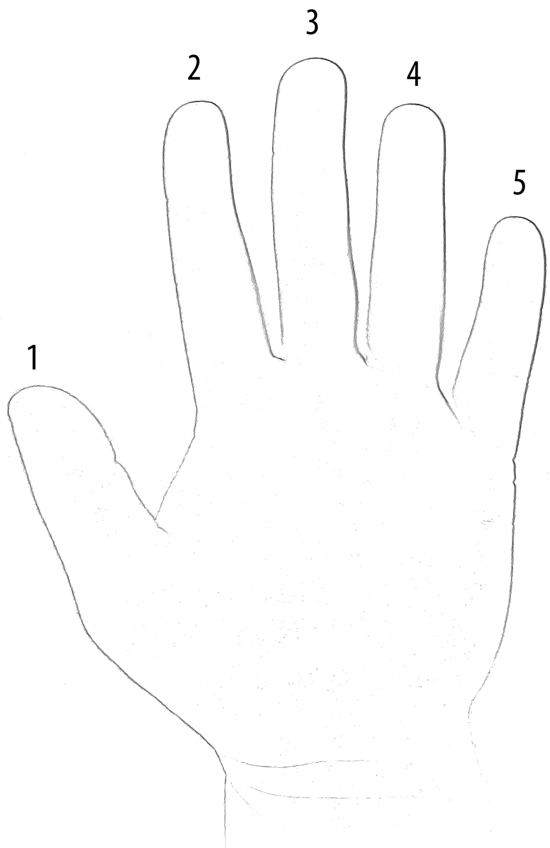


Figure 2.5: The order of the finger-to-thumb movements during the finger opposition test was D1-D5, D1-D2, D1-D4, D1-D3. These four movements constitute a complete sequence. Although the Figure shows the palmar side of the left hand, the movements were executed with the right hand.

2.2.2 RSME

After each factorial condition, the rating scale for mental effort (RSME; Zijlstra, 1993) was used to assess the participants' perceived level of invested mental effort. The rating scale for mental effort is an univariate scale, represented by a continous line ranging from 0 to 150 mm and has nine descriptive indicators along its axis (Capa, Audiffren, & Ragot, 2008). Every 10 mm there is a dash on the continous line. According to Zijlstra, the scale represents a valid and reliable indicator of workload and information processing during the execution of a task. It can also serve as a control measure of subjective fatigue (Van der Linden, Frese, & Meijman, 2003).

2.3 Apparatus

This section considers the setup used for measurement of the taps. The basic design of the original *tapbox* (Figure 2.6 on page 37) already existed and has already been used in a master's thesis and for bimanual tapping experiments.

2.3.1 Tapbox

The original model was connected via parallel interface to a PC. Because of the multitasking layout of modern operating systems, maintaining timing consistency can be quite challenging. Furthermore, the modifications on the original design (the added force key, cf. section 2.3.2) made it necessary to use an analogue-to-digital-converter (ADC). Therefore, the tapbox interface was modified and now polled by the ADC. The ADCs used within these studies were equipped with hardware-timers. When the voltages were acquired using streaming mode (i.e., voltage samples being collected at a high frequency and then delivered to the PC in bulks of queued packages), the timestamps were already set by the ADC—thereby profiting from the benefit of using a dedicated hardware-based system. The PC was completely relieved from timestamp-generation duty.

The ADCs used in the experiments were the U12 and U6 by *LabJack*, both connected via USB. The first experiment relied on the U12, which allowed for a maximum sampling rate of 1.2 kHz and a resolution of 12 bit. However, because two channels had to be scanned simultaneously (photoelectric sensor as well as the force key), the sampling rate was limited to 600 MHz per channel. In Experiments 2–5, parts of the

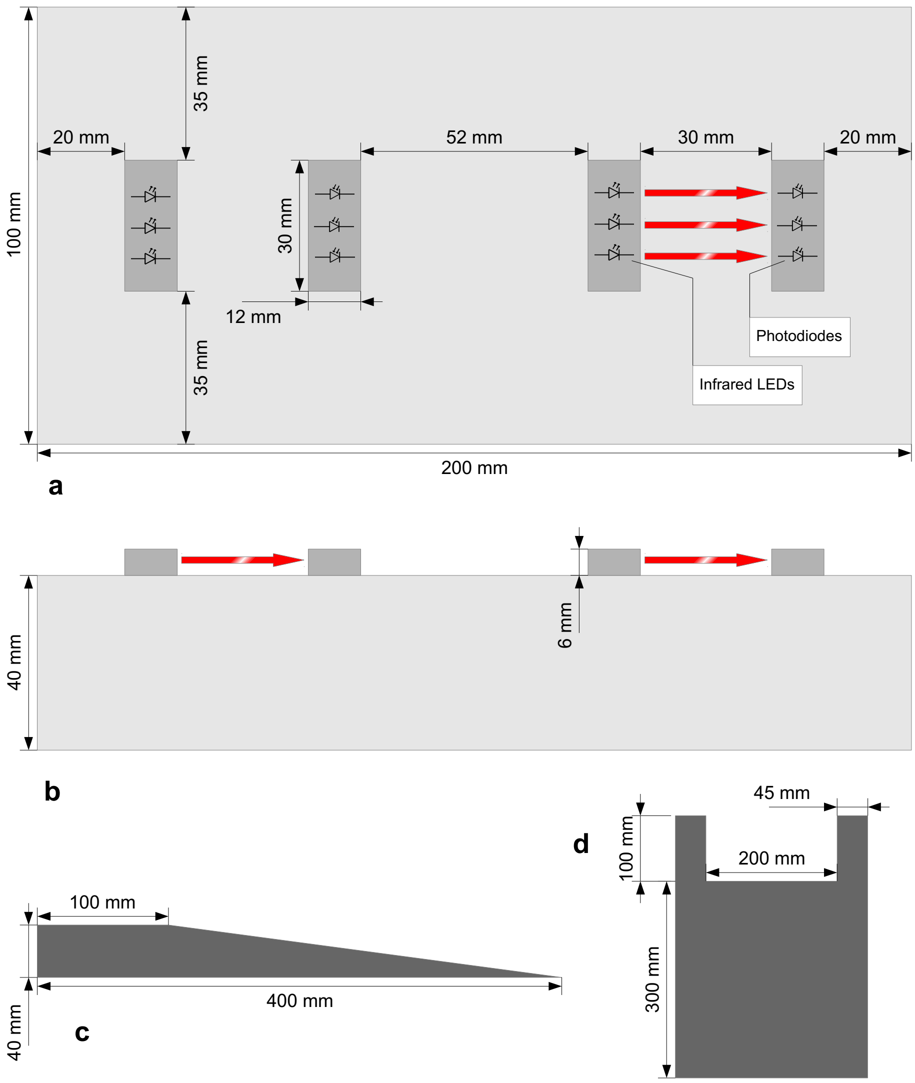


Figure 2.6: Schematic drawing of the original tapbox. a) top view: on both tapping areas, three photodiodes are mounted facing three infrared LEDs, creating an overlap which reduces the chance of unrecognized taps. b) front view: the photodiodes are mounted roughly 3 mm above the surface. c) lateral and d) top view of the ramp constructed as arm rest. The original model shown here did not include a force key, which has later been fitted at the area covered by the right photoelectric sensor.

experimental setup had to be controlled by the PC during the course of the experiment. Both of the ADCs also offer digital-to-analog (DAC) capabilities, which could be used for these tasks. Because of the better analogue input quality of the U6 (16 bit resolution, sampling rate up to 50 kHz), the U6 was set as main ADC for the purpose of data acquisition, with the U12 now serving as dedicated DAC to control the experimental setup.

2.3.2 The force key

For the experiments described in the following chapters, the original tapbox was fitted with a force key to collect data about the forces applied during tapping movements. The force key basically consisted of a piece of spring steel, fitted with a strain gauge. When pressure is applied onto the tip of the force key, the spring steel is slightly deformed (10 N will cause a displacement smaller than 1 mm). The strain gauge is glued tightly to the surface of the spring steel, so that it is also affected by the deformation. The deformation of the strain gauge leads to a change of its electrical resistance, which can be measured. At the beginning of each session, the force key was calibrated by several reference weights.

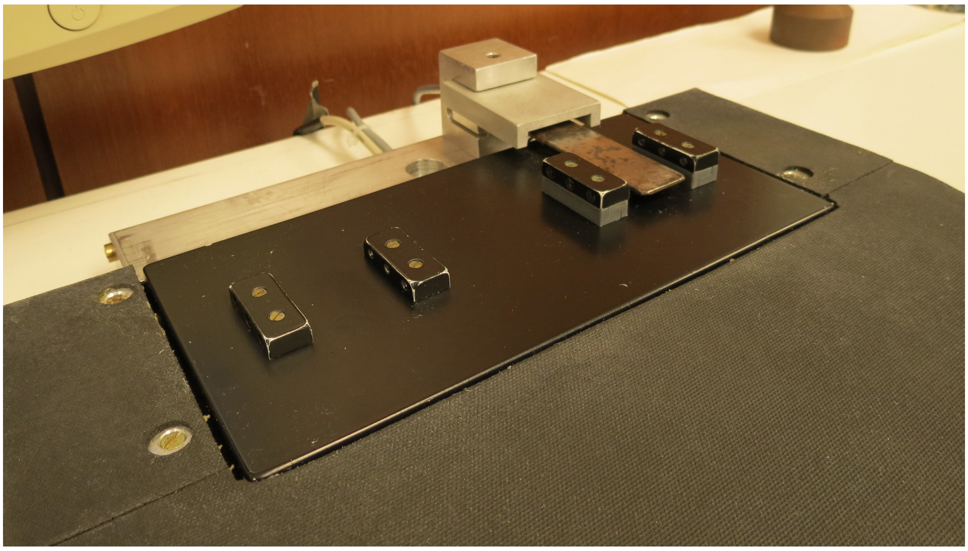
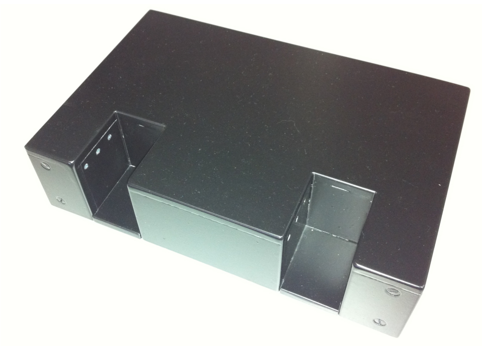
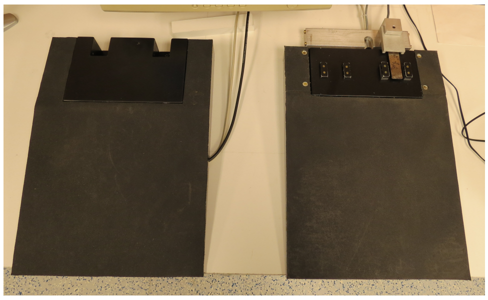


Figure 2.7: Picture of the modified tapbox. The LEDs and photodiodes of the photoelectric sensor have been raised to allow the installation of the force key.



(a) The tapbox for contact-free tapping.



(b) Both tapboxes with ramps.

Figure 2.8: Pictures of both tapboxes. (a) shows the tapbox for contact-free tapping without the additional ramp. On (b), both tapboxes are shown in a side-by-side comparison. The constructions were not fixed on the table to allow a certain level of adaptation to the physique of the participant.

2.3.3 Contact-free Tapbox

When assessing the influence of an additional form of tactile feedback, a major problem is the confounding influence of the natural sensory reafferences. This is basically the problem with every sensory modality, whether visual, auditive, tactile or kinesthetic—all can influence the results to some extent and make inference hard or impossible at all. However, the coexistence of a sensory reafference on the same modality is especially challenging.

The auditive modality can be controlled for relatively easy by presenting white noise over headphones, visual stimuli can be suppressed by occlusion of the eyes. The tactile and kinesthetic reafferences instead are more difficult to control. A sedation is not desirable as it changes the motor characteristics of the effector—not to mention the additional ethical considerations. Hence, the kinesthetic sense remained untouched. However, the tactile sense, in particular, could be eliminated by technological means, as the same movements can be executed but without surface contact.

To allow for contact-free tapping movements, another tapbox (Figure 2.8a) has been developed. The electrical components and layout remained the same. The chassis, however, was modified to allow tapping movements as similar as possible to the original tapbox, but without a surface contact of the finger at any time.

2.3.4 Verification

The experiment was controlled using a PC with a 3 GHz quad-core CPU and the Microsoft Windows 7 (x64) operating system. The experimental software for controlling the experiment as well as collecting the data (consisting of voltages and timestamps) was written in Python 2.7.3, using PyGame 1.92a0. Originally, PyGame was used for timing during data acquisition via parallel interface; since the introduction of LabJack ADCs for data acquisition (cf. Section 2.3.1), it was only used for the user interface.

A Thurlby Thandar TG1304 programmable function generator was used to verify instrument integrity. The function generator was integrated into the system in place of the tapbox. There, it generated ideal square waves of 2 Hz and 4 Hz. The acquired data samples were analyzed to determine the accuracy of the setup. A system-induced variability $\leq 0.1\,\text{ms}^2$ was measured, which was deemed sufficient.

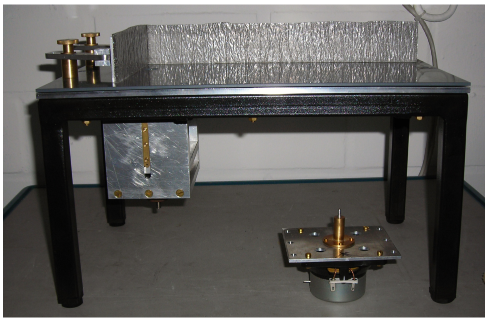
2.3.5 Surrogate Tactile Feedback Stimulator

The first version of the surrogate tactile feedback consisted of a wooden box for the surrogate tactile feedback. The box was equipped with a simple magnetic plunger, located at the edge of the box, beneath the left big toe resp. the index finger. During the tapping task, participants had to place their bare left foot (or their left hand, depending on the factor Locus). The box was about 14 cm high, the other foot was placed on a dummy to compensate for the height.

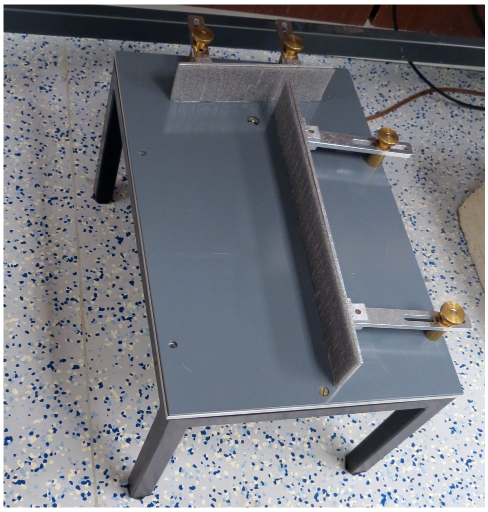
The magnet was active in half of the trials of the experiment (feedback conditions). There were no clues about when the magnet was active. When voltage was applied (triggered by the light barrier of the tapbox), the magnetic plunger moved upward until it knocked the skin.

The duration between voltage application and skin contact was around 12 ms. This was considered as too long. Therefore, this device was only used in the first experiment. For experiments 2–5, a new version was constructed.

The new version of the feedback stimulator (Figure 2.9) was based on a loudspeaker. A lightweight alloy plunger was mounted on the membrane of the speaker. End stops were fitted to protect the system from mechanical damage. Upon activation, the amplitude of the plunger (about 5 mm) was reached in less than 2 ms. To ensure reliable stimulation, the speaker was individually adjusted to a distance of about 1 mm between the tip of the plunger and skin surface of the left big toe.



(a) Side view and spare unit.



(b) Top view.

Figure 2.9: Pictures of the new tactile stimulator. a) the lateral part of the setup with height adjustment as well as a replacement unit. The feet was first positioned by adjusting both guidance plates (b). Afterwards, the height of the speaker was set so that a reliable skin contact is guaranteed.

2.4 Processing and Analysis of Behavioral Data

This section covers the methods employed to prepare and analyze the data acquired by the PC, which comprised the timing data as well as the force data. All statistical calculations were performed using the statistical computing environment `R` (R Core Team, 2016) along with the packages `afex` (Singmann, Bolker, & Westfall, 2015) for repeated-measures ANOVA, `Rmisc` (Hope, 2013) for descriptive statistics, `multcomp` (Hothorn, Bretz, & Westfall, 2008) for post-hoc testing, and `coin` (Hothorn, Hornik, van de Wiel, & Zeileis, 2008) for the Wilcoxon signed-rank test. In all plots, error bars depict 95% confidence intervals for within-subjects designs (Morey, 2008).

Unless stated otherwise, the behavioral data was analyzed using repeated measures ANOVA as provided by `afex`. In case of more than one observation per cell, the analyis function used for the computation of the ANOVA (`aov_ez()`) automatically aggregated the data using the mean. Post-hoc tests were done using Tukey's HSD and Bonferroni-Holm adjusted p-values. Correlations and t-tests were obtained by first aggregating the dependent variables of interest over subject id and then submitting them to the analysis functions (e.g., `cor.test()` or `t.test()`).

As recommended by Osborne and Overbay (2004), outliers have been removed from the analysis to increase accuracy and decrease errors of inference. The criterion employed for outlier identification was 2 SDs. Due to the requirements of a balanced design for the analyis, ouliers have been replaced with participant means. As measure of effect size, generalized eta squared (η_G^2; Olejnik & Algina, 2003) was used because its value is comparable across studies that incorporate the factor and outcome of interest, regardless of whether the factor is between or within subjects (Bakeman, 2005).

The timing data consist of the ITIs as measured by the photoelectric sensor. Timing data was evaluated based on four measures described in the following subsection: the constant error, the variable error and the estimators for central as well as peripheral variance. All measures were computed for a complete tapping trial, thus one continuation phase at a time. The analysis was based solely on the continuation phase, synchronization data was not further analyzed. The first three taps were omitted to exclude possible artifacts by the transition from synchronization to continuation phase, analogous to other tapping studies (e.g., Drewing et al., 2002).

2.4.1 Constant and Variable Error

Common measures used in measuring movement accuracy include the constant and variable error. The constant error is the mean deviance of the produced ITIs from the target interval T. In a sequence S with length N of intervals i, thus $\{i_n; n = 1, \ldots, N\}$, the constant error CE_c is

$$CE_S = \sum_{n=1}^{N} \frac{i_n - T}{N}.$$

The variable error is a measure of consistency and precision. High precision is indicated by a small variable error (typically the standard deviation or variance; Kandil, Diederich, & Colonius, 2014). In this thesis, the variance was used as dependent variable to compute the ANOVAs, essentially because the distribution of the variances fitted to the requirements of the ANOVA and transformation of the results was thus not necessary. The variance calculated with Bessel's correction applied (Lakens, 2013) consists of the squared deviation of each sample from the mean ITI, thus for the above-mentioned sequence S, the variable error s^2_{N-1} is

$$s^2_{N-1} = \sum_{n=1}^{N} \frac{(i_n - \mu_S)^2}{N-1},$$

where

$$\mu_S = \sum_{n=1}^{N} \frac{i_n}{N}.$$

For better comparability with a broader range of literature, the variable error is additionally stated using the standard deviation s_{N-1}, calculated as follows:

$$s_{N-1} = \sqrt{\sum_{n=1}^{N} \frac{(i_n - \mu_S)^2}{N-1}}.$$

2.4.2 Wing-Kristofferson Analysis

This section describes the methodological issues during the collection of appropriate tapping sequences. For the derivation of the estimators of central and peripheral variance, refer to Section 1.2.2.

The computation was carried out by a Python script, employing parallel processing to speed up the computation. Only ITIs which passed the "quality check" (i.e., that lay between 0.5×Target Interval on the lower bound and 1.5×Target Interval on the upper bound) were considered during model computation—consinstent with other studies, for instance, by Helmuth and Ivry (1996).

Furthermore, the results have been screened for drift (i.e., the length of interresponse intervals increasing with the position within the sequence), since this would lead to errors in the estimation of the central and peripheral variance (Vorberg & Wing, 1996). Next to visual inspections of the data, this was achieved by splitting the sequences in halves and the encoded factor was introduced to an ANOVA computed on the mean interresponse interval durations.

2.4.3 Force Analysis

The taps were not only measured in terms of triggering the photoelectric sensor, but also by means of the force key, so that the force, which was applied during tapping could be analyzed. Analysis was carried out after the raw data from all participants had been collected.

Data Preprocessing

Sampling rates and filtering Within the first experiment, voltages from the force key were sampled at 600 Hz. Later, the hardware changed and sampling rates in the range of 2 kHz to 5 kHz were used.

The higher sampling rates revealed a distortion in the force measurement (Figure 2.10). A closer look at the baseline (including plotting and counting wave cycles by hand) allowed for the identification of the frequency as a rough sine of about 162 Hz. The origin of this disturbance remained unclear.

To clean up data, a 4th-order Butterworth lowpass filter with a cutting frequency of 150 Hz was applied during post-processing (dual-pass). Tests on several participants' data sets showed that this effectively removed the disturbance from the data, but retained the original characteristics. The only drawback was a small filtering artifact at the beginning of each tap, in form of a slight local minimum preceding each tap. However, since the boundaries of each tap are defined by the voltages of the photoelectric sensor, this artifact was not considered within the analysis.

Drift Detection and Compensation The measured voltages from the force key were found to be influenced by drift, presumably originating from the bridged amplifier. The drift characteristics varied across the different participants, typically showing the biggest deviation on the first participant in the morning. On participants, which were tested later in the daytime and with the experimental equipment already running a few hours, the voltage remained nearly constant.

Originally, it was planned to compensate for a possible drift by conducting reference measurements before and after each experiment. With the non-linearity of the drift becoming apparent, this seemed no longer appropriate.

The original plans included a spectral analysis of the amplitudes over time. Spectral analysis has been employed frequently in the analysis of tapping tasks (e.g. Delignieres, Lemoine, & Torre, 2004; Liu, Forrester, & Whitall, 2006; Rigoli, Holman, Spivey, & Kello, 2014). Therefore, a more complex method for drift detection was employed. An algorithm picked every thousandth sample from the raw data.

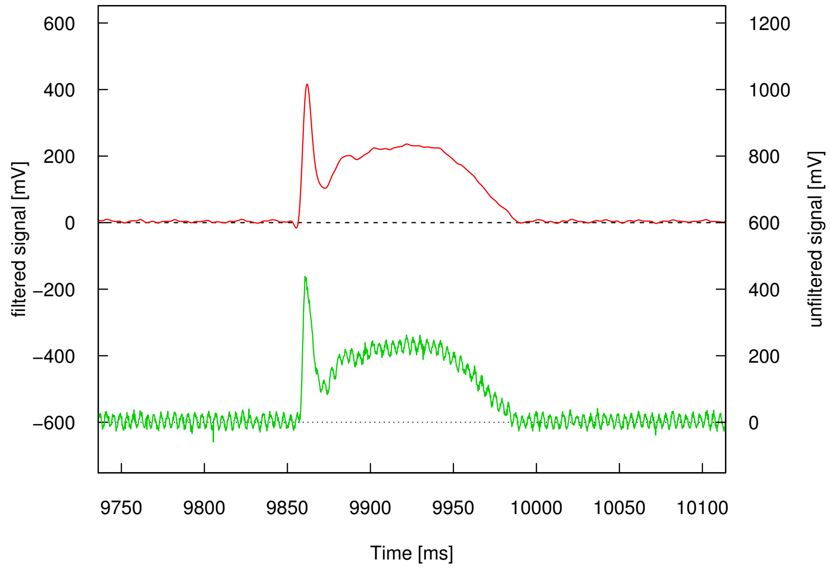


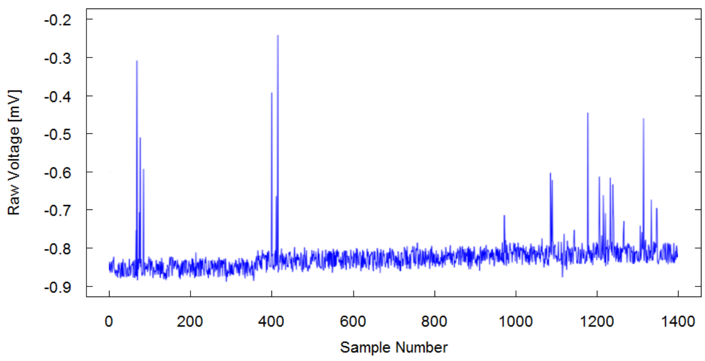
Figure 2.10: Graphical depiction of a tap by means of the voltage measured by the force key. The raw data is shown by the green line, the red line shows the data after lowpass filtering. Note that the offset of the raw data has been shifted downwards by 600 mV to improve comparability.

After checking that the sample did not lay within a tap, the baseline data were used to fit a basis spline (Figure 2.11 c). This estimation of the drift function was then subtracted from the raw data before further processing.

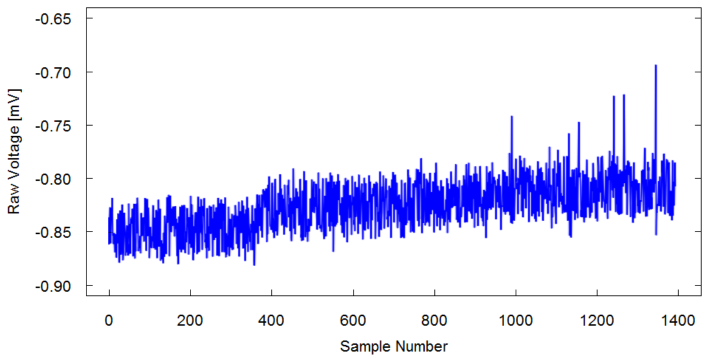
Parametrization

Within the first experiment, the only parameters being extracted from the force data were relatively basic: the mean of all data points collected within the boundaries of each single tap, as well as the peak value of each single tap. This allowed for rough estimates of the overall effects of feedback on force application.

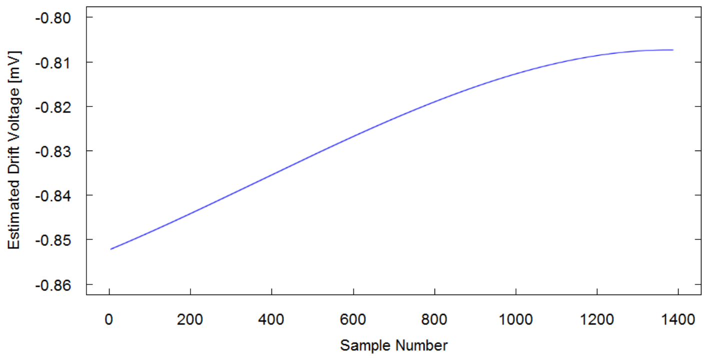
However, a closer inspection of the data revealed a variety of inter-individually different characteristics of the force-curve over time. Therefore, a more sophisticated analysis of the data was implemented. The method was based on the finding of Cong-Khac (2012), that the force-curve of taps basically consist of two components: an initial peak, followed by a more flat and steady part.



(a) Extracted baseline—still with taps.



(b) Extracted baseline—clean.



(c) Basis spline representing the drift of one experimental session.

Figure 2.11: Drift detection within the raw data of a single participant. Samples were taken from the baseline, while ensuring that there were no taps in it, a sample still containing taps is depicted in Subfigure (a). Subfigure (b) shows the proper baseline, which was used to fit the basis spline (c) representing the drift for the respective participant. Note the different scaling of the y-axes.

Similar to Cong-Khac, each tap was split into two segments (Figure 2.12). However, the algorithm used to identify the segments as well as the extracted measures were different. At first, the tap border points L1 and L3 as well as the local minimum L2 were determined. As an additional criterion for the localization of L2, a minimum duration of 15 ms was assumed for the first segment. The local maxima M1 and M2 were then determined for each segment.

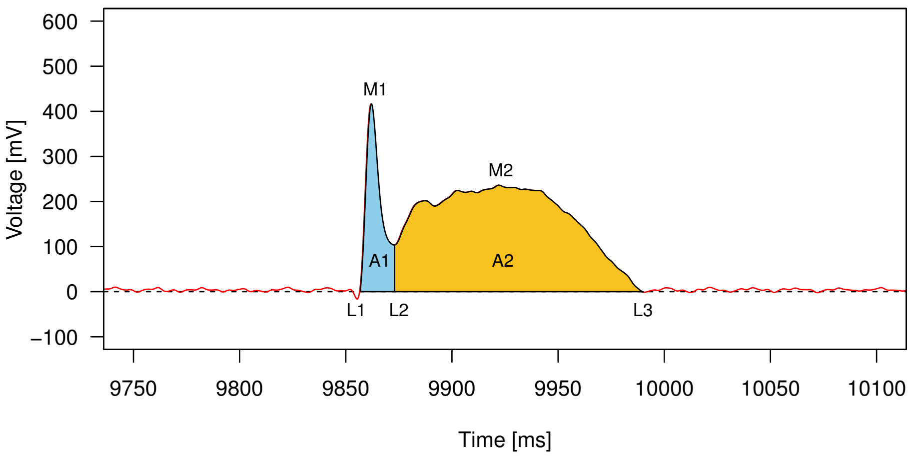


Figure 2.12: Parametrization conducted on every single tap. The taps were divided into two segments (blue and yellow shaded area). Within each segment, the local maxima (M1 and M2) were then detemined, followed by areas A1 and A2 (integration using the segment durations L2-L1 and L3-L2).

Furthermore, the duration of both segments was determined using the points L1, L2, and L3. The duration was then used to integrate the voltage to allow for a measure which comprises the segment duration as well. Simpson's rule was used to compute the numerical approximation of the definite integrals A1 and A2 (Figure 2.12).

If the algorithm failed to properly identify the features, the respective tap was dropped and not considered during further analysis. An exception would be raised in case there were more than 10 dropped taps—however, in all collected taps (up to 7200 per participant, depending on the experiment), this never happened. Another benefit of this method was that each tap can be analyzed seperately (as opposed to aggregation over a tapping trial in the first experiment), thereby offering enhanced statistical power. However, prior to statistical tests such as ANOVA, the data were still automatically aggregated per subject and cell of design.

Chapter 3

Experiment 1: Influence of Feedback Location

This experiment was designed to investigate the effects of additional surrogate feedback on the temporal coordination of sequential motor actions. The two-level timing model suggested by Wing and Kristofferson (1973a) was chosen as theoretical framework (Vorberg & Wing, 1996; Repp, 2005) since it is an established paradigm, which may allow to differntiate at which level the surrogate tactile feedback affects the temporal coordination under certain circumstances. Therefore, participants performed a tapping task with or without additional feedback under two different tapping speeds.

3.1 Introduction

The primary objective was to test the influence of surrogate tactile feedback on the components of the two-level timing model. It has been shown that tactile information from the fingertips contributes to movement timing accuracy (Goebl & Palmer, 2008). Based on the notion of Drewing and Aschersleben (2003), who offered auditive feedback in addition to the endogenous tactile-kinaesthetic feedback, it was expected that the additional sensory reafferences on both locations lead to a decreased central variance.

For bare anatomical reasons, sensory signals take more time to propagate from the foot to the brain than from the hand to the brain. The length difference from the hallux (big toe) to the brain compared to the digitus secundus (index finger) is approximately 70 cm for a male european with a height of 184 cm. Given a medium nerve conduction velocity of $44.3\,\mathrm{m\,s^{-1}}$ for the legs innervation and a velocity of

$54.3\,\mathrm{m\,s^{-1}}$ for the arm (medium values of a population of scandinavian workers, age 30–39, Davis-King, Sweeney, Wille, Steenland, & Arezzo, 1992), a length of approximately 110 cm from the finger tip to the atlas vertebra (C1) and a length of 180 cm for that particular male, signals from the fingertip will take around 20 ms to C1. Signals from the hallux to C1 instead take around 40 ms, therefore yielding a theoretical signal transit time difference of ca. 20 ms between the two extremities. In terms of the negative asynchrony, taps produced by using the foot precede taps of the hand by about 20 ms (Aschersleben & Prinz, 1995), thus fitting well to the theoretical calculations made above. From a theoretical perspective, it will be intersting to see whether the location of the surrogate tactile feedback (and thus the difference in signal transit time) has an influence on the components of the two-level timing model.

The application of the surrogate tactile feedback at two locations for comparison is also relevant regarding the practical aspects of this thesis. This factor (*locus*) can be important when it comes to the determination of the feedback site of a future assistant system. Regarding the practicability of such a system, it would be desireable to integrate the feedback actuators invisibly. Furthermore, a novel control method for prosthetics is a combination of pressure-switches integrated into the sole of a shoe (Resnik, Klinger, Etter, & Fantini, 2014). In this scenario, an integration of an additional actuator means combining the control and feedback unit within the shoe, which would be more efficient than two distinct units.

3.2 Method

3.2.1 Participants

A total of 24 individuals (all right-handed) participated in the study. The mean age of the group which received the surrogate tactile feedback at their foot was 25.67 years ($SD = 4.33$, age range = 18–33 years). There were 7 female participants in this group. The other group of participants, who received the surrogate tactile feedback on their hand, had a mean age of 25.25 years ($SD = 4.81$, age range = 19–35 years). There were 4 female participants in this group.

The participants were mostly students recruited by advertisements at the local universities or via social networks. In return for their participation, they received either €10 or course credits. All participants gave informed consent.

3.2.2 Design

The factorial design of the experiment consisted of the factors Locus (hand, foot) × Feedback (on, off) × Target Interval (250 ms, 500 ms) × Block (1, 2, 3, 4). Locus was a between-subjects factor, all other factors were varied within subjects.

The factors Locus and Feedback were assigned using a Latin square design, based on the participant id number. The two target intervals were counter-balanced across participants: for each element in the Latin square, participants with an uneven id number started with 250 ms target intervals, follwed by 500 ms target intervals, and vice versa for participants with an even id number. Each target interval in each element of the latin square was repeated two times in succession. This pattern constituted a block and was repeated four times.

The analysis was carried out using complete trials as observations. During the experiment, each completed trial was immediately checked for misses or double taps: each of the collected ITIs had to be at least 0.5×Target Interval long and shorter than 1.5×Target Interval at the same time. If this was not the case, the trial was repeated up to three times. In case it failed for a fourth time, the sequence was accepted and a note was written to the log file—however, this was never the case in this experiment.

3.2.3 Procedure

After being greeted and informed about their rights, the participants signed the informed consent and the pretests (Finger Opposition Test (FOT) and Two-Point Discrimination test (TPD)) were conducted.

The FOT was conducted before and after the main experimental task, thereby serving as a test for sensorimotor fatigue. Counted were the number of correctly executed sequences and the number of erroneus sequences within the 30 second task duration. The TPD served as a control measure of individual tactile sensitivity.

Afterwards, the experimental task followed, starting with a printed description of the experimental task followed by a practice phase.

The practice phase lasted about two minutes and showed filled circles on the screen, which changed their color when the photoelectric sensor on the tapping device was triggered. After the participants have tapped for a short time, the experimenter activated the surrogate feedback. The intention of the practice phase was to show participants the behaviour of the system (tapbox as well as the surrogate feedback).

Additionally, the practice phase was used to properly adjust the feedback stimulator to the participant and to teach the participant the correct position of the hand during tapping—wrist and all fingers except the index finger had to rest on the surface during the tapping task.

When ready, participants had to start each trial by themselves. After each block (about 10 minutes), there was a short rest and participants were encouraged to limber up a bit, but did not have to. After the tapping task, the experience with musical instruments was queried as well as demographics. The whole experiment lasted about 1 hour. Participants were then thanked, paid and debriefed.

3.3 Results

3.3.1 Pretests

As mentioned in the previous chapter, the pretests were conducted for several reasons, at first hand to gather information about the homogeneity of the sample population. They ensured a certain level of tactile sensibility (two point discrimination) as well as hand agility (FOT). Summary statistics for the two-point discrimination ability are given in Tables 3.1 and 3.2. Descriptive statistics for the measures of the FOT are shown in Tables 3.3 and 3.4.

Table 3.1: Stats of the two-point discrimination test for the group of participants who received the surrogate tactile feedback at their hand.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
left index finger	2.00	2.20	3.10	3.38	4.25	6.40
right index finger	2.00	2.60	2.80	3.17	3.45	5.80
left big toe	5.60	7.45	8.30	8.15	9.05	9.80

A Wilcoxon signed rank test with continuity correction on the FOT scores showed that there is a significant difference between the number of correctly executed sequences at the two time points for both groups (Locus := hand: $W = 10$, $Z = -2.01$, $p = 0.044$, $r = 0.58$; Locus := foot: $W = 14$, $Z = -1.77$, $p = 0.098$, $r = 0.58$), which seems to constitute a learning effect. The number of erroneusly executed sequences instead showed no difference in both groups (Locus := hand: $W = 12.5$, $Z = -1.16$, $p = 0.251$, $r = 0.33$; Locus := foot: $W = 21.5$, $Z = -0.95$, $p = 0.324$, $r = 0.33$).

Table 3.2: Stats of the two-point discrimination test for the group of participants who received the surrogate tactile feedback at their foot

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
left index finger	2.00	3.20	3.80	3.65	4.20	4.60
right index finger	2.40	2.95	3.40	3.42	3.85	4.20
left big toe	5.80	7.00	8.30	7.98	8.90	10.20

Table 3.3: Descriptive statistics for the number of correctly and wrongly executed sequences at the FOT for the group of participants who received the surrogate tactile feedback at their hand. Before/after refers to the point in time of the test relative to the main experiment.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	7.00	14.00	16.00	17.20	21.00	28.00
Correct (after)	9.00	15.80	20.00	19.20	22.20	34.00
Errors (before)	0.00	0.00	0.00	0.92	1.00	6.00
Errors (after)	0.00	0.00	1.00	1.58	2.50	5.00

3.3.2 Constant and Variable Error

Constant error There were 178 outliers removed from a total of 3840 observations (4.64%). The constant error was significantly affected by the interaction of Target Interval and Feedback (F[1,22] = 10.97, $p < .01$, $\eta^2_G = .007$, see Figure 3.1). At the faster tapping speed (4 Hz/250 ms), the constant error was smaller (closer to zero) without surrogate feedback ($M_{\text{FB-off}} = -6.45$ ms, $SD_{\text{FB-off}} = 16.33$ ms) compared to the condition with surrogate feedback: $M_{\text{FB-on}} = -9.27$ ms, $SD_{\text{FB-on}} = 16.43$ ms; $p < .001$). However, when tapping at slower speed (2 Hz/500 ms), the opposite was found: $M_{\text{FB-off}} = -8.87$ ms ($SD_{\text{FB-off}} = -8.87$ ms) opposed to $M_{\text{FB-on}} = -5.83$ ms ($SD_{\text{FB-on}} = -5.83$ ms; $p < .0001$).

Furthermore, there was an interaction of Locus and Block (F[2.46,54.06] = 3.21, $p = 0.04$, $\eta^2_G = .006$; see Figure 3.2). When feedback was applied at the ipsilateral hand, the constant error in the first block was significantly higher than in the second block ($p < .0001$). This was not the case when the feedback was applied at the left foot ($p > .99$). In the third block, the constant error with feedback at the foot had significantly increased compared to the first block ($p < .0001$).

Table 3.4: Descriptive statistics for the FOT by the group of participants who received the surrogate tactile feedback at their foot.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	14.00	17.00	19.00	19.20	20.80	26.00
Correct (after)	16.00	19.00	21.00	21.70	23.00	29.00
Errors (before)	0.00	1.00	1.50	1.83	2.25	5.00
Errors (after)	0.00	1.00	2.00	2.58	4.00	7.00

Besides these interaction effects, the main effect of Block on the constant error was also significant (F[2.46,54.06] = 15.06, $p < .0001$, $\eta^2_G = .03$; see Table 3.5). Within the first block, the constant error was significantly smaller (closer to zero) than within the subsequent three blocks ($p < .0001$). The other blocks did not differ significantly.

Table 3.5: Main effect of Block on the constant error. The only significant difference was between the first block and all other blocks.

Block	Constant Error [ms^2]	SD	SE	CI
1	-3.07	18.81	0.61	1.19
2	-7.65	16.57	0.53	1.05
3	-9.69	17.38	0.56	1.10
4	-10.00	17.79	0.57	1.13

Variable error There were 120 outliers removed from a total of 3840 observations (3.12%). A significant interaction of Locus, Feedback and Target Interval on the variable error was found (F[1,22] = 8.68, $p < .01$, $\eta^2_G = .003$). The effect is shown in Figure 3.3. However, there was only one marginally significant difference ($p = 0.05$): Within the slower tapping conditions, the unpartitioned variance was lower with feedback than without, but only when the feedback was applied at the finger.

As expected based on the findings by Stevens (1886), a main effect of Target Interval on the unpartitioned variance was found (F[1,22] = 133.63, $p < .0001$, $\eta^2_G = .56$). The unpartitioned variance was higher for the 500 ms target intervals ($M = 779.77\,\text{ms}^2$, $SD = 555.61\,\text{ms}^2$; $M_s = 26.92\,\text{ms}$, $SD_s = 9.45\,\text{ms}$) than compared to the 250 ms target intervals ($M = 273.94\,\text{ms}^2$, $SD = 336.31\,\text{ms}^2$; $M_s = 15.3\,\text{ms}$, $SD_s = 7.75\,\text{ms}$), thus replicating the findings of Stevens (1886).

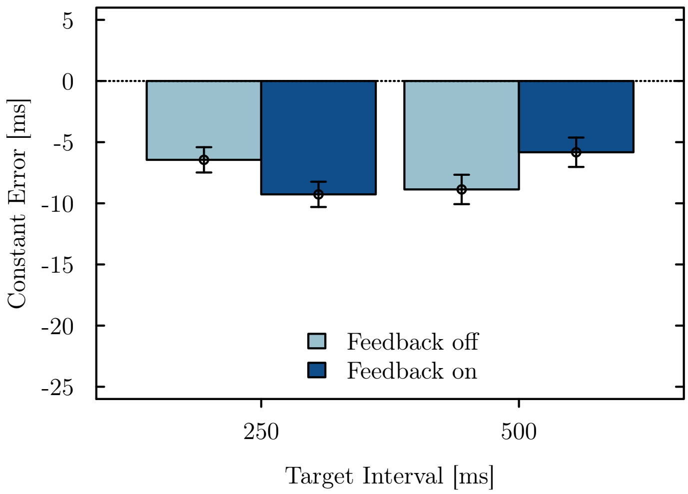


Figure 3.1: Interaction of Feedback and Target Interval on the constant error. At faster tapping speed, the deviation from the target interval was larger with the surrogate tactile feedback, contrary to the slower tapping speed. Error bars show 95% confidence intervals.

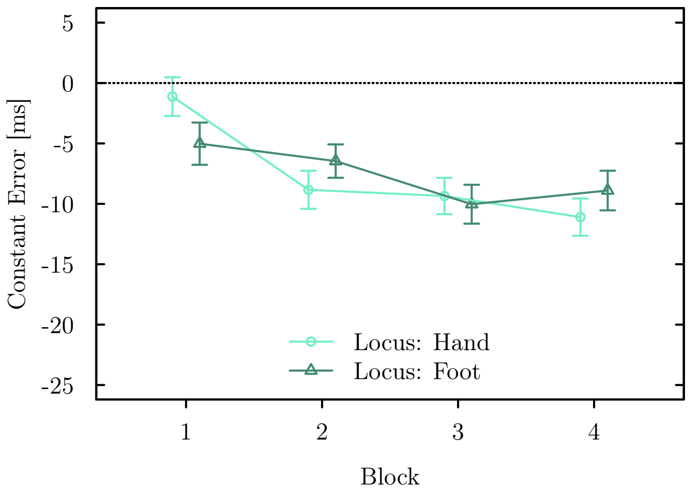
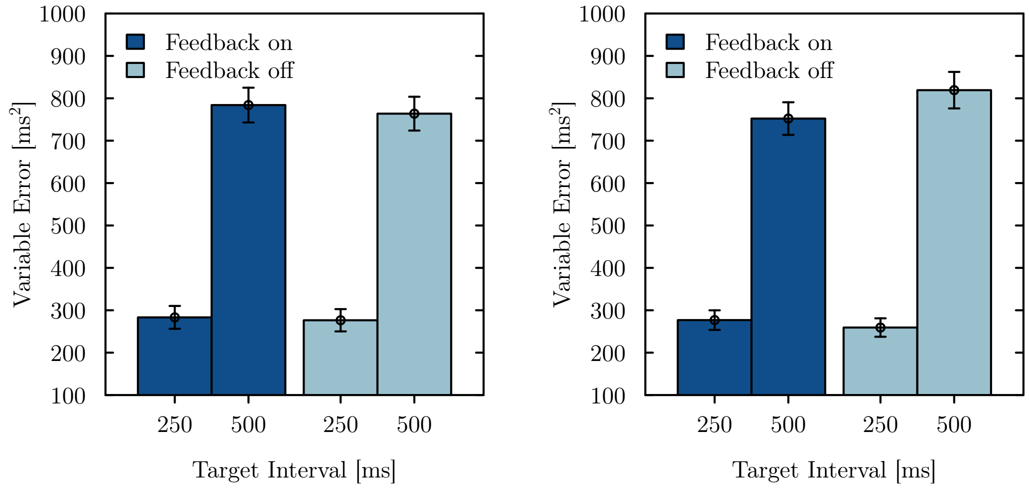


Figure 3.2: Interaction of Locus and Block. Initially, the constant error is smaller when surrogate feedback is applied at the hand. Both locations eventually show the same level of constant error. Error bars show 95% confidence intervals.



(a) Locus: Foot (b) Locus: Hand

Figure 3.3: Three-way interaction of Locus, Feedback and Target Interval on the variable error. The small difference which can be found in Figure 3.3b at the 500 ms target intervals is only present when the surrogate feedback is applied at the ipsilateral hand. Error bars show 95% confidence intervals.

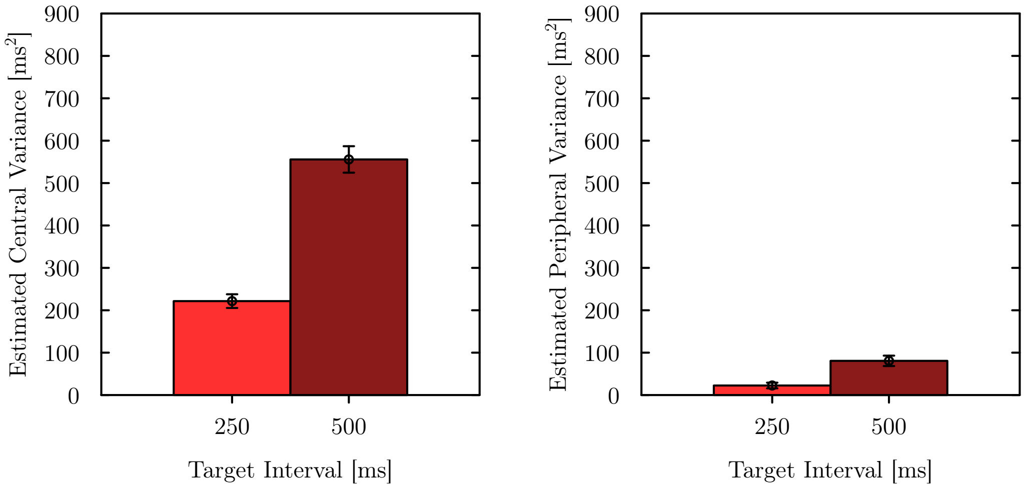
3.3.3 Wing-Kristofferson Analysis

Central variance There were 101 outliers removed from a total of 3840 observations (2.63%). Locus did not elicit differences in the central variance ($p = 0.89$).

The surrogate tactile feedback caused significant differences within the central variance ($F[1,22] = 4.86$, $p = 0.04$, $\eta^2_G = .002$). With surrogate tactile feedback, the estimate of the central variance was lower ($M = 378.98\,\text{ms}^2$, $SD = 594.38\,\text{ms}^2$) and higher without the surrogate tactile feedback ($M = 398.37\,\text{ms}^2$, $SD = 612.6\,\text{ms}^2$).

There was also a main effect of Target Interval ($F[1,22] = 156.40$, $p < .0001$, $\eta^2_G = .42$) on the central variance component (see Figure 3.4a). As expected by the model predictions, the estimated central variance was higher for the longer (500 ms) target intervals ($M = 555.76\,\text{ms}^2$, $SD = 697.71\,\text{ms}^2$) than for the shorter (250 ms) target intervals ($M = 221.59\,\text{ms}^2$, $SD = 361.14\,\text{ms}^2$).

Peripheral variance There were 171 outliers removed from a total of 3840 observations (4.45%). The peripheral variance was not influenced by the surrogate tactile



(a) Central Variance

(b) Peripheral Variance

Figure 3.4: Central and peripheral variance components. Target Interval exerted a significant effect in both dependent variables. Based on the predictions by Vorberg and Wing (1996), only the central variance should increase with target interval. Error bars show 95% confidence intervals.

feedback ($p = 0.27$). Locus also did not elicit differences in the peripheral variance ($p = 0.45$).

Similar to the central variance estimate, there was a significant difference found within the peripheral variance component based on Target Interval, $F[1,22] = 22.38$, $p < .001$, $\eta^2_G = .21$. The effect is shown in Figure 3.4b. It showed the same direction as the central variance estimate: with longer target intervals, the peripheral variance estimate was higher ($M = 80.71\,\text{ms}^2$, $SD = 273.83\,\text{ms}^2$) than with shorter target intervals ($M = 22.55\,\text{ms}^2$, $SD = 148.65\,\text{ms}^2$). This result was unexpected, since the two-level timing model predicts a constant peripheral variance across different target intervals.

Furthermore, there was a two-way interaction effect of Block and Target Interval: $F[2.32,50.97] = 3.13$, $p = 0.05$, $\eta^2_G = .02$ (Figure 3.5). The peripheral variance estimates for the 500 ms target intervals did not differ significantly. With the shorter target intervals, however, the peripheral variance estimate was higher in the first block than in the third ($p = 0.076$) and fourth block ($p = 0.035$).

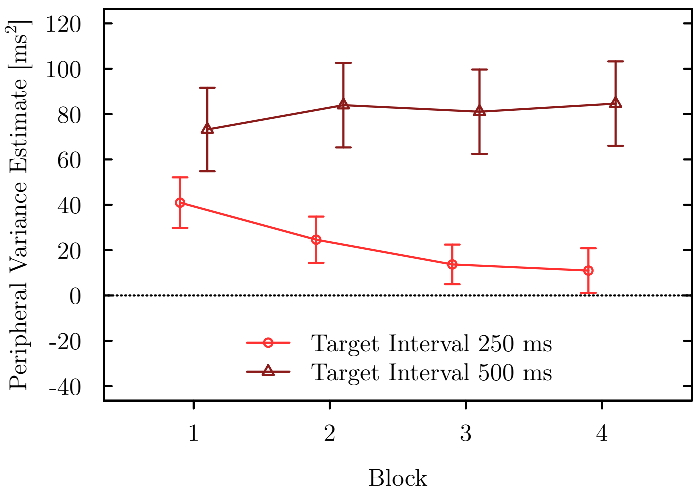


Figure 3.5: Interaction of Target Interval and Block found within the peripheral variance estimate. With short intervals, the peripheral variance decreases along the course of the experiment. Interestingly, it does not change for longer target intervals. Error bars show 95% confidence intervals.

3.3.4 Force Analysis

The force exerted during a tap was measured by means of a force key. There were 200 outliers removed from a total of 3840 observations (5.21%). However, the mean force did not show any significant differences across all conditions, neither Locus ($p = 0.14$), nor Feedback ($p = 0.37$) led to different mean force amplitudes.

The force variability was measured to assess the regularity of the applied tap force. There were 90 outliers removed from a total of 3840 observations (2.34%). Neither Locus ($p = 0.37$), nor Feedback ($p = 0.22$) led to different variability of the force amplitudes.

Target Interval exerted a significant effect on the variability ($F[1,22] = 7.98$, $p = 0.01$, $\eta^2_G = .02$). Similar to the estimated central variance and the variable error, force variability was higher for the longer (500 ms) target intervals ($M = 0.09\,\mathrm{N}^2$, $SD = 0.05\,\mathrm{N}^2$) than for the shorter (250 ms) target intervals ($M = 0.07\,\mathrm{N}^2$, $SD = 0.06\,\mathrm{N}^2$).

3.3.5 Rating Scale of Mental Effort

There were 13 outliers removed from a total of 384 observations (3.39%). Feedback ($p = 0.11$) and Locus ($p = 0.11$) did not elicit differences in the mental effort ratings.

The ratings were subject to a significant interaction of Target Interval and Block ($F[1.97, 43.27] = 4.30$, $p = 0.02$, $\eta^2_G = .01$). The effect is shown in Figure 3.6. The ratings of the faster tapping conditions remained constant over blocks. The effort ratings in the slower conditions instead increased during the course of the experiment: ratings in the third ($p = 0.031$) and fourth ($p < .01$) block were significantly higher compared to the first block.

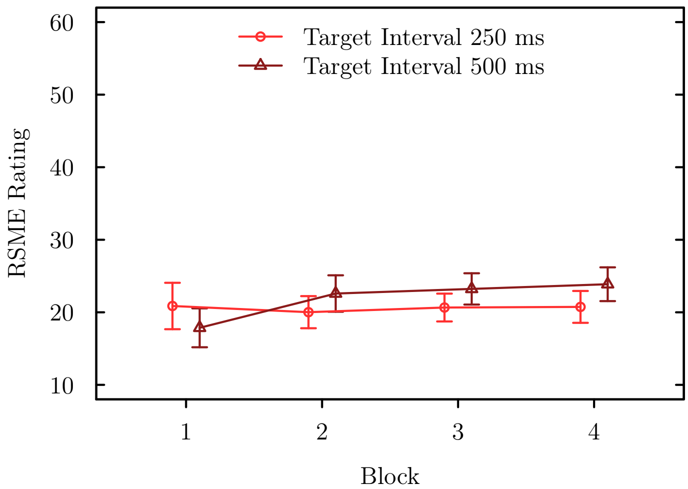


Figure 3.6: Interaction of Target Interval and Block on the ratings of mental effort. Error bars show 95% confidence intervals.

3.4 Discussion

The objective of the experiment was to apply the two-level timing model (Wing & Kristofferson, 1973a) and to assess the influence of surrogate tactile feedback on both the partitioned variance components and the overall model fit. As expected, the surrogate tactile feedback led to a lower central variance, which fits into the notion of Drewing and Aschersleben (2003) that additional sensory reafferences are integrated by the central timekeeper to enhance movement precision. Furthermore, the central variance showed the expected (Wing & Kristofferson, 1973a) increase of the central variance with longer target intervals. However, the peripheral variance should remain unaffected by the target interval duration (Vorberg & Wing, 1996), which was not the case in this experiment. Instead, the peripheral variance increased as well with target interval duration—which is not in accordance with the model predictions. Similar findings have been reported in other studies as well (Harrington et al., 1998; Harrington, Lee, Boyd, Rapcsak, & Knight, 2004). The authors do not offer any insights about the cause of these findings. In the current study, however, a construction-conditioned delay of the magnet (about 12 ms) was present, which could also have caused the abnormal effect within the results. Drewing (2013), for instance, showed that participants reacted to delayed auditory feedback with compensation of the inter-tap-intervals. The issue of the effects of a delayed surrogate tactile feedback signal will be investigated in experiments 4 and 5.

As stated in the introduction, the behavior of the estimators (like the increase of the peripheral variance with increasing target interval) could at least in part be due to unfulfilled assumptions and requirements of the Wing-Kristofferson model, which would make the computation of both estimators unjustified. Therefore, the following experiment will examine the model assumptions in closer detail.

Another interesting effect was found within the constant error. The surrogate tactile feedback led participants to produce a smaller constant error compared to the control condition without the surrogate tactile feedback, but only at faster tapping speeds. During the slower tapping speeds, the opposite was true. Goebl and Palmer (2008) conclude that moderate tapping speeds allow for different performance techniques (more degrees of freedom how to carry out a movement) and that performance gets more similar as the tapping speed increases. The reason for the interaction pattern could therefore be that the additional reafferences given by the surrogate tactile feedback were only properly integrated into the perception scheme at the slower tapping speeds, while causing interference and hence a drop in performance at the faster speeds. However, since motion tracking was not used in this thesis, this assumption cannot be directly tested.

Concerning the effect of the location of the surrogate tactile feedback, there was a small difference in the slower tapping conditions, indicating a slightly lower variable error when the feedback was applied at the hand. This was not the case when feedback was applied at the foot. Furthermore, there seems to be a steeper learning effect for the feedback when applied at the hand, since the difference between the first two blocks is significant when the feedback is applied at the hand. When the feedback was applied at the foot, the drop over blocks is more even (i.e., there was no significant difference between the first two blocks). Eventually, in the last two blocks, the constant error reaches comparable levels.

The reason for this difference found in the variable error remains unclear, it might be due to the higher sensibility of the index finger compared to the tip of the big toe. On the other hand, the central variance estimate and constant error both show pronounced effects of Feedback, but independent of the location where the feedback is applied. The multiple sensory reafference advantage found in other studies (Drewing et al., 2002; Drewing & Aschersleben, 2003) therefore seems not to be limited to the hands. Instead, sensory input from other body areas seems to be integrated as well. Tapping force and ratings of mental effort did not differ for the two feedback locations either, which supports this assumption. The differences in nerve signal transit time between both locations therefore seem to be irrelevant for the application of surrogate tactile feedback, at least based on the results of the present blocked between-subjects design. Therefore, the foot is suitable as a location for the surrogate tactile feedback and will be used as feedback location in all following experiments.

The RSME showed only an influence between the two target intervals, with a reversing of their relative rating from the first to the second block. This basically shows that initially, the faster tapping speed was rated as more demanding. From the second block onwards, however, maintaining of slower tapping speed was rated as more demanding. Therefore, this effect reflects a customization effect.

Target interval was also the only factor affecting the tapping force variability. This effect may reflect a form of compensatory behavior. However, the surrogate tactile feedback did not have any significant influence on the force measures. Therefore, in Experiment 2, the force applied during tapping movements will be investigated in more detail. Additionally, Experiment 2 will employ contact-free tapping to minimize the endogenous tactile reafferences.

Chapter 4

Experiment 2: Contact-Free Tapping

The results of Experiment 1 showed the expected reduction of the central variance estimate caused by the surrogate tactile feedback. However, the peripheral variance was influenced by the target interval, which should not be the case—Wing and Kristofferson (1973a) postulated that since the movement characteristics remain identical (except for the times between the movements) for different target intervals, the peripheral variance should not change due to this factor.

It was assumed that these patterns in the results of Experiment 1 originate (at least partially) in the construction-conditioned delay of the tactile stimulator. To examine this assumption, a new experimental setup was devised, which addressed this issue by offering a more precise, low-delay tactile feedback. Experiment 1 confirmed that feedback at the foot could be integrated into the body scheme, since there were no major differences found regarding the location of the surrogate feedback. Hence, the feedback in this experiment will be given at the foot only.

Furthermore, a main objective of this experiment was to examine whether surrogate tactile feedback can serve as replacement for the endogenous tactile reafferences regarding the contribution of tactile feedback to the timing in sequential motor actions. Similar to the device used by Drewing et al. (2002), a tapping device which allowed contact-free tapping was constructed and used within the experiment in comparison to the classical tapping device. This way, the tactile reafferences originating from the skin-surface contact could be disabled almost completely. However, proprioceptive kinaesthetic signals as well as tactile signals from the stretching skin remain unaffected by this manipulation.

Drewing et al. employed a bimanual (simultaneously) tapping task. They varied the tactile feedback stemming from the additional hand by contact-free tapping and found a reduced bimanual advantage compared to both hands tapped on a solid surface. The current study employs the same principle but with an unimanual tapping task. Unimanual contact-free tapping has also been used before as control task in tapping studies with anesthesized participants (Aschersleben et al., 2001). With the setup used within this experiment, the total amount of tactile feedback dependeds on the combination of two factors: Tapmode (i.e., contact-free tapping vs. contact tapping on a solid surface) and Feedback (i.e., surrogate tactile feedback at the left foot either switched on or off). Except for the lower delay of the surrogate tactile feedback, the contact tapping conditions were essentially replicating Experiment 1.

Based on the findings by Drewing et al., it was expected that the missing tactile reafferences lead to a higher central variance compared to the classical tapping task on a solid surface. Furthermore, the surrogate tactile feedback should lower the central variance in both conditions.

4.1 Method

4.1.1 Participants

A total of 24 individuals (15 female, all right-handed) participated in the study. Their mean age was 23.92 years ($SD = 3.66$, age range = 18–30 years). The participants were mostly students recruited by advertisements at the local universities or via social networks. In return for their participation, they received either €10 or course credits. All participants gave informed consent.

4.1.2 Design

The factorial design of the experiment consisted of the factors Tapmode (air, contact) × Feedback (on, off) × Target Interval (250 ms, 500 ms) × Block (1, 2, 3, 4). All factors were within-subjects factors.

The factors Tapmode and Feedback were assigned using a Latin square design, based on the participant id number. The two target intervals were counter-balanced across participants: for each element in the Latin square, participants with an uneven id number started with 250 ms target intervals, follwed by 500 ms target intervals, and vice versa for participants with an even id number. Each target interval in each element of the latin square was repeated two times in succession. This pattern constituted a block and was repeated four times.

The analysis was carried out using complete trials as observations, except for the force analysis and the related correlations, where each tap was used as observation. During the experiment, each completed trial was immediately checked for misses or double taps: each of the collected ITIs had to be at least 0.5×Target Interval long and shorter than 1.5×Target Interval at the same time. If this was not the case, the trial was repeated up to three times.

4.1.3 Procedure

After being greeted and informed about their rights, the participants signed the informed consent and the pretests (Finger Opposition Test (FOT) and Two-Point Discrimination test (TPD)) were conducted. For details on the pretests, please refer to Sections 2.2.1 (p. 31) and 3.2.3 (p. 51).

In this experiment, the tactile sensitivity was also controlled via the Semmes-Weinstein monofilaments, which yield the value for the touch-pressure threshold of the participants' fingertips. The detailed procedure is described in Section 2.2.1.

Afterwards, the experimental task followed, starting with a printed description of the experimental task followed by a practice phase, which lasted about 2 minutes and showed circles on the screen, which changed their color when the photoelectric sensor on the tapping device was triggered. After the participants tapped for a short time, the experimenter activated the surrogate feedback. The intention of the practice phase was to show participants the behaviour of the system (both tapboxes as well as the surrogate feedback—the new verion with an onset delay of about 2 ms). Additionally, the practice phase was used to properly adjust the feedback stimulator to the participant and to teach the participant the correct position of the hand during tapping—wrist and all fingers except the index finger had to rest on the surface during the tapping task.

When ready, participants had to start each trial by themselves. After each block (about 10 minutes), there was a short rest and participants were encouraged to limber up a bit, but did not have to. After the tapping task, the experience with musical instruments was queried as well as demographics. The whole experiment lasted about one hour. Participants were then thanked, paid and debriefed.

4.2 Results

4.2.1 Pretests

Summary statistics for the two-point discrimination ability are given in Table 4.1.

Table 4.1: Stats for the two-point discrimination test.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	2.75	3.00	3.25	3.28	3.50	3.80
left index finger	1.50	2.40	3.12	3.04	3.75	4.00
left big toe	6.00	8.09	8.60	8.75	9.75	11.50

In addition to the two tests conducted in Experiment 1, Semmes-Weinstein monofilaments were used to assess touch pressure threshold (Table 4.2).

Table 4.2: Distribution of the touch pressure thresholds at different body locations, measured using the Semmes-Weinstein monofilament test. The column headers represent the markings on the monofilaments, their thickness ascending with the numbers.

	1.65	2.36	2.44	2.83	3.22	3.61	4.08	4.17	4.31	4.56
right index finger	1	9	9	5						
left index finger		16	7		1					
left big toe			1	4	7	7	1	1	1	2

Table 4.3: Descriptive statistics for the number of correctly and wrongly executed sequences at the Finger Opposition Task. Before/after refers to the point in time of the test relative to the main experiment.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	10.00	15.00	17.00	17.20	19.20	24.00
Correct (after)	13.00	16.80	21.00	20.60	23.20	29.00
Errors (before)	0.00	0.00	1.00	1.25	2.00	4.00
Errors (after)	0.00	0.00	0.00	0.88	1.00	5.00

Descriptive statistics for the FOT measures are shown in Table 4.3. A Wilcoxon signed rank test with continuity correction shows that there is a significant difference between the number of correctly executed sequences at the two time points (W = 0, Z = −4.26, p < .0001, r = 0.87), which seems to constitute a learning effect—comparable to the results of the previous experiment.

The number of erroneusly executed sequences instead showed no difference (W = 74, Z = 1.54, p = 0.18, r = 0.31).

4.2.2 Constant and Variable Error

Constant error There were 86 outliers removed from a total of 1536 observations (5.6%). Tapmode exerted a significant influence on the constant error (F[1,23] = 6.85, p = 0.02, $\eta^2_G = .01$). The constant error was higher in the classical tapping conditions (tapping with surface contact; $M = -10.95$ ms, $SD = 20.9$ ms), as opposed to the contact-free tapping conditions ($M = -7.01$ ms, $SD = 25.89$ ms).

The main effect of Target Interval (F[1,23] = 11.43, p < .01, $\eta^2_G = .10$) was significant. Tapping at faster speed led to a constant error closer to zero: $M = -3.21$ ms, $SD = 21$ ms. The longer intervals resulted in a larger constant error ($M = -14.75$ ms, $SD = 23.42$ ms).

Also, a main effect of Block (F[2.14,49.27] = 15.62, p < .0001, $\eta^2_G = .02$) was present; means and additional statistics are printed in Table 4.4. Similar to Experiment 1, the error increased with the number of blocks (p = 0.016, p < .0001, p < .0001).

Table 4.4: Main effect of Block on the constant error. The constant error measured in the first block is closer to zero than the other three blocks, which in turn do not differ from each other.

Block	Constant Error [ms]	SD	SE	CI
1	-4.85	19.66	1.00	1.97
2	-8.20	18.28	0.93	1.83
3	-10.59	19.17	0.98	1.92
4	-12.28	19.21	0.98	1.93

There was as well a significant interaction effect between Tapmode and Target Interval (F[1,23] = 10.08, p < .01, $\eta^2_G = .02$, depicted in Figure 4.1). Generally, constant error in tapping tasks is slightly negative for non-musicians (Repp, 2010). A negative constant error was also found in all conditions in Experiment 1. Here, it is clearly visible that the constant error in the contact-free condition off “normal” limits, even positive, which is unusual and could be related to anticipation. However, this was only the case during shorter target intervals. The constant error during fast tapping speed but on a solid surface is within the usual limits (slightly negative), but still smaller than the conditions with slow tapping speed (p's $< .0001$). The slow tapping speed conditions did not differ regarding the tapmode ($p = 0.476$).

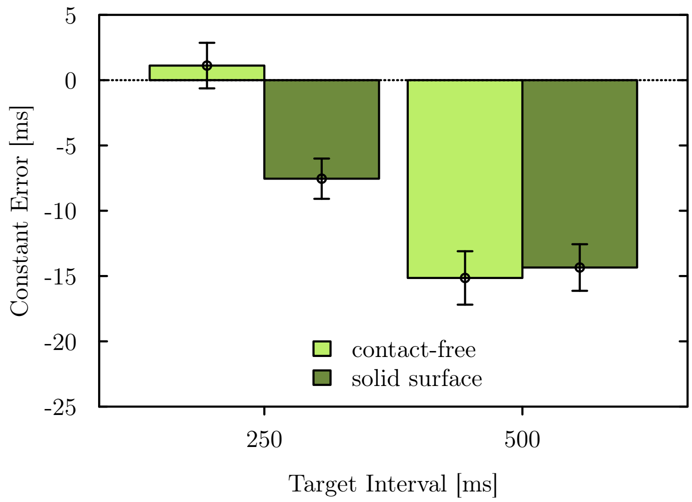


Figure 4.1: Interaction of Target Interval and Tapmode. Contact-free tapping at fast tapping speed led to a positive constant error, but at slow tapping speed. Error bars show 95% confidence intervals.

Furthermore, the interaction effect of Feedback and Target Interval ($F[1,23] = 14.35$, $p < .01$, $\eta^2_G = .004$; depicted in Figure 4.2) was significant. This interaction effect was comparable to the one found in the previous experiment: In the slower tapping conditions, the feedback led to shorter produced intervals as compared to slower tapping coditions without surrogate tactile feedback ($p = 0.028$). In Experiment 1, during faster tapping intervals, the surrogate tactile feedback led to longer intervals. Visual inspection of the current results (Figure 4.2) showed a tendency towards this pattern, too—however, the difference here did not reach significance ($p = 0.109$).

Variable error There were 16 outliers removed from a total of 1536 observations (1.04%). In contrast to the constant error, the variable error was not significantly influenced by Feedback ($p = 0.19$) or Tapmode ($p = 0.11$).

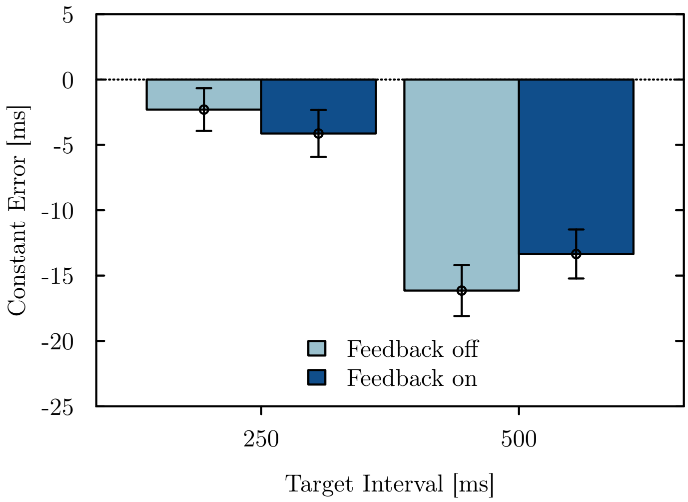


Figure 4.2: Interaction of Target Interval and Feedback on the constant error. The pattern of results was comparable to the one found in Experiment 1 (cf. Figure 3.1 on page 55). Error bars show 95% confidence intervals.

The variable error was subject to a main effect of Target Interval ($F[1,23] = 112.11$, $p < .0001$, $\eta^2_G = .42$). The variable error increased with interval duration: short intervals yielded a mean variable error of $327.14\,ms^2$ ($SD = 320.57\,ms^2$; $M_s = 17.26\,ms$, $SD_s = 6.66\,ms$). At the long target intervals, the mean value of the variable error was $853.96\,ms^2$ ($SD = 518.24\,ms^2$; $M_s = 28.34\,ms$, $SD_s = 8.25\,ms$).

Additionally, there was a significant main effect of Block ($F[2.16,49.61] = 3.58$, $p = 0.03$, $\eta^2_G = .009$), viz. the variable error decreased with practice. Means and other statistics can be found in Table 4.5. However, post-hoc tests showed that there was only a marginally significant difference between the first and last block ($p = 0.074$), all other blocks did not significantly differ from each other.

4.2.3 Wing-Kristofferson Analysis

Central variance There were 13 outliers removed from a total of 1536 observations (0.85%). There was a main effect of Tapmode: $F[1,23] = 6.07$, $p = 0.02$, $\eta^2_G = .02$. As expected, tapping on a solid surface generally led to a lower central variance estimate ($M = 472.67\,ms^2$, $SD = 632.46\,ms^2$) than tapping in the contact-free condition without surface contact ($M = 564.86\,ms^2$, $SD = 686.91\,ms^2$).

Table 4.5: Main effect of Block on the variable error (VE and VE_s (SD)). The fourth block is marginally significant lower than the first block. Other blocks did not differ.

Block	VE [ms^2]	SD	SE	CI	VE_s [ms]	SD_s [ms]
1	625.38	474.39	24.21	47.60	23.55	8.78
2	605.03	470.06	23.99	47.16	23.10	8.84
3	586.73	467.63	23.86	46.92	22.68	8.98
4	545.05	444.32	22.67	44.58	21.87	8.73

As expected based on the model predictions, there was a main effect of Target Interval ($F[1,23] = 60.96$, $p < .0001$, $\eta^2_G = .26$) on the central variance estimate. Longer target intervals led to a higher central variance ($M = 734.76\,ms^2$, $SD = 714.64\,ms^2$) than shorter target intervals ($M = 302.77\,ms^2$, $SD = 427.55\,ms^2$).

Additionally, a marginally significant interaction effect of Feedback, Tapmode and Target Interval on the estimated central variance appeared ($F[1,23] = 3.11$, $p = 0.09$, $\eta^2_G = .002$). While the faster tapping speed with a target interval of 250 ms showed no effects of Feedback, this was not the case for the slower tapping conditions with a target interval of 500 ms. In this interaction effect, without surrogate tactile feedback, the contact-free tapping conditions led to a higher central variance estimate ($p = 0.064$; Figure 4.3a), as expected and also indicated by the previously mentioned main effect of Tapmode. However, with surrogate feedback, the central variance in the contact-free tapping condition decreased so that there was no difference between both tapmodes anymore ($p > .99$; Figure 4.3b). This confirmed the expectation, that additional tactile sensory input has a positive (decreasing) influence on the variability of the central timekeeper, to some extent.

Interestingly, the central variance estimated in the classical tapmode was not significantly affected by the surrogate tactile feedback in this experiment. In contrast, this was the case in Experiment 1, which was essentially comparable to the classical tapping condition in this experiment.

Peripheral variance There were 28 outliers removed from a total of 1536 observations (1.82%). The conditions with feedback did not significantly differ from those without feedback ($p = 0.49$).

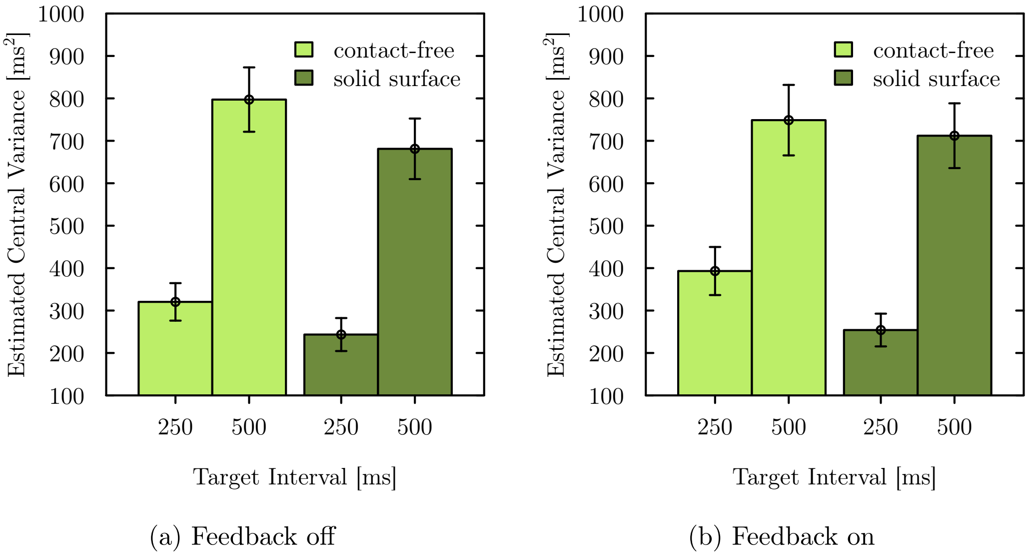


Figure 4.3: Central variance component. Feedback in combination with Tapmode and Target Interval is responsible for an interaction effect. Without surrogate tactile feedback (Figure 4.3a), there is a significant difference in the 500 ms conditions between both tapmodes, whereas with surrogate tactile feedback, this difference cannot be found (Figure 4.3b). Error bars show 95% confidence intervals.

There was a marginally significant effect of Tapmode on the peripheral variance estimate ($F[1,23] = 3.94$, $p = 0.06$, $\eta_G^2 = .010$). Tapping on a solid surface led to a higher estimate ($M = 46.74\,\text{ms}^2$, $SD = 175.23\,\text{ms}^2$) compared to tapping in the contact-free condition ($M = 26.94\,\text{ms}^2$, $SD = 194.18\,\text{ms}^2$), thus mirroring the effect found on the central variance estimate.

The peripheral variance estimate was significantly influenced by Target Interval ($F[1,23] = 14.44$, $p < .001$, $\eta_G^2 = .06$). The shorter 250 ms intervals led to a lower estimate of the peripheral variance ($M = 12.33\,\text{ms}^2$, $SD = 134.37\,\text{ms}^2$) as compared to the longer 500 ms intervals ($M = 61.36\,\text{ms}^2$, $SD = 219.87\,\text{ms}^2$). Thus, the slope of the effect had the same direction as in the central variance, similar to the previous experiment—but not in accordance with the model predictions.

Furthermore, the peripheral variance in the last (fourth) block was significantly lower than the two previous blocks (difference to third block: $p = 0.068$; difference to second block: $p < .01$; $F[2.62,60.31] = 5.48$, $p < .01$, $\eta_G^2 = .02$). For means and additional statistics, see Table 4.6. Thus, the practice effect differed in comparison to Experiment 1 because, in Experiment 1, only the conditions with faster intervals showed a decrease of the peripheral variance estimate during the course of the experiment.

Table 4.6: Main effect of Block on the peripheral variance estimate. The fourth block was estimated significantly lower than the previous two blocks.

Block	Estimate [ms^2]	SD	SE	CI
1	38.27	147.77	7.54	14.83
2	51.58	153.60	7.84	15.41
3	40.49	158.90	8.11	15.94
4	17.03	142.64	7.28	14.31

Model validity assessment

Since the peripheral variance in this experiment as well as in Experiment 1 were influenced by Target Interval, this section will examine the model assumptions. There were 948 (61.72%) valid trials, where $-1/2 \leq \rho_I(1) \leq 0$. The autocorrelations for lags greater than 1 often were not equal to 0. For instance, at lag 4, the mean autocorrelation was $M = 0.04$ ($SD = 0.19$), significantly different from zero: $t[23] = 6.52$, $p < .0001$. Further tests for different lags can be found in Table 4.7.

There are several methods to deal with violations of the lag 1 autocorrelation within the tapping literature (O'Boyle, Freeman, & Cody, 1996). Common methods include:

1. Inclusion of all trials, disregarding violations of proposed $\rho_I(1)$ limits (Ivry & Keele, 1989)
2. Elimination of affected trials from the analysis (O'Boyle et al., 1996)
3. For affected trials, setting peripheral variance to zero and central variance equal to the raw variance (Ivry & Keele, 1989)
4. Inclusion of values from the first non-violating run only from each subject (Pastor, Jahanshahi, Artieda, & Obeso, 1992)

According to O'Boyle et al. (1996), the statistical power of these methods differs to some extent, but generally, the pattern of differences between conditions concerning central, peripheral, and raw variance do not change substantially. To verify this with the current data, method 2 from the list above was also applied to the data from the current study—the first method (considering all values, irrespective of lag 1 violations) has already been applied during the initial analysis in Section 4.2.3.

To apply the second method, the 588 (38.28%) violating trials were excluded from the analysis. This affected the balance, so that proper analysis by means of ANOVA was not possible. Therefore, linear mixed effects analysis by means of the `R`-packages `lme4` (Bates, Maechler, Bolker, & Walker, 2015) and `afex` (Singmann et al., 2015) was used. Fixed effects included Feedback, Tapmode, Target Interval, Block, and their interactions. The remaining random effects structure included the fully crossed fixed effects, nested in subjects, since Barr, Levy, Scheepers, and Tily (2013) recommend to "keep it maximal", i.e., including random intercepts and slopes for all fixed effects in the random effects structure. According to the authors, this keeps the tests from being too progressive. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity. To improve the deviation from normality, the dependent variables were log-transformed prior to the analysis.

The results of method 2 (only consider valid trials; O'Boyle et al., 1996) were comparable to method 1 (inclusion of all trials): Target Interval had a significant effect on the central variance estimate ($F[1,22.71] = 163.5$, $p < .0001$), as well as Tapmode ($F[1,22.74] = 4.28$, $p = 0.05$). However, there was no evidence for a three-way interaction of Feedback, Target Interval and Tapmode: $F[1,22.44] = 0.01$, $p = 0.908$.

Even with the exclusion of trials with violated assumptions, the peripheral variance still showed a strong effect of Target Interval ($F[1,22.63] = 55.51$, $p < .0001$). There was, however, no sign of an effect of Block ($F[3,19.91] = 1.94$, $p = 0.157$) nor Tapmode ($F[1,22.66] = 0.31$, $p = 0.583$). This means that an exclusion of trials with violated assumptions offers no benefits compared to the standard analysis—even more, the effects of interest have been filtered out.

4.2.4 Force Analysis

Compared to the basic force analysis in Experiment 1, the force data acquired in this experiment subjected to a more detailed analysis. At first, specific elements of each tap were determined (Peaks M1 and M2 as well as points L1, L2 and L3; cf. Section 2.4.3 on page 45 for details). Subsequently, the areas A1 and A2 were calculated, as

Table 4.7: Test statistics of the autocorrelations at lag 2 to lag 9 (alternative hypothesis: true mean is not equal to 0). Confidence levels are 99%.

	df	t-value	p-value	sample mean	lower CI bound	upper CI bound
lag 2	23	6.86	0.000	0.064	0.038	0.091
lag 3	23	2.69	0.013	0.024	-0.001	0.049
lag 4	23	6.52	0.000	0.041	0.023	0.059
lag 5	23	0.16	0.872	0.001	-0.014	0.016
lag 6	23	2.25	0.035	0.013	-0.003	0.029
lag 7	23	-1.09	0.285	-0.007	-0.026	0.011
lag 8	23	2.60	0.016	0.013	-0.001	0.028
lag 9	23	-3.51	0.002	-0.018	-0.032	-0.004

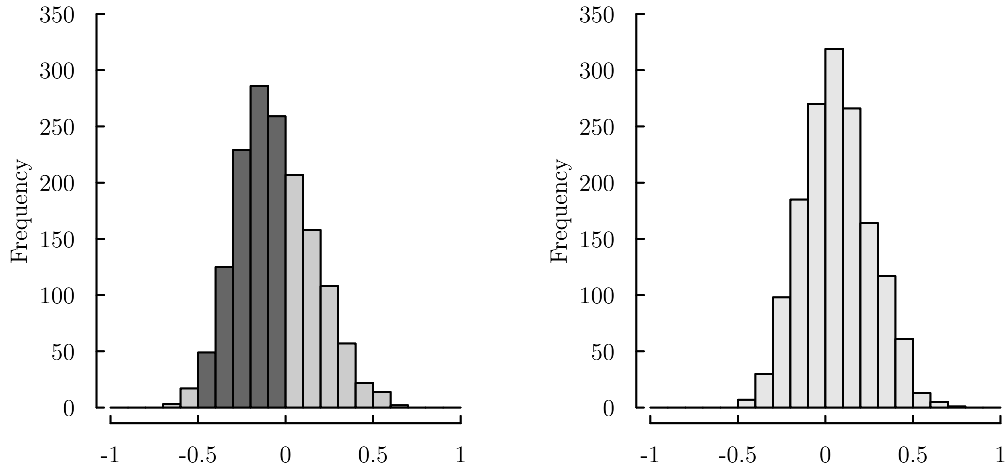
well as the time-to-peak (TTP: the time between the beginning of the tap (L1) and the first maximum (M1)). Of course, these analyses were only possible for contact tapping, thus the factor Tapmode was not present during this analysis.

M1 Amplitude

There were 2076 outliers removed from a total of 32050 observations (6.48%). A marginally significant interaction between Feedback, Target Interval and Block became apparent (F[2.52,57.95] = 2.85, p = 0.05, $\eta^2_G = .0008$; Figure 4.5). The mean M1 amplitude during the first block with feedback ($M = 3.06$ N, $SD = 1.32$ N) is lower than the M1 amplitude without feedback ($M = 2.8$ N, $SD = 1.08$ N; $p < .01$)—but only during slower tapping speeds (Figure 4.5b), not in the faster tapping speeds (Figure 4.5a).

Target interval also had an influence on the first maximum, M1 (F[1,23] = 9.50, $p < .01$, $\eta^2_G = .01$). The mean value of the M1 peak in short target intervals was $M = 3.01$ N ($SD = 1.38$ N), lower than the peaks found during the longer target intervals ($M = 3.41$ N, $SD = 1.54$ N).

Furthermore, there was an effect of Block on the M1 peak: F[1.51,34.77] = 10.59, $p < .001$, $\eta^2_G = .02$. Means and standard deviations for all levels of Block are printed in Table 4.8. The M1 value during the first block is significantly lower than in all other three blocks ($p < .0001$).



(a) Lag 1 autocorrelation (b) Lag 2 autocorrelation

Figure 4.4: Histogram of lag 1 autocorrelation (Figure 4.4a) and lag 2 autocorrelation (Figure 4.4b). Lag 1 should be bound between -.5 and 0 (colored in dark grey), Lag 2 should be around zero.

M2 Amplitude

There were 1945 outliers removed from a total of 32050 observations (6.07%). The interaction effect found in the M1 amplitude was not present within the M2 amplitude. Feedback also did not elicit a significant effect on the M2 amplitude ($p = 0.93$).

Only a main effect of Target Interval was found: $F[1,23] = 17.55$, $p < .001$, $\eta^2_G = .02$. The exerted force at the M2 component was higher during the longer 500 ms target interval ($M = 1.45$ N, $SD = 0.66$ N) compared to the shorter 250 ms target interval ($M = 1.23$ N, $SD = 0.59$ N).

Time to Peak (TTP)

The TTP measures how fast the M1 amplitude is reached from the beginning of the tap in milliseconds. It was measured only for the first peak and served as an estimate of the downward movement speed of the index finger[1].

[1]Measuring the TTP2, i.e., the time to the second peak was not regarded as necessary because, in contrast to the first peak, it would have had no specific meaning.

Table 4.8: Main effect of Block on the M1 component. The M1 measured in the first block is significantly lower than the other three blocks, which in turn do not differ from each other.

Block	M1 Amplitude [N]	SD	SE	CI
1	2.74	1.32	0.01	0.03
2	3.38	1.14	0.01	0.02
3	3.35	1.10	0.01	0.02
4	3.36	1.10	0.01	0.03

There were 1117 outliers removed from a total of 32050 observations (3.49%). The TTP was subject to an interaction of Feedback, Target Interval and Block: F[2.68,61.58] = 4.99, $p < .01$, $\eta^2_G = .003$; see Figure 4.6. While there is a significant decrease in TTP from the first block to the second in most conditions (p's $< .0001$), there was one exception: TTP remained constant over blocks only with surrogate tactile feedback in the slower tapping conditions ($p > .99$, Figure 4.6b).

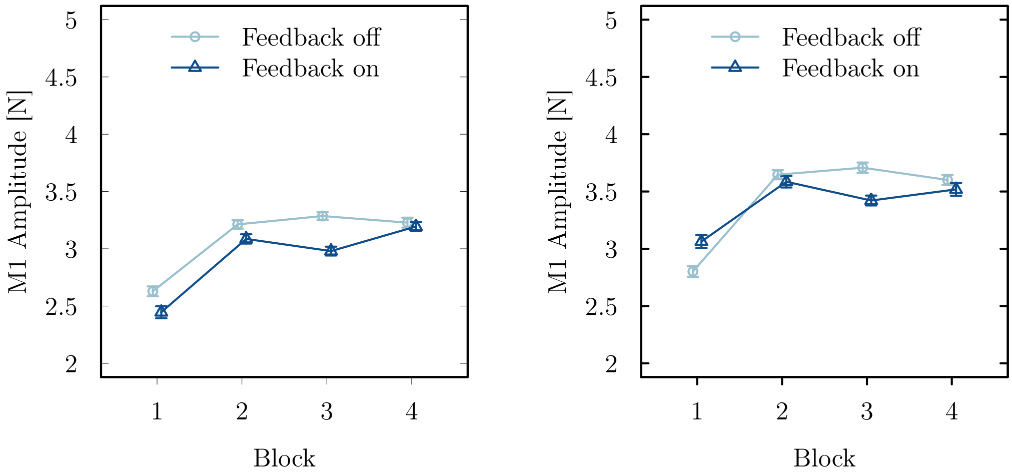
There was also a main effect of Target Interval: F[1,23] = 13.04, $p < .01$, $\eta^2_G = .01$. The M1 peak was reached faster during the slower tapping speed ($M = 3.69$ ms, $SD = 1.17$ ms) than during the faster tapping speed ($M = 3.9$ ms, $SD = 1.22$ ms).

Furthermore, TTP depended on Block (F[1.73,39.79] = 9.51, $p < .001$, $\eta^2_G = .02$). The means are shown in Table 4.9. Only during the first block, the TTP was significantly longer than the other three blocks ($p < .0001$), which in turn did not differ from each other.

Table 4.9: Main effect of Block on the Time To Peak (TTP). The TTP measured in the first block is significantly longer than the other three blocks.

Block	TTP [ms]	SD	SE	CI
1	4.05	1.05	0.01	0.02
2	3.68	0.94	0.01	0.02
3	3.73	0.91	0.01	0.02
4	3.72	0.97	0.01	0.02

There was a strong correlation between TTP and the following force peak (M1), $r(22) = -0.41$, $p = 0.045$. This means that on a short TTP, a large peak followed and vice versa.



(a) Target Interval: 250 ms (b) Target Interval: 500 ms

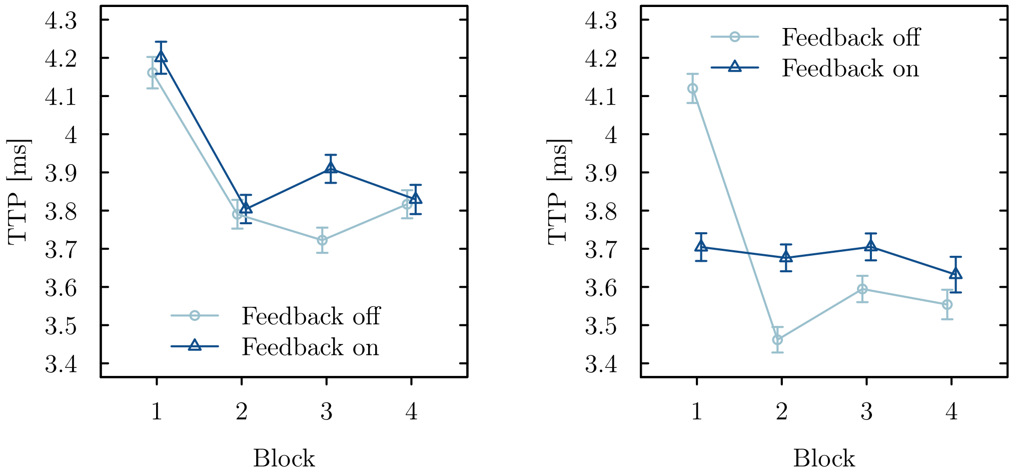
Figure 4.5: Three-way-interaction of Feedback, Target ITI and Block. The mean M1 amplitude during the first block with feedback is lower than without feedback—but only during slower tapping speed (Figure 4.5b). Error bars show 95% confidence intervals.

Momentum (A1 and A2)

To quantify the applied kinetic energy of the tapping movement components, each tap was split and the definite integral was computed, as described in Section 2.4.3. Both momenta served as measures of effort. The first momentum A1 was the initial peak with the M1 amplitude on top, the second momentum A2 was the larger part (in terms of duration) with usually lower peaks (M2 Amplitude).

A1 There were 1708 outliers removed from a total of 32050 observations (5.33%). Feedback had no effect on the first momentum (p = 0.07).

The first momentum differed between both target intervals. At shorter intervals, participants applied a lower momentum ($M = 11.52$ N ms, $SD = 4.04$ N ms) compared to the longer 500 ms target intervals ($M = 12.53$ N ms, $SD = 4.2$ N ms; F[1,23] = 9.98, $p < .01$, $\eta^2_G = .008$). Since both of the other measures concerned with the first component (M1 amplitude and TTP) were also affected by Target Interval, this effect was expected.



(a) Target Interval: 250 ms (b) Target Interval: 500 ms

Figure 4.6: Three-way-interaction of Feedback, Target ITI and Block on the time-to-peak (TTP). In all conditions, TTP changed with the course of the experiment, except for the combination of surrogate tactile feedback and slow tapping speed. Error bars show 95% confidence intervals.

Additionally, the A1 momentum showed a main effect of Block: $F[1.90,43.77] = 9.55$, $p < .001$, $\eta^2_G = .01$). Means and additional statistics are shown in Table 4.10. The first block was significantly lower than all subsequent blocks (p's < .0001), which in turn did not differ significantly from each other (p's = 0.207).

Table 4.10: Main effect of Block on the A1 momentum. The first block is significantly lower than each of the following blocks, which in turn did not significantly differ.

Block	A1 [N ms]	SD	SE	CI
1	10.85	3.59	0.04	0.08
2	12.43	3.19	0.04	0.07
3	12.36	3.05	0.03	0.07
4	12.46	3.44	0.04	0.08

A2 There were 1451 outliers removed from a total of 32050 observations (4.53%). Like the first momentum, the second momentum was not influenced by Feedback ($p = 0.17$).

The second momentum differed between both target intervals ($F[1,23] = 39.28$, $p < .0001$, $\eta^2_G = .10$). The direction of the effect was comparable: at shorter intervals, participants applied less effort ($M = 54.37$ N ms, $SD = 50.98$ N ms) compared to the longer 500 ms target intervals ($M = 89.43$ N ms, $SD = 65.35$ N ms).

4.2.5 Mental Effort

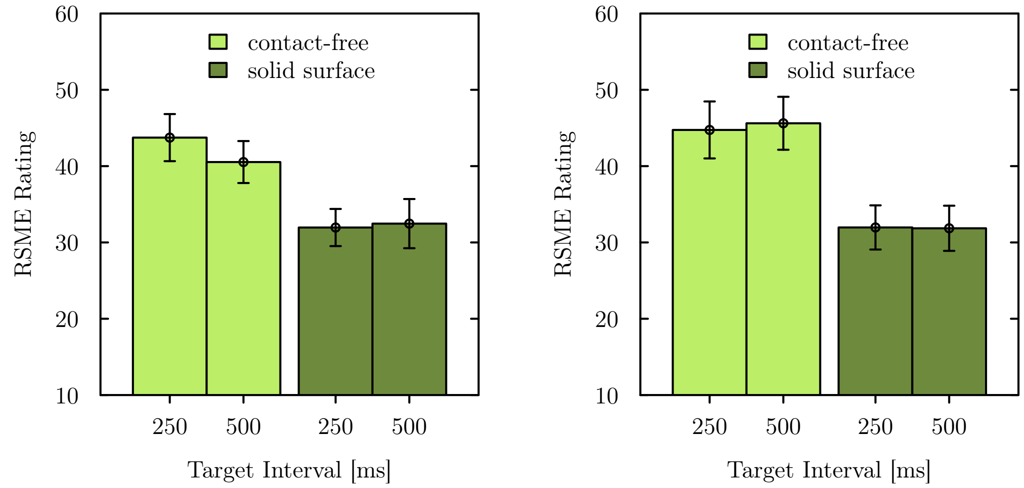
There were 53 outliers removed from a total of 768 observations (6.9%). A main effect of Tapmode was found ($F[1,23] = 37.37$, $p < .0001$, $\eta^2_G = .06$). Contact-free tapping was generally rated as requiring more mental effort ($M = 43.66$, $SD = 21.51$) than classical tapping with surface contact ($M = 32.06$, $SD = 18.8$).

Furthermore, there was a significant interaction between Feedback, Tapmode and Target Interval: $F[1,23] = 5.11$, $p = 0.03$, $\eta^2_G = .0007$. All eight affected conditions are plotted in Figure 4.7. The interaction is visible in Figure 4.7a, showing a difference in ratings of contact-free conditions: the slower condition seems to have been rated as less effortful than the faster condition. However, in post-hoc analysis, this difference did not reach significance ($p = 0.186$).

4.3 Discussion

The aims of this experiment were manifold. The applicability of the two-level timing model in this context was questioned after the first experiment because the peripheral variance increased with the target interval duration, which is against the model predictions, yet not uncommon (Harrington et al., 1998; Harrington et al., 2004, Vardy, Daffertshofer, & Beek, 2009). It was suspected that, among others, the construction-related delay of the first tactile stimulator could have influenced this measure. Therefore, a new stimulator with a lower delay was developed and used within this experiment. The resulting peripheral variance though still showed an influence of the target interval.

Therefore, an assessment of the model validity in terms of the predictions regarding the autocorrelations at lag 1 to 9 was conducted. Another analysis method was ap-



(a) Feedback off

(b) Feedback on

Figure 4.7: Feedback in combination with Tapmode and Target Interval is responsible for an interaction effect on the ratings of mental effort. Without feedback (Figure 4.7a), there is a difference between the two tapping speeds in the contact-free condition, whereas with feedback, this difference cannot be found (Figure 4.7b). Error bars show 95% confidence intervals.

plied: the non-fitting trials (about a third of the total number of trials) were excluded and the remaining trials subsequently analyzed via linear mixed-effects modeling. This method showed effects comparable to the results of the first method (analyze all trials regardless of violations of the model predictions). The peripheral variance still showed a significant influence of target interval. Therefore, the first method was maintained (inclusion of all trials).

According to (Vorberg & Wing, 1996), the autocorrelation of the lags 2 and greater should be equal to zero. In this experiment, it was found that this was not the case for several lags. A probable cause for the unexpected increase in the peripheral variance with target interval seems to be a violation of the assumption that intervals in a sequence more than one steps apart are independent from each other. Theoretically, decomposition of the model variance is not justified if the assumptions are not met. However, to allow for further comparisons with the findings of Drewing et al. (2002), Drewing and Aschersleben (2003), and Drewing (2013), the variance decomposition was applied continuing in the following experiments.

The influence of the surrogate tactile feedback was not as pronounced as in the previous experiment. Within the contact-free tapping conditions, the central variance was generally higher than when participants tapped onto a solid surface, therefore augmenting the results of Drewing et al. (2002).

During the slower tapping speed, the surrogate tactile feedback decreased the central variance estimated at contact-free tapping, to the level of the classical tapping with surface contact. Hence, it seems that the surrogate tactile feedback could be integrated into the body scheme and was used to compensate for the missing tactile sensory reafferences, which is in line with the results of Drewing et al. (2002). The faster tapping speeds though were seemingly too fast to allow for this integration.

A reasonable account on these findings seems to be provided by Ernst and Bülthoff (2004) and their notion of multisensory integration in form of a perception-action loop. Their idea is that humans combine information following two general strategies:

1. Maximizing information by combining all available sensory information
2. Increase reliability by reducing variance in the sensory estimate

According to Ernst and Banks (2002), this happens in a optimal weighted fashion. Hence, it seems that the signals of proprioceptive origin were allocated more weight than the surrogate tactile feedback signals.

The constant error essentially confirms the findings from the first experiment. Faster tapping speeds lead to a constant error closer to zero than slower tapping speeds, and generally, the constant error increases about a few milliseconds during the course of the experiments, as shown by the effect of Block. The interaction pattern of Feedback and Target Interval was also found within the first experiment—although in this experiment, the difference in the slower tapping conditions was not as pronounced as in the first experiment. This ruled out the idea of the larger delay of the tactile stimulator used in Experiment 1 as possible cause for the interaction pattern. Instead, it supports the notion derived from the effects on the central variance, that proper integration of surrogate tactile feedback is problematic at the faster tapping speeds.

Compared to the first experiment, the more sophisticated force analysis allowed a deeper insight to the force mechanisms taking place turing a tap. Both components, the M1 and the M2, were influenced by Target Interval, with slower tapping speed yielding a higher force and vice versa. This is in line with earlier research (Carlton, Carlton, & Newell, 1987). The authors found an increase of force peak amplitude with force pulse duration. Ulrich and Wing (1991) proposed a model for this increase. Since the longer target intervals in this experiment also yielded higher momenta, both findings fit together.

Interestingly, the first momentum showed an influence of Block, while the second did not. Comparably, the first amplitude also showed an influence of block, while the second did not. The differences found between both amplitudes and momenta could originate in a combination of initiation and stabilization of the force application. A possible explanation for the differences may be that both components rely on different neural mechanisms. The first peak (initialization) could originate in a central loop, which could explain the influence of surrogate feedback. The the second peak (stabilization) in contrast seems to be of peripheral origin, probably conrolled by a long loop reflex. Experiments 4 and 5 will further investigate this point.

Furthermore, the surrogate tactile feedback showed marginal influences only in the M1 component: In the faster tapping conditions, the M1 amplitude was lower with surrogate tactile feedback than without feedback in the first three blocks. In the slower tapping conditions however, the first block shows the opposite (larger M1 with surrogate tactile feedback than without). Summed up, there seems to be an unsystematic feedback effect on the M1 amplitude. The reason for these differences remains unclear. It could be that the force adaption to the surrogate tactile feedback requires a longer period and is reached only at the last block. Considering the earlier mentioned notion by Ernst and Bülthoff (2004), sensory information is limited, therefore the two available signals (natural and surrogate feedback) for the tactile modality are being integrated. A possible interpretation would be that the participants had difficulties with the integration of both tactile signals, which led to the difference in force amplitudes. Eventually (in the fourth block), the artificial signal could have been integrated correctly, leading to comparable force amplitudes. This assumption is supported by the constant and variable error, which show effects of Block as well, essentially representing a learning curve to successfully integrating the surrogate tactile feedback to increase precision. However, as mentioned earlier, it cannot be verified because it remains unknown what would have happened after the last block.

Finally, the ratings of mental effort were influenced by Tapmode: contact-free tapping seems to require additional resources. Furthermore, the surrogate feedback only affected the effort ratings in contact-free tapping in combination with slower tapping speed. Interestingly, this factorial combination was the same for the effect of the surrogate tactile feedback on the central variance. The increased mental effort at least indirectly supports the earlier made assumption that the surrogate tactile feedback did indeed contribute to the timing of movements.

In summary, Experiments 1 and 2 suggest that surrogate tactile feedback requires considerable practice to be properly integrated into the timing of movements. Therefore, in Experiment 3, an attempt is made to decrease the amount of required practice by increasing the familiarity with the surrogate tactile feedback.

Chapter 5

Experiment 3: Tactile Pacing

5.1 Introduction

The surrogate tactile feedback in two different versions used in Experiments 1 and 2 caused effects on the behavioral measures (e.g., constant error) and on the estimated variance components from the two-level timing model, but these effects were sometimes not very pronounced. Based on the force analysis of Experiment 2, it was hypothesized that the feedback could not have been integrated successfully into the body scheme before the last block of the experiment.

Since participants got always paced during the synchronization phase by an auditive metronome, this could have led to difficulties with the sensory integration of the surrogate tactile feedback. Therefore, the idea of this experiment was to enforce the meaning of the surrogate tactile feedback by making it the only available modality, as surrogate feedback and as metronome. It will be tested whether the emphasis on the tactile feedback actuator leads to more pronounced effects of feedback within the components of the two-level timing model.

Tactile metronomes have been used before in tapping studies (Elliott, Wing, & Welchman, 2010; Wing, Doumas, & Welchman, 2010). Both studies studied only synchronization accuracy. Wing et al. used a Phantom 1.5 lightweight robot to pace the participants' left index finger. The task was to synchronize tapping movements of the right index finger to the tactile metronome or the audio metronome, as precisely as possible. Elliott et al. instead used a tactile actuator to deliver tactile pulses to the left index finger, thus more comparable to the actuator used in this experiment. However, both of these studies measured synchronization accuracy in terms of the negative onset asynchrony (Aschersleben & Prinz, 1995) and did not employ a continuation phase.

To maintain comparability with the previous two experiments, the current experiment will study the effects of tactile pacing within the synchronization-continuation paradigm and test whether a tactile pacing will improve the sensory integration of the surrogate tactile feedback during the continuation phase, by means of the two-level timing model as well as the constant and variable error.

Furthermore, only contact-free tapping was used within this experiment to eliminate as much reafferent tactile feedback as possible, because it may interfere with the surrogate feedback signal. Considering the context of assistance systems, this experiment is of high relevance since it would allow to broaden the methods available for studying the effects of surrogate feedback on healthy participants and use the results for improving surrogate feedback implementation.

5.2 Method

5.2.1 Participants

A total of 24 individuals (all right-handed, 13 female) participated in the study. Their mean age was 24.17 years ($SD = 3.07$, age range = 18–30 years). The participants were mostly students recruited by advertisements at the local universities or via social networks. In return for their participation, they received either €10 or course credits. All participants gave informed consent.

5.2.2 Design

The factorial design of the experiment consisted of the factors Pacing (audio, tactile) × Feedback (on, off) × Target Interval (250 ms, 500 ms) × Block (1, 2, 3, 4). All factors were within-subjects factors.

The factors Pacing and Feedback were assigned using a Latin square design, based on the participant id number. The two target intervals were counter-balanced across participants: for each element in the Latin square, participants with an uneven id number started with 250 ms target intervals, follwed by 500 ms target intervals, and vice versa for participants with an even id number. Each target interval in each element of the latin square was repeated two times in succession. This pattern constituted a block and was repeated four times.

The analysis was carried out using complete trials as observations. During the experiment, each completed trial was immediately checked for misses or double taps: each of the collected ITIs had to be at least 0.5×Target Interval long and shorter than 1.5×Target Interval at the same time. If this was not the case, the trial was repeated up to three times. In case it failed for a fourth time, the sequence was accepted and a note was written to the log file—however, this was never the case in this experiment.

5.2.3 Procedure

In this experiment, the procedure was identical to Experiment 2, except for the changes made to the apparatus. For the tactile pacing, the signal from the photoelectric sensor, which was used in Experiments 1 and 2 for triggering the surrogate tactile feedback stimulator, was blocked in the synchronization phase. Instead, it was driven to produce a isochronous sequence of tactile pulses on the toe, to which the participants had to synchronize. After 15 pulses, the normal surrogate feedback mechanism was activated seamlessly.

5.3 Results

5.3.1 Pretests

The same pretests as in Experiment 2 were conducted in advance to the main task. Summary statistics for the two point discrimination test are given in Table 5.1. In this experiment, the sensitivity was especially important since in half of the trials the pacing relied on the tactile sensitivity of the participants.

Compared to the values of the participants in Experiment 2 (Table 4.1 on page 66), the sensitivity was generally comparable, while the participants in this experiment were a bit more sensitive regarding the two-point discriminatory ability at their toes. The touch pressure thresholds measured by the Semmes-Weinstein monofilament test (Table 5.2) were generally comparable to the ones measured in Experiments 1 and 2.

The results of the Finger Opposition Task are reported in Table 5.3. A Wilcoxon signed rank test with continuity correction shows that there is a significant difference between the number of correctly executed sequences at the two time points ($W = 10$, $Z = -3.92$, $p < .001$, $r = 0.8$), thus yielding the same learning effect as the previous two

Table 5.1: Stats for the two-point discrimination test.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	1.60	2.80	3.10	3.08	3.45	4.40
left index finger	1.00	2.80	3.20	3.18	3.80	4.60
left big toe	3.60	7.15	8.10	8.46	10.40	13.80

Table 5.2: Distribution of the touch pressure thresholds at different body locations, measured using the Semmes-Weinstein monofilament test. The column names headers represent the markings on the monofilaments, their thickness ascending with the numbers.

	2.36	2.83	3.22	2.44	3.61	3.84	4.08
right index finger	15	8	1				
left index finger	18	3	1	2			
left big toe		6	7	3	3	4	1

experiments. Also, the number of erroneously executed sequences showed no difference ($W = 29.5$, $Z = -0.31$, $p = 0.784$, $r = 0.06$).

5.3.2 Constant and Variable Error

Constant error There were 78 outliers removed from a total of 1536 observations (5.08%). The pacing method did not influence the constant error ($p = 0.39$).

There was a significant interaction effect of the two factors Feedback and Block on the constant error ($F[2.91,67.04] = 5.38$, $p < .01$, $\eta^2_G = .007$). With feedback, the constant error constantly decreased (Figure 5.1). The last block was significantly lower than the first ($p < .001$). Without feedback, the constant error did not change. This difference might reflect a learning process to use the feedback. Furthermore, it is interesting to note that the change in the constant error during the course of the experiment within the feedback condition represents a comparable finding to the two previous experiments (decrease over the course of the experiment), while the condition without surrogate feedback and without change over blocks does not. In Experiments 1 and 2, the constant error decreased during the course of the experiment mostly independent of feedback (except for Experiment 1, where the location of the feedback (hand vs. foot) determined how fast the constant error decreased).

Table 5.3: Descriptive statistics for the number of correctly and wrongly executed sequences at the Finger Opposition Task. Before/after refers to the point in time of the test relative to the main experiment.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	8.00	15.00	18.50	18.30	22.00	26.00
Correct (after)	13.00	19.80	22.00	21.80	24.00	31.00
Errors (before)	0.00	0.00	1.00	0.92	1.00	4.00
Errors (after)	0.00	0.00	1.00	1.62	1.00	22.00

Additionally, there was a significant interaction effect of Target Interval and Block ($F[2.41,55.36] = 4.97$, $p < .01$, $\eta^2_G = .008$). Initially, during the first block, the constant error for both target intervals is at the same level (Figure 5.2). Beginning with the second block, the constant error for the 500 ms target intervals significantly decreases, while the constant error for the shorter intervals remain at their initial level (p's $< .0001$). A comparable effect was also found in Experiment 2.

Variable error There were 18 outliers removed from a total of 1536 observations (1.17%). Similar to the constant error, there was no significant effect of Feedback on the variable error ($p = 0.15$), nor was there any significant difference induced by Pacing ($p = 0.69$).

The variable error was subject to a significant main effect of the factor Target Interval ($F[1,23] = 57.48$, $p < .0001$, $\eta^2_G = .16$). As expected, the variable error increased with interval duration: at 250 ms intervals, the mean variable error was 404.97 ms^2 ($SD = 797.98\,\mathrm{ms}^2$; $M_s = 18.43\,\mathrm{ms}$, $SD_s = 10.85\,\mathrm{ms}$). At 500 ms intervals, the mean variable error amounted to 792.55 ms^2 ($SD = 656.46\,\mathrm{ms}^2$; $M_s = 27.22\,\mathrm{ms}$, $SD_s = 8.8\,\mathrm{ms}$).

Additionally, there was a significant main effect of Block ($F[1.71,39.37] = 10.01$, $p < .001$, $\eta^2_G = .04$). Means and other statistics can be found in Table 5.4. Post-hoc tests showed that the variable error in the first block was significantly higher than in all other three blocks (p's $< .0001$), furthermore was the last block also lower than the second block ($p = 0.014$). A similar pattern was found in Experiment 2.

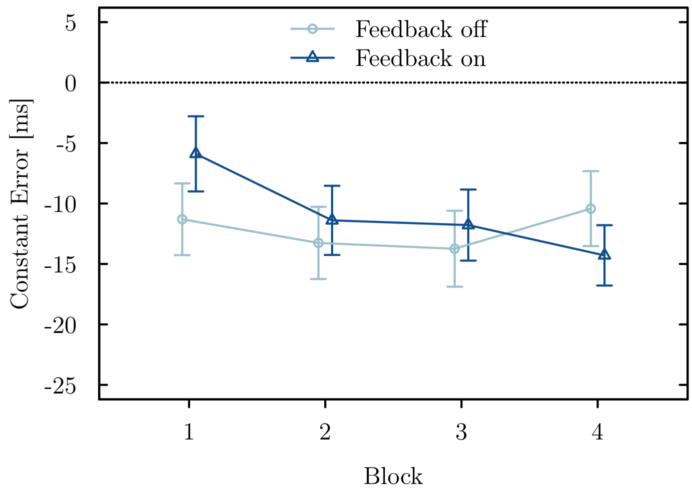


Figure 5.1: Interaction of Feedback and Block on the constant error. Without Feedback, the constant error did not change significantly across blocks. Error bars show 95% confidence intervals.

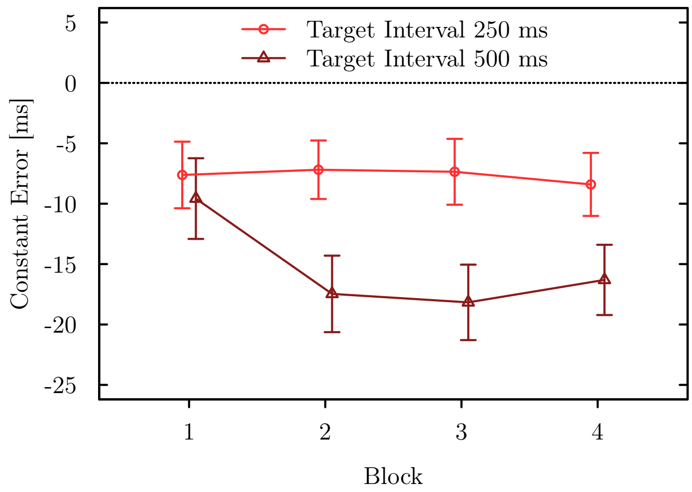


Figure 5.2: Interaction of Target Interval and Block on the constant error. The constant error increases from the first to the second block and then remains unchangend for the last three blocks, but only in the 500 ms condition. Exactly this pattern was also found in Experiments 1 and 2, but for both target intervals. Error bars show 95% confidence intervals.

Table 5.4: Main effect of Block on the variable error (VE and VE_s (SD)). The VE is significantly higher in the first block than in the fourth block.

Block	VE [ms^2]	SD	SE	CI	VE_s [ms]	SD_s [ms]
1	735.77	937.69	47.85	94.08	24.83	11.80
2	607.09	592.81	30.25	59.48	23.11	9.13
3	557.52	459.84	23.47	46.14	22.26	8.47
4	494.68	377.10	19.24	37.84	21.09	7.70

5.3.3 Wing-Kristofferson Analysis

Central variance There were 19 outliers removed from a total of 1536 observations (1.24%). There was no significant effect of feedback on the central variance ($p = 0.52$), nor was there any significant difference induced by Pacing ($p = 0.28$). Instead of making the surrogate tactile feedback more prominent, the use of two pacing methods seems to have removed the influence of tactile feedback on the central variance.

As expected based on the model predictions, there was a main effect of Target Interval ($F[1,23] = 32.41$, $p < .0001$) on the central variance component. Longer target intervals led to a higher central variance ($M = 778.74\,ms^2$, $SD = 859.53\,ms^2$) than the shorter target intervals ($M = 428.71\,ms^2$, $SD = 1024.94\,ms^2$).

There was also an effect of Block on the central variance: $F[1.50,34.39] = 5.53$, $p = 0.01$ (Figure 5.3). The last block yielded a significantly lower central variance than the first block ($p < .0001$). In the previous two experiments, this effect was not present in the central variance estimate, but instead in the peripheral variance estimate, where it is also found in other studies (Drewing & Aschersleben, 2003).

Peripheral variance There were 16 outliers removed from a total of 1536 observations (1.04%). The peripheral variance showed a marginally significant main effect of pacing ($F[1,23] = 3.81$, $p = 0.06$, $\eta^2_G = .007$). The tactile pacing method led to a lower peripheral variance estimate ($M = -11.4\,ms^2$, $SD = 215.47\,ms^2$) than the audio method ($M = 8.67\,ms^2$, $SD = 241.88\,ms^2$). The mean peripheral variance estimate for the tactile method was negative, which was not found in any of the previous experiments.

Furthermore, there was a significant interaction effect of Pacing and Target Interval ($F[1,23] = 5.83$, $p = 0.02$, $\eta^2_G = .009$). The effect is shown in Figure 5.4. The combi-

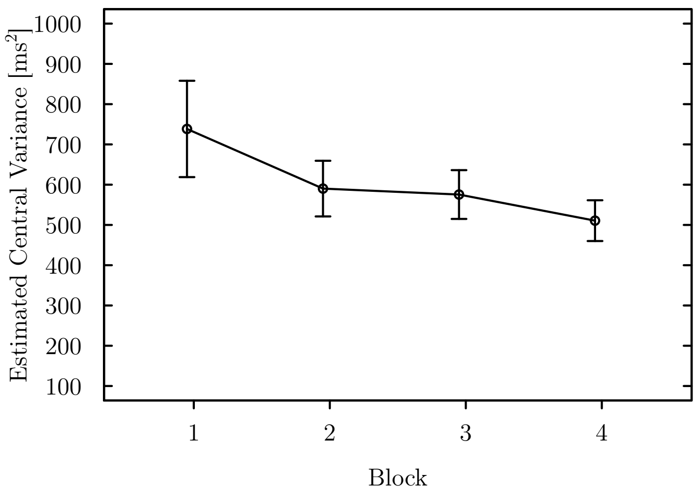


Figure 5.3: Central variance estimate across blocks. Only the difference between the first and last block was significant, the differences between the other blocks were not. Error bars show 95% confidence intervals.

nation of audio pacing and slow target intervals was the only condition, in which the mean estimate of the peripheral variance was positive (and significantly higher than all other conditions; p's $< .01$). The other three combinations of the two factors all yielded negative estimates, which did not differ from each other. Naturally, there are no negative variances by definition—however, because of the mathematical structure of the two-level timing model and since the estimators of the two variance components are derived from the autocorrelations, negative values are generally possible.

Model validity assessment

There were 785 (51.11%) valid trials, where $-1/2 \leq \rho_I(1) \leq 0$. Similar to the previous experiments, the autocorrelations for lags greater than 1 often were not equal to 0. For instance, at lag 4, the mean autocorrelation was $M = 0.06$ ($SD = 0.18$), which significantly differed from zero: $t[23] = 8.22$, $p < .0001$. For additional statistics of the autocorrelations at different lags see Table 5.5. As mentioned above, the occurence of negative variance estimators indicated problems with the estimation process. Since only half of the trials comply with the original model assumptions regarding the value of $\rho_I(1)$, this indicates a problem with the assumption of stationarity.

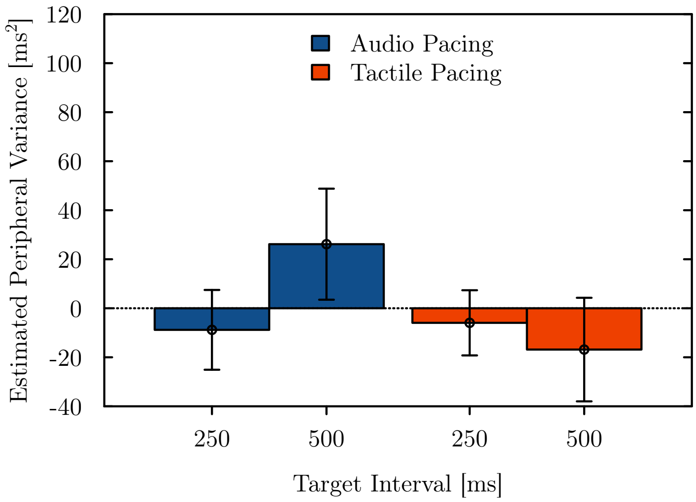


Figure 5.4: Interaction of Pacing and Target Interval on the peripheral variance estimate. Note that tapping with audio pacing and slow speed was the only factorial combination yielding a valid estimate—all other three combinations were negative. Error bars show 95% confidence intervals.

5.3.4 Mental Effort

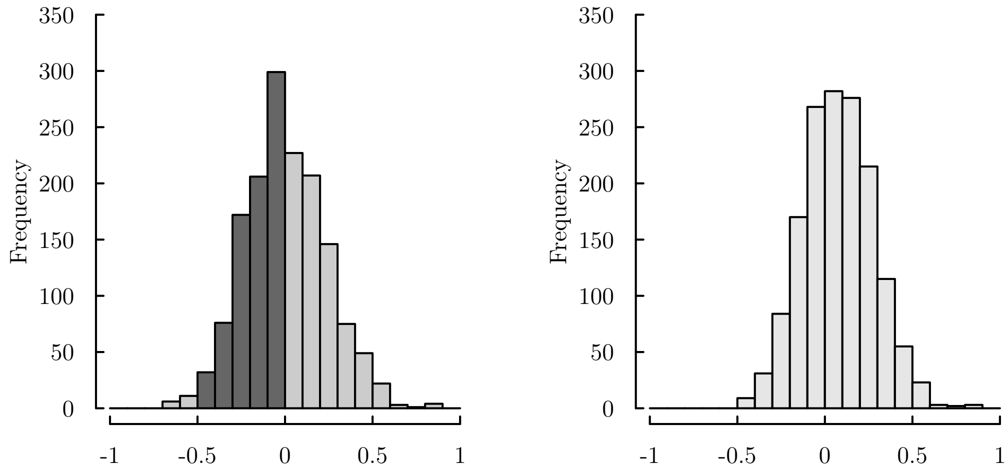
After each condition resulting from the factorial design, participants had to fill in the Rating Scale of Mental Effort (RSME). The ratings were used to get a further perspective on the application of surrogate tactile feedback.

There were 41 outliers removed from a total of 768 observations (5.34%). There was a marginally significant interaction effect found between Target Interval and Block: F[2.25,51.73] = 2.74, p = 0.07, $\eta^2_G = .002$. All affected conditions are plotted in Figure 5.6. Although there seem to be differences during the first blocks, post-hoc tests did not yield any significant differences.

Furthermore, there was an interaction effect of the factors Feedback and Block (F[2.31,53.20] = 3.43, p = 0.03, $\eta^2_G = .001$). This effect is shown in Figure 5.7. The ratings seem to alternate from block to block, however, post-hoc tests did not yield any significant differences.

Table 5.5: Test statistics of the autocorrelations at lag 2 to lag 9 (alternative hypothesis: true mean is not equal to 0). Confidence levels are 99%.

	df	t-value	p-value	sample mean	lower CI bound	upper CI bound
lag 2	23	5.86	0.000	0.078	0.041	0.116
lag 3	23	4.76	0.000	0.044	0.018	0.070
lag 4	23	8.22	0.000	0.056	0.037	0.075
lag 5	23	3.19	0.004	0.023	0.003	0.042
lag 6	23	3.12	0.005	0.022	0.002	0.042
lag 7	23	1.02	0.317	0.007	-0.012	0.025
lag 8	23	3.22	0.004	0.018	0.002	0.034
lag 9	23	-0.17	0.863	-0.001	-0.014	0.013



(a) Lag 1 autocorrelation (b) Lag 2 autocorrelation

Figure 5.5: Histogram and density function of lag 1 autocorrelation (Figure 5.5a) and lag 2 autocorrelation (Figure 5.5b). Lag 1 should be bound between -.5 and 0 (colored in dark grey), Lag 2 should be around zero.

5.4 Discussion

The objectives to be tested in this experiment were twofold: first, to test whether the familiarity of the surrogate tactile feedback could be enhanced by using it to convey the pace of the tapping trials to the participants and second, how these differences

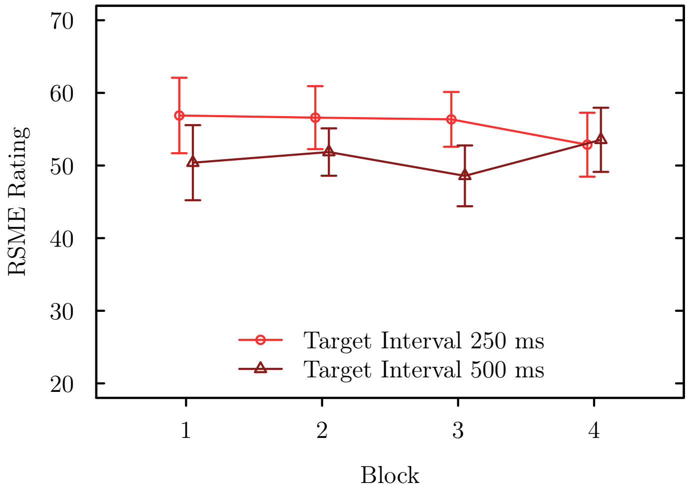


Figure 5.6: Ratings of mental effort. Target Interval in combination with Block is responsible for an interaction effect. Error bars show 95% confidence intervals.

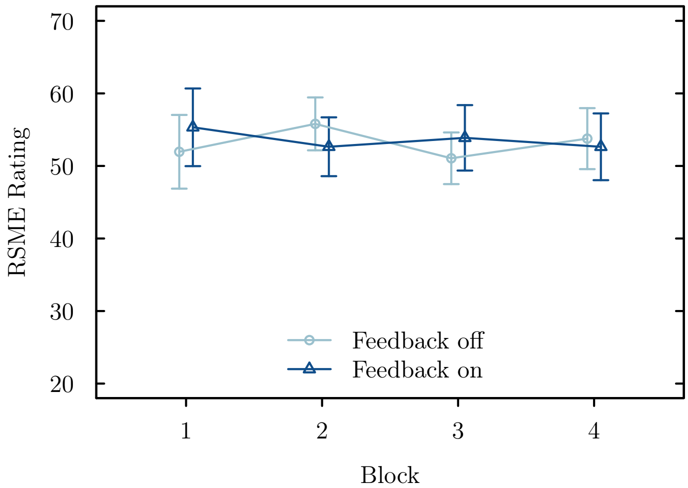


Figure 5.7: Interaction of Feedback and Block. Post-hoc tests did not yield significant differences. Error bars show 95% confidence intervals.

would reflect on the variance components of the two-level timing model.

The results were not as expected. There was no influence of the presence of feedback nor the pacing modality on the variable error and the central variance estimate. In terms of the peripheral variance, there was indeed an influence of pacing modality, with the tactile pacing yielding a lower estimate than the standard audio pacing. A possible interpretation would be an increased familiarity with the motion, similar to the findings of Drewing and Aschersleben (2003) and the first two experiments of this thesis. However, since it was the only measure influenced by pacing, this familarity effect seemed not very likely. Therefore, the idea of using tactile pacing in combination with contact-free tapping to increase the relevance in continuation tapping was not supported by the results.

Furthermore, the mean estimate for the peripheral variance in the tactile pacing condition was negative. Negative variances may be regarded as an undesireable feature of the estimators of the two-level timing model and seem to happen in about 30% of practical cases (Kampen & Snijders, 2002).

Although the results have been screened for drift by splitting the tapping sequences and comparing both halves, the occurence of negative peripheral variances indicate that there still could have been a trend in the results. Vorberg and Wing (1996) showed that even small trends that violate the assumption of stationarity can lead to errors in the estimation of the central and peripheral variance. For guarding against nonstationarity, they recommend experimental control and data screening.

Concrete suggestions regarding experimental control include the use of training and a synchronization phase, which was applied in every experiment in this thesis. Furthermore, they recommend the use of many shorter trials as opposed to few longer trials, since the effect of nonstationarity tends to increase with the length of a tapping trial. Long and short in this context remains unspecified, Vorberg and Wing give two hypothetic examples with length $n = 30$ for a short and $n = 100$ for a long sequence of inter-tap-intervals. The value of $n = 45$ used in this thesis therefore could be considered as shorter sequence, where the estimators of central and peripheral variance are more robust. Data screening was conducted by the above mentioned method of comparing first and second halves of intertapping sequences, accompanied by an outlier analysis and replacement previous to submitting the estimators of individual sequences to the analysis.

Different strategies to cope with sequences violating the model predicitons regarding the autocorrelation at lag 1 ($-0.5 \leq \rho_I(1) \leq 0$) have been discussed in the previous chapter (cf. Section 4.2.3 on page 72), leading to the conclusion that the results remain more or less the same regardless of which strategy is actually chosen (O'Boyle et al., 1996). This was also confirmed in Experiment 2 by means of post-hoc analysis using linear mixed-effects modelling.

However, the percentage of trials with a negative motor variance was 52.28% in this experiment, which seems to be higher than in the previous two experiments. Since the trials with a negative motor variance are distributed almost evenly between the two pacing methods (audio: 27.15% valid trials, tactile: 25.13%), the high amount of trials with a negative motor variance estimate was most certainly due to the contact-free tapping task. Therefore, and because of comparability with the majority of other tapping studies, the following two experiments will again employ audio pacing in place of tactile pacing and a standard tapping task with a solid surface.

Chapter 6

Experiment 4: Feedback Delay

The setup of the first experiment employed a tactile actuator with a construction conditioned delay of about 12 ms. The applicability of the two-level timing model was questioned because the peripheral variance increased with target interval and the deviations of the autocorrelations from zero for lags greater than one. Therefore, for the setup of the second experiment, a new tactile stimulator with a low delay (less than 2 ms) was constructed and used for the following experiments. Nevertheless, the peripheral variance remained influenced by Target Interval.

Still, the idea to study the effects of a delayed feedback signal remained—first, because it is theoretically relevant and second, because it is of high relevance for development and construction of assistance systems. As mentionend earlier, in a recent study, Drewing (2013) used feedback delay in a bimanual tapping task. In their study, participants tapped alternating with both hands. Taps were accompanied with an auditory feedback on each tap—however, for one hand (i.e., for every other tap), the feedback was delayed. The participants reacted with subconscious partial compensation of the inter-tap-intervals. In an unimanual condition, Drewing confirmed the compensation partially.

Regarding the initially mentioned notion of multisensory integration (Ernst & Banks, 2002; Ernst & Bülthoff, 2004), it would be interesting to see whether the results would be comparable to the ones obtained by Drewing, when the surrogate feedback is of the same modality as the proprioceptive tactile-kinaesthetic feedback generated by the index finger during the tapping movements. If this is the case, the influence of the surrogate tactile feedback should decrease with increasing delay.

Another way to manipulate the reliability of the feedback signal would be to introduce a jitter factor into the feedback signal (i.e., a variable error instead of a constant error). However, to allow for a comparison with Experiment 1 and other studies (e.g. Drewing, 2013), a number of constant delays were chosen as reliability manipulation.

The unimanual condition employed by Drewing (2013) had two delay conditions: every other tap delayed by 30 ms and a control condition without delay. They did this to compute the “inter sensory consequence intervals” by using taps without matching sensory consequences (viz., delayed auditory feedback) as well as matching feedback (undelayed auditory feedback) within a tapping trial. To maintain consistency with the earlier experiments in this thesis, the delay in this experiment will be applied to each tap. This way, phase correction (i.e., the process of adapting the tempo after perturbations (Repp, 2005) does not confound with the measurements since there is no within-sequence perturbation as in the sequence pattern used by Drewing.

This experiment solely used the classical tapping task (tapping on a solid surface) known from Experiments 1 and 2. The decision to not employ a contact-free tapping task was based on two considerations: first, the body of available literature is larger for the classical tapping task and second, the contact-free tapping task seems not to be described by the two-level timing model as good as the classical task (see previous experiment). Furthermore, the classical tapping device allows evaluation of the applied force during the tapping movements.

6.1 Method

6.1.1 Participants

A total of 26 individuals (all right-handed, 21 female) participated in the study. Their mean age was 24.15 years ($SD = 2.85$, age range = 18–31 years). The participants were mostly students recruited by advertisements at the local universities or via social networks. In return for their participation, they received either €10 or course credits. All participants gave informed consent.

6.1.2 Design

The factorial design of the experiment consisted of the factors Delay (0, 12, 24, 48 ms) × Target Interval (250 ms, 500 ms) × Block (1, 2, 3, 4). All factors were within-subjects factors. Additionally, there was a control condition without tactile feedback.

The factor Delay and the control condition without feedback were assigned using a Latin square design, based on the participant id number. The two target intervals were counter-balanced across participants: for each element in the Latin square, participants with an uneven id number started with 250 ms target intervals, follwed by 500 ms target intervals, and vice versa for participants with an even id number. Each target interval in each element of the latin square was repeated two times in succession. This pattern constituted a block and was repeated four times.

The analysis was carried out using complete trials as observations, except for the force analysis and the related correlations, where each tap was used as observation. During the experiment, each completed trial was immediately checked for misses or double taps: each of the collected ITIs had to be at least 0.5×Target Interval long and shorter than 1.5×Target Interval at the same time. If this was not the case, the trial was repeated up to three times. In case it failed for a fourth time, the sequence was accepted and a note was written to the log file—however, this was never the case in this experiment.

6.1.3 Procedure

In this experiment, the procedure was identical to Experiment 2, except for the changes made to the apparatus.

To realize the artificial delayed signal, an Arduino Uno microcomputer was integrated into the experimental setup. Depending on the state of a 2 bit interface, the Uno delayed the incoming signal (TTL from the tapboxes indicating the status of the photoelectric sensor) 0, 12, 24 or 48 milliseconds. The microcomputer offered submillisecond temporal precision.

6.2 Results

6.2.1 Pretests

The same pretests as in Experiments 2 and 3 were conducted prior to the main task. Summary statistics for the two point discrimination test are given in Table 6.1.

The values yielded by the Semmes-Weinstein monofilament test are reported in Table 6.2. Generally, the participants showed tactile sensibility values comparable to the ones obtained in the previous experiments.

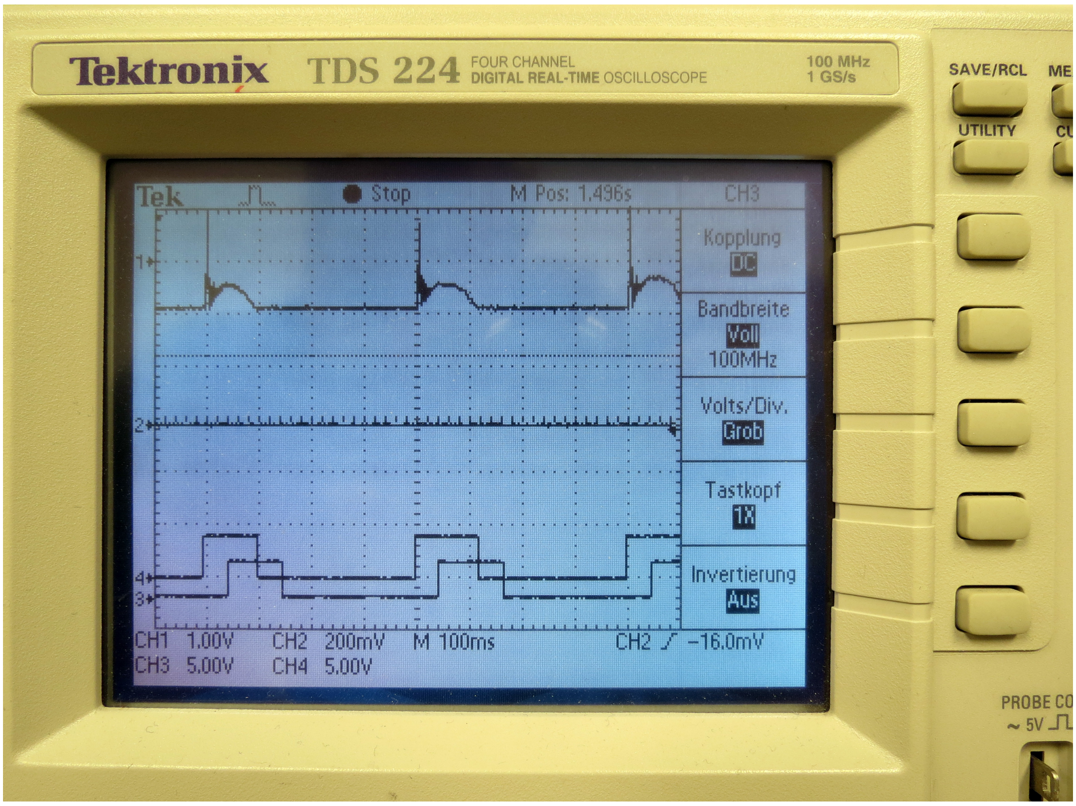


Figure 6.1: Control measurement of the delayed feedback signal. Channel 1 shows the voltage emitted by the force key, channel 3 shows the logic level of the photoelectric sensor and channel 4 the delayed tactile signal output (here the 48 ms condition).

Descriptive statistics for the Finger Opposition Task are shown in Table 6.3. A Wilcoxon signed rank test with continuity correction shows that there is a significant difference between the number of correctly executed sequences at the two time points ($W = 58.5$, $Z = -2.79$, $p < .01$, $r = 0.55$), showing the same learning effect known from the previous experiments. The number of erroneusly executed sequences instead showed no difference ($W = 47.5$, $Z = 0.23$, $p = 0.913$, $r = 0.05$).

6.2.2 Constant and Variable Error

Constant error There were 96 outliers removed from a total of 2080 observations (4.62%). An interaction effect of Delay and Target Interval was present in the ana-

Table 6.1: Stats for the two-point discrimination test.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	2.40	3.20	3.50	3.60	4.00	5.80
left index finger	2.00	3.00	3.20	3.41	3.90	6.40
left big toe	5.60	7.45	8.20	8.25	9.35	10.80

Table 6.2: Distribution of the touch pressure thresholds at different body locations, measured using the Semmes-Weinstein monofilament test. The column headers represent the markings on the monofilaments, their thickness ascending with the numbers.

	1.65	2.36	2.4	2.44	2.83	3.22	3.61	3.84	4.08
right index finger	2	12	1	5	4	2			
left index finger	1	19		4		2			
left big toe					8	10	4	2	2

lyzed data (F[3.42,85.62] = 3.88, $p < .01$, $\eta_G^2 = .003$). The effect is plotted in Figure 6.2. Post-hoc tests showed that with zero delay ($p < .01$) and in the control condition entirely without surrogate tactile feedback ($p < .001$), the constant error is significantly higher for the 500 ms than the 250 ms Target Interval. With a delay of 12 ms and higher, the differences between both target intervals blurred ($p > .99$).

Furthermore, there was a significant main effect on the constant error induced by the factor Block (F[1.77,44.18] = 6.53, $p < .01$, $\eta_G^2 = .02$). Block means and additional statistics are printed in Table 6.4. The only difference between blocks, which was non-significant, was the difference between the second and third block ($p = 0.06$). All other differences were significant. The constant error thus increased in the course of the experiment, which replicates the findings from Experiment 1 and 2 (as well as Experiment 3, but only in the condition with surrogate feedback).

Variable error There were 111 outliers removed from a total of 2080 observations (5.34%). The delay of the surrogate tactile feedback did not have a significant influence on the variable error ($p = 0.28$).

The variable error was subject to a significant effect of the factor Target Interval (F[1,25] = 397.81, $p < .0001$, $\eta_G^2 = .65$). As expected based on the previous experi-

Table 6.3: Descriptive statistics for the number of correctly and wrongly executed sequences at the Finger Opposition Task. Before/after refers to the point in time of the test relative to the main experiment.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	10.00	13.20	16.50	17.90	20.80	30.00
Correct (after)	12.00	15.00	18.50	20.40	23.00	38.00
Errors (before)	0.00	0.00	1.00	1.19	2.00	5.00
Errors (after)	0.00	0.00	1.00	1.19	2.00	4.00

Table 6.4: Main effect of Block on the constant error. The only difference between the blocks, which was not significant, is the difference between the second and third block—all other differences were significant.

Block	Constant Error [ms]	SD	SE	CI
1	-4.96	18.08	0.79	1.56
2	-7.98	16.81	0.74	1.45
3	-10.01	17.10	0.75	1.47
4	-11.27	17.22	0.76	1.48

ments as well as other studies (Stevens, 1886), the variable error increased with interval duration: at the shorter 250 ms intervals, the mean variable error was 284.82 ms^2 ($SD = 202.88\,ms^2$; $M_s = 16.38\,ms$, $SD_s = 5.14\,ms$). In conditions employing the longer 500 ms intervals, the mean variable error amounted to 779.3 ms^2 ($SD = 376.15\,ms^2$; $M_s = 27.44\,ms$, $SD_s = 6.66\,ms$).

The amount of variable error also changed over blocks ($F[2.77,69.22] = 6.04$, $p < .01$, $\eta^2_G = .02$). Means and other statistics can be found in Table 6.5. The variable error in the fourth block is considerably lower than in the first and second block (p's = 0.014). This was also found in Experiments 1 and 2.

6.2.3 Wing-Kristofferson Analysis

Central variance There were 95 outliers removed from a total of 2080 observations (4.57%). Contrary to the expectations, Delay did not have a significant influence on the central variance estimate ($p = 0.13$).

As expected from the model predictions, there was a large main effect of Target

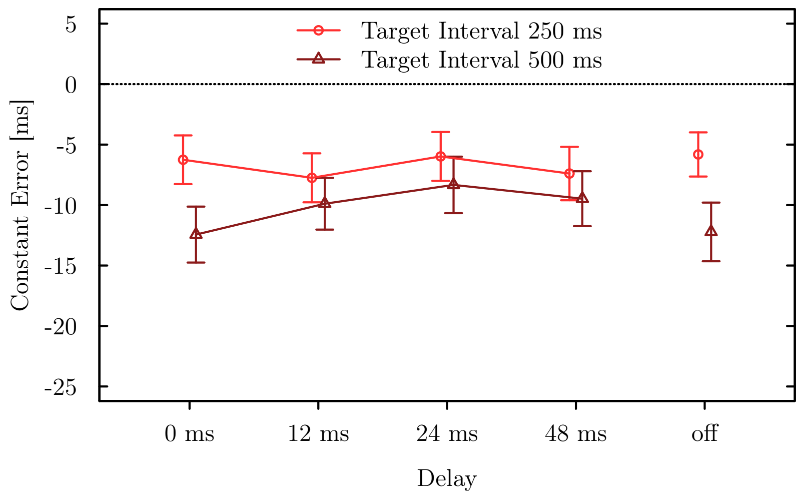


Figure 6.2: Interaction of Delay and Target Interval on constant error. The constant error differs for the two target intervals if the surrogate feedback is undelayed or missing (control condition). The other levels of Delay did not yield significant differences. Error bars show 95% confidence intervals.

Interval ($F[1,25] = 425.63$, $p < .0001$, $\eta^2_G = .50$) on the central variance component. The slow target intervals led to a higher central variance estimate ($M = 633.58\,\text{ms}^2$, $SD = 444.95\,\text{ms}^2$) than the fast target intervals ($M = 240.74\,\text{ms}^2$, $SD = 246.69\,\text{ms}^2$).

Peripheral variance There were 107 outliers removed from a total of 2080 observations (5.14%). The delay of the surrogate did not have a significant influence on the peripheral variance estimate ($p = 0.18$).

A significant difference induced by Target Interval was found within the peripheral variance component ($F[1,25] = 12.09$, $p < .01$, $\eta^2_G = .05$). Similar to the central variance estimates, long target intervals led to a higher peripheral variance estimate ($M = 59.76\,\text{ms}^2$, $SD = 182.18\,\text{ms}^2$) than the short target intervals ($M = 20.55\,\text{ms}^2$, $SD = 106.47\,\text{ms}^2$).

Model validity assessment

There were 1226 (58.94%) valid trials, where $-1/2 \leq \rho_I(1) \leq 0$. The autocorrelations for lags greater than 1 often were not equal to 0. For instance, at lag 4,

Table 6.5: Main effect of Block on the variable error (VE and VE_s (SD)). The fourth block is marginally significant lower than the first block. Other blocks do not differ.

Block	VE [ms^2]	SD	SE	CI	VE_s [ms]	SD_s [ms]
1	556.81	367.71	16.13	31.68	22.54	7.64
2	551.01	386.49	16.95	33.30	22.31	8.10
3	525.76	386.97	16.97	33.34	21.71	8.18
4	494.66	364.49	15.98	31.40	21.06	8.07

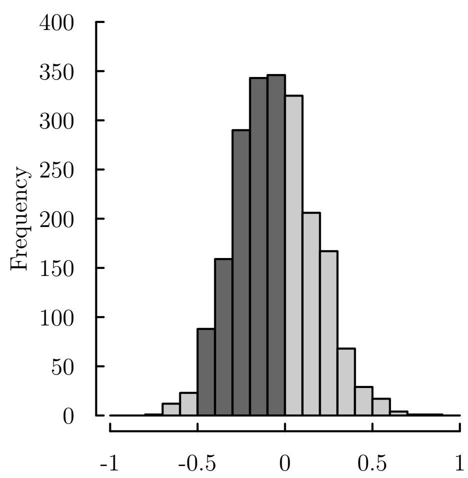
the mean autocorrelation was $M = 0.04$ ($SD = 0.18$), which significantly differed from zero: $t[25] = 8.33$, $p < .0001$. For additional statistics of the autocorrelations at different lags see Table 6.6.

Table 6.6: Test statistics of the autocorrelations at lag 2 to lag 9 (alternative hypothesis: true mean is not equal to 0). Confidence levels are 99%.

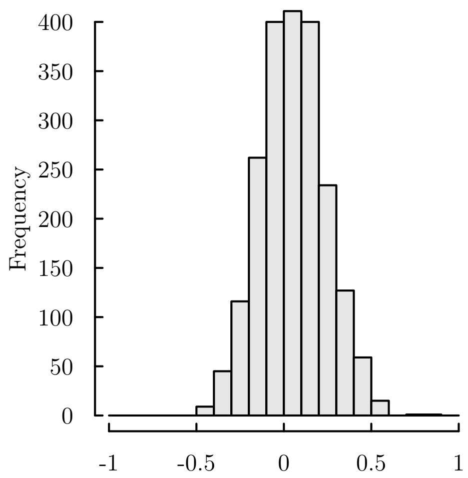
	df	t-value	p-value	sample mean	lower CI bound	upper CI bound
lag 2	25	6.77	0.000	0.055	0.032	0.077
lag 3	25	3.22	0.004	0.021	0.003	0.039
lag 4	25	8.33	0.000	0.037	0.025	0.050
lag 5	25	0.34	0.739	0.002	-0.012	0.015
lag 6	25	2.17	0.040	0.010	-0.003	0.022
lag 7	25	-2.61	0.015	-0.010	-0.022	0.001
lag 8	25	0.40	0.694	0.002	-0.011	0.015
lag 9	25	-3.13	0.004	-0.013	-0.024	-0.001

6.2.4 Force Analysis

The force data of the current experiment were analyzed as in Experiment 2: first, distinct specific elements of each tap were determined (Peaks M1 and M2 as well as points L1, L2 and L3; cf. Section 2.4.3 on page 45 for details), followed by momenta A1 and A2.



(a) Lag 1 autocorrelation



(b) Lag 2 autocorrelation

Figure 6.3: Histogram and density function of lag 1 autocorrelation (Figure 6.3a) and lag 2 autocorrelation (Figure 6.3b). Lag 1 should be bound between -.5 and 0 (colored in dark grey), Lag 2 should be around zero.

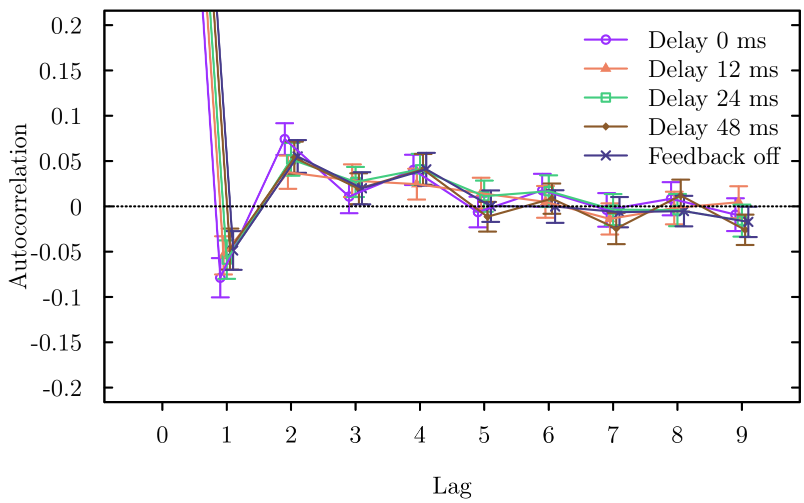


Figure 6.4: Autocorrelation function across lags 0 to 9, split by Delay. Error bars show 95% confidence intervals.

M1 Amplitude

There were 4106 outliers removed from a total of 91803 observations (4.47%). The M1 amplitude differed across the different levels of Delay (F[3.03,75.80] = 4.39, $p < .01$, $\eta^2_G = .002$). The effect is shown in Figure 6.5. The effect showed an interesting V-shaped curve. The M1 at 12 ms and 48 ms delay did not differ ($p = 0.866$). All other differences were significant (p's < .01). The control condition entirely without surrogate tactile feedback resulted in an M1 amplitude higher than any condition with surrogate tactile feedback, regardless of delayed or not ($p < .0001$).

Target interval also had an influence on the first maximum (F[1,25] = 12.75, $p < .01$, $\eta^2_G = .01$). The effect showed the same pattern as in Experiment 2: slower speeds lead to a greater amplitude. The mean value of the M1 peak found during the shorter target intervals was $M = 2.15$ N ($SD = 0.99$ N), lower than the peaks found during the longer target intervals ($M = 2.42$ N, $SD = 1.02$ N).

Futhermore, the M1 changed over blocks (F[1.44,35.89] = 12.58, $p < .001$, $\eta^2_G = .03$). Mean values and additional statistics are shown in Table 6.7. The amplitude measured at the M1 increased continously with the course of the experiment, each block being significantly higher than the previous block. This was comparable to the pattern found in Experiment 2, where the M1 in the first block was lower than the subsequent three blocks.

Table 6.7: Main effect of Block on the M1 component. The M1 increases significantly from block to block. The unit of the values is Newton.

Block	M1 amplitude [N]	SD	SE	CI
1	2.00	0.87	0.01	0.01
2	2.21	0.73	0.00	0.01
3	2.40	0.77	0.01	0.01
4	2.52	0.84	0.01	0.01

M2 Amplitude

There were 4402 outliers removed from a total of 91803 observations (4.8%). Again, similar to the M1 amplitude, the M2 amplitude varied with different levels of Delay (F[3.08,77.11] = 3.12, $p = 0.03$, $\eta^2_G = .003$). The effect is shown in Figure 6.5. The effect shows a V-shaped curve, comparable to the one found in the M1 component. All differences were significant (p's $< .0001$). The control condition entirely without surrogate tactile feedback, again, similar to the M1, resulted in a M2 amplitude higher than any condition with surrogate tactile feedback, regardless of delayed or not ($p < .0001$).

Like the M1, Target interval also had a significant influence on the second maximum ($F[1,25] = 9.88$, $p < .01$, $\eta^2_G = .010$). The mean value of the M2 peak found during the shorter target intervals was $M = 0.84\,\mathrm{N}$ ($SD = 0.36\,\mathrm{N}$), which was lower than the peaks found during the longer target intervals ($M = 0.91\,\mathrm{N}$, $SD = 0.39\,\mathrm{N}$).

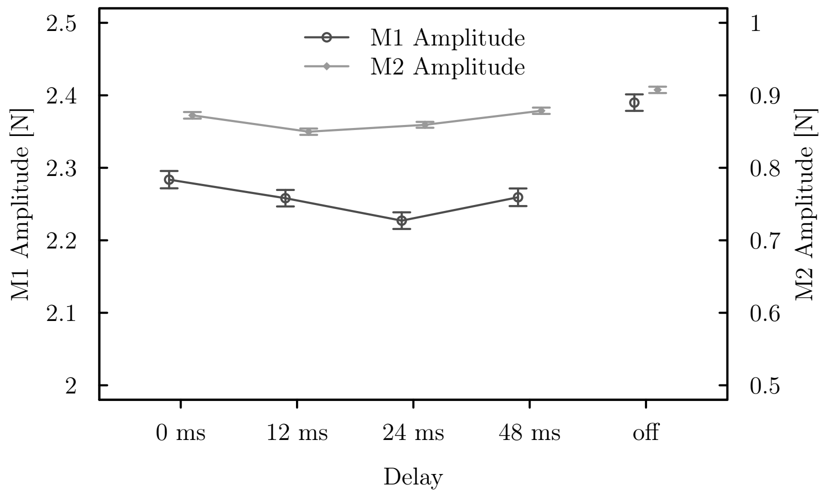


Figure 6.5: Main effect of Delay on both amplitudes, M1 and M2. Note the different intercepts, the M2 has been shifted by 1.5 N up to allow for better comparison of the curve shape. Both show essentially a V-shape. However, the distance of the control condition without surrogate tactile feedback is greater within the M1 amplitude. Error bars show 95% confidence intervals.

Correlations To further examine the assumption that the amplitudes M1 and M2 are the result of different neuronal origins (cf. discussion of Experiment 2), correlations between both amplitudes were computed for each tapping trial. Prior to submitting them to the ANOVA, they were z-transformed and outliers were replaced as described in the general methods. There were 43 outliers removed from a total of 1040 observations (4.13%). The overall spearman correlation coefficient collapsed across all conditions was strong ($r_s = 0.61$). The explained variance ($r^2 = 0.37$) is likelky due to the shared baseline of both peaks, viz. if a tap is generally executed with more pressure than others in a sequence, both components are likely to be influenced.

A main effect of Block became apparent: F[1.74,43.46] = 5.66, p < .01, $\eta^2_G = .03$. Means are plotted in Figure 6.6. Delay did not influence the correlation between both amplitudes (p = 0.12).

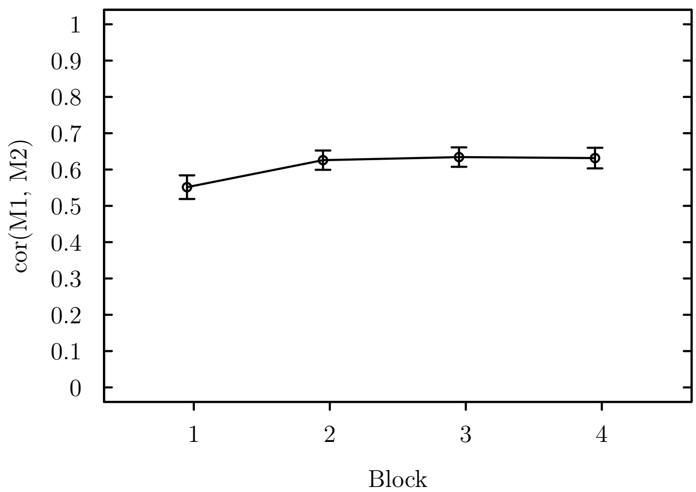


Figure 6.6: Correlation between M1 and M2 variance across blocks. Error bars show 95% confidence intervals.

Time to Peak (TTP)

There were 3990 outliers removed from a total of 91803 observations (4.35%). TTP was subject to a marginally significant effect of the factor Delay: F[3.39,84.78] = 2.26, p = 0.08, $\eta^2_G = .002$; see Figure 6.7. The TTP at 12 ms was significantly higher than the TTP at 0 ms (p < .01), while the TTP at 24 ms, in turn, is higher than the TTP measured at 12 ms delay. (p < .001). The TTP with no surrogate tactile feedback at all was lower than all other levels of Delay (p < .0001).

Similar to Experiment 2, there was an effect of Target Interval: F[1,25] = 13.07, p < .01, $\eta^2_G = .02$. The M1 amplitude was reached faster during the longer 500 ms target interval ($M = 4.58$ ms, $SD = 0.93$ ms) compared to the shorter 250 ms target interval ($M = 4.78$ ms, $SD = 0.98$ ms).

TTP also depended on Block (F[1.38,34.54] = 9.19, p < .01, $\eta_G^2 = .03$). The means are shown in Table 6.8. At each block, the TTP was significantly smaller than the previous blocks (p < .0001), the first block being the longest.

Table 6.8: Main effect of Block on the Time To Peak (TTP), reported in milliseconds. The TTP measured at each block is significantly lower than the respective previous block.

Block	TTP [ms]	SD	SE	CI
1	4.86	0.88	0.01	0.01
2	4.73	0.73	0.00	0.01
3	4.61	0.73	0.00	0.01
4	4.53	0.75	0.00	0.01

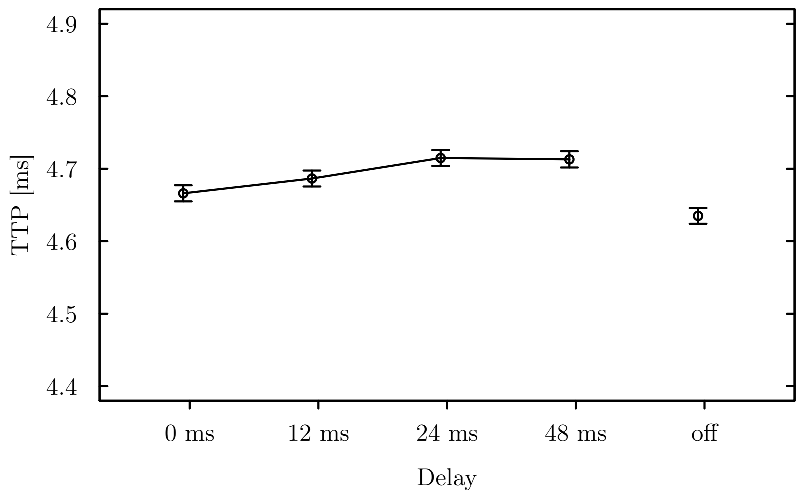


Figure 6.7: Main effect of Delay on the time-to-peak (TTP). Error bars show 95% confidence intervals.

There was a strong correlation between TTP and the following force peak (M1), $r(24) = -0.85$, p < .0001. This means that on a short TTP, a large peak followed and vice versa.

Momentum (A1 and A2)

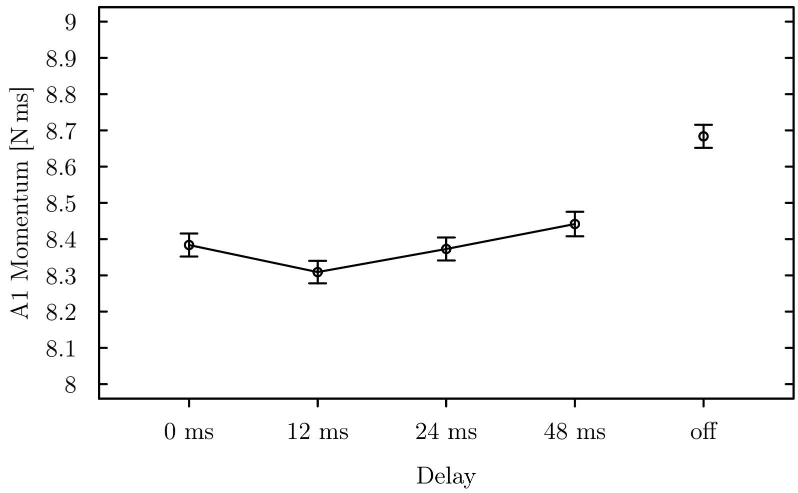


Figure 6.8: Main effect of Delay on the A1 Momentum. Error bars show 95% confidence intervals.

A1 There were 3790 outliers removed from a total of 91803 observations (4.13%). There was a main effect of Delay on the first momentum: F[2.74,68.51] = 3.04, p = 0.04, $\eta^2_G = .001$. The effect is shown in Figure 6.8. Post-hoc analysis showed that all factor levels significantly differed from each other (p's < .01), except between 24 ms and 0 ms delay (p = 0.597).

Additionally, the momentum differed between both target intervals. At shorter intervals, participants applied a lower momentum ($M = 8.14$ N ms, $SD = 2.76$ N ms) compared to conditions employing the longer 500 ms target interval ($M = 8.74$ N ms, $SD = 2.78$ N ms; F[1,25] = 9.41, p < .01, $\eta^2_G = .008$).

Finally, the momentum showed a main effect of Block: F[1.74,43.62] = 8.00, p < .01, $\eta^2_G = .01$). Means and additional statistics are shown in Table 6.9. Every block differs from each other significantly (p's < .0001), showing an increased momentum with each block.

A2 There were 2971 outliers removed from a total of 91803 observations (3.24%). Contrary to the A1 momentum, there was no effect of Delay on the A2 (p = 0.21).

Table 6.9: Main effect of Block on the A1 momentum. Each block significantly differs from each other.

Block	A1 [N ms]	SD	SE	CI
1	7.85	2.43	0.02	0.03
2	8.29	2.08	0.01	0.03
3	8.68	2.16	0.01	0.03
4	8.94	2.27	0.02	0.03

The only significant influence on the A2 momentum was exerted by the target interval. At shorter intervals, participants applied a lower momentum ($M = 38.22$ N ms, $SD = 30.98$ N ms) compared to the longer 500 ms target intervals ($M = 57.03$ N ms, $SD = 42.69$ N ms; F[1,25] = 31.04, p < .0001, $\eta^2_G = .09$).

Correlations The correlations between both momenta A1 and A2 were also analyzed using the same procedure as described for both amplitudes. There were 44 outliers removed from a total of 1040 observations (4.23%). The overall spearman correlation coefficient collapsed across all conditions was low ($r_s = 0.34$).

Target Interval exerted the only significant influence on the correlation coefficient between A1 and A2 (F[1,25] = 9.87, p < .01, $\eta^2_G = .02$). The correlation between A1 and A2 was higher for longer target intervals $M = 0.38$ ($SD = 0.29$) compared to shorter target intervals ($M = 0.3$; $SD = 0.3$). Delay did not influence the correlation between both momenta (p = 0.16).

6.2.5 Mental Effort

After each condition resulting from the factorial design, participants had to fill in the Rating Scale of Mental Effort (RSME). The ratings were used to get a further perspective on the application of surrogate tactile feedback. There were 56 outliers removed from a total of 1040 observations (5.38%). Delay had no significant effect on the ratings of mental effort (p = 0.48).

The factor Target Interval was part of an interaction effect in combination with the factor Block: F[2.34,58.62] = 4.87, p < .01, $\eta^2_G = .004$. The effect is shown in Figure 6.9. The differentces between the two target intervals were different in the last two blocks: clearly for the third (p < .0001), but also at the fourth block (p = 0.043).

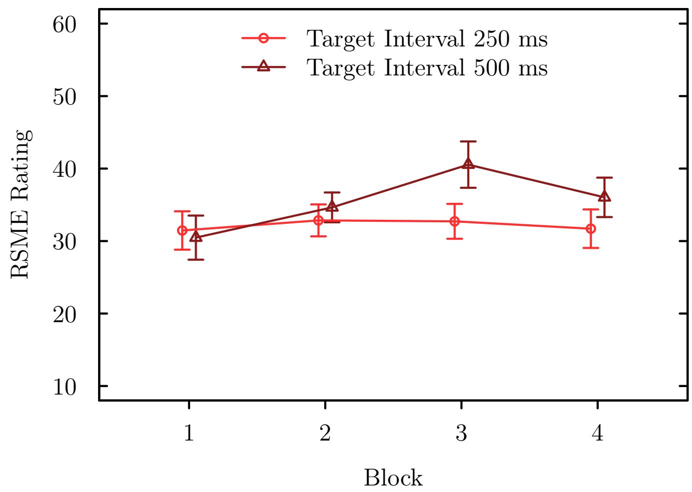


Figure 6.9: Ratings of mental effort as a function of Block, split by Target Interval. Error bars show 95% confidence intervals.

6.3 Discussion

The goal of this experiment was to test the influence of delayed surrogate tactile feedback on the performance at a tapping task. Contrary to the expectations, the delay neither had an effect on the central variance estimate, nor on the peripheral variance estimate. The number of trials consistend with the model assumptions at lag 1 was around 60%, which was comparable to Experiments 1 and 2. Additionally, the usual increase on the central variance with longer target intervals was found, as well as the unusual increase of the peripheral variance with longer target intervals.

A possible cause of the absence of an effect of the delay could have its origin in the unreliability of the feedback signal, which was introduced with the delay itself. If the delay of the feedback did really reduce the perceived reliability of the signal, it could have been ignored by the motor system, since through reducing the reliability of a sensory signal, the acceptance and relevance towards this signal decreases (Elliott et al., 2010).

The delay had an influence on the constant error: the longer target intervals led to a larger constant error in two situations: 1) when the feedback was undelayed and 2) in the control condition without surrogate tactile feedback. These two conditions were at the same level, the conditions with delayed feedback (12, 24 and 48 ms) instead led to values comparable to all conditions with the shorter target interval, which showed no differences across the different levels of delay.

The plunger used in Experiment 1 (with a delay of about 12 ms) led to a lower constant error (around −6 ms, cf. Figure 3.1 on page 55) compared to the condition without feedback (about −12 ms) during the short target intervals. In the conditions with longer target intervals, the opposite was found (smaller constant errors with feedback as compared to greater errors without feedback).

While data from Experiment 2 seemed to support this interaction pattern in the results, Experiment 4 provided evidence against this notion. In the discussion of Experiment 2, it was assumed that the underlying pattern was essentially the same and the sample difference just failed to reach significance. But the above mentioned interaction pattern did not show up in Experiment 4. In fact, there were only minor, non-significant differences within the fast tapping conditions of Experiment 2 related to feedback, as confirmed by Experiment 4. If the interaction pattern would have been confirmed, the lines of both target intervals in Figure 6.2 would have intersected, which is not the case. Instead, the feedback at the 250 ms target interval does not seem to exert any influence—as opposed to the 500 ms target interval, which does show influence of surrogate tactile feedback. Together, this supports the assumption made in Experiment 1, that the faster tapping speed seems to be too fast to integrate additional tactile input.

The differences found on the 500 ms target intervals instead showed influence of (delayed) feedback. However, since the constant error with undelayed surrogate tactile feedback was comparable to the constant error without surrogate tactile feedback, it seems that the surrogate tactile feedback in the delayed conditions perturbed or at least interfered with the temporal coordination—at least in terms of the constant error. These findings therefore verfied the assumption that the delay of the surrogate tactile feedback is of importance for the effective use as surrogate signal to enhance temporal coordination even at a range of less than 12 ms. However, this perturbation was not reflected by the variable error.

The measures extracted from the force data instead showed influences of delay, in both amplitudes (M1 and M2) as well as the first momentum (A1). This was interesting, since the second maximum M2 and the first momentum A1 were not influenced by the surrogate tactile feedback in Experiment 2. In Experiment 4, however, both amplitudes showed a comparable influence of the delay, best described as V-shape. While the conditions with feedback (delayed and undelayed) generally yield lower force amplitudes than the control condition without feedback, the gap is much more distinct in M1 than in M2.

Contrary to the amplitudes, the delay only manifested in the first momentum. Interestingly, the effect of Block also only affected the measures of the first peak (M1 and A1). Both essentially show an increase during the course of the experiment. This pattern was also found in Experiment 2 and seems to constitute a practice-related effect. This would fit to the notion of differnt neurological origins for both tap components. Additional evidence comes from the correlations between both measures: first, the correlation between M1 and M2 changed during the course of the experiment (and could be the result of a learning effect manifested in the M1) and second, the correlation between both measures of effort (A1 and A2) was generally low.

Furthermore, an effect of tapping speed was found on all measures: M1, M2, TTP, A1 and A2. This was comparable to the one found in Experiment 2. Generally, slower tapping speeds led to higher amplitudes and more effort. This fits to the findings of Vardy et al. (2009), who also found a general increase in tapping force with target interval.

Finally, a post-hoc comparison using Welch's unequal variances t-test (Welch, 1947) showed that the pooled mean force generally was 0.89 N ($SD = 0.83$ N) lower than in Experiment 2 ($t[35.49] = 2.05$, $p = 0.047$), which could have been caused by the large amount of delayed conditions present in the design. Verifying this assumption was one of many reasons for conducting Experiment 5.

In summary, it can be said that since the delay had an effect on the force measurements and the constant error, it was a) recognized and b) a working manipulation of reliability of the sensory signal offered by the surrogate feedback. The absence of Delay effects on the two-level timing model estimators therefore seems more likely due to the problems regarding the unmet model assumptions. This assumption will be further tested in Experiment 5 by again employing delayed surrogate tactile feedback, next to other factors.

Chapter 7

Experiment 5: Influence of Feedback Modality and Age

Experiment 4 studied the effects of an artificially delayed feedback. Contrary to the expectations, the different levels of delay were not reflected by the variable error and both variance components of the two-level timing model, only by the constant error. Within the constant error, in turn, there was an influence of delay found only in the slower tapping speed. A proposed explanation was that the surrogate tactile feedback was not integrated into the perception at the fast tapping speed.

However, the surrogate tactile feedback did exert effects on all force measures in all conditions. According to the notion of weighted sensory reafferences (Ernst & Banks, 2002), it seems plausible to assume that surrogate tactile feedback does contribute to the force regulation, but not to the temporal coordination, when the quality of the signal is not reliable in terms of temporal precision. Of course, this assumption depends on the premise that the the constant delay of the feedback signal decreased the perceived reliability.

An alternative explanation would be that the delay of the feedback signal allows for an effective integration in terms of economic force regulation, since both amplitudes (M1 and M2) in Experiment 4 were lowest at 12 ms and 24 ms, respectively. This suprsising result could mean that immediate tactile surrogate feedback interfered with the sensory reafferences, which hindered proper integration and hence, optimal economic force regulation in terms of lesser force application.

Force regulation is very economic in humans, as shown by studies of grip force regulation: when lifting an object, only the absolutely necessary force plus a safety margin is applied (Johansson & Westling, 1987, Nowak, Glasauer, & Hermsdörfer, 2004). Studies with anaesthesized grasping fingers in turn showed inefficiently increased grip forces when handling hand-held objects (Nowak et al., 2001).

Nowak et al. (2004) concluded that visual feedback was used to compensate for the missing tactile sensory reafferences in a deafferented patient. If cross-modal sensory feedback can be incorporated into the force regulation as shown by Nowak et al. (2004) and the assumption that there is an intereference between the endogenous and immediate surrogate tactile feedback is true, this means that the force amplitudes measured under the influence of surrogate audio feedback would not show a V-shape across the different levels of delay as found in Experiment 4, but instead a linear decline or even remain constant across the different levels of delay.

To address this point, this experiment will employ the same pattern of delayed surrogate feedback signals, but with an auditory modality as comparison. Delayed auditory feedback was often used in the tapping literature. More than five decades ago, Chase, Harvey, Standfast, Rapin, and Sutton (1959) found that delayed auditory feedback also impairs tapping tasks comparable to the effect of disrupt human speech (Lee, 1950). For speech, the impairment increases with the delay and reaches asymptote at around 270 ms (P. Q. Pfordresher, 2006). Finney and Warren (2002) successfully expanded these findings to rhythmic tapping.

The maximum delay of the feedback signals used in the current experiment is 48 ms with the shortest target interval being 250 ms, thus far away from the maximum impairment zone found by Finney and Warren (2002). However, as Experiment 4 showed, there was already a disruption found within the smallest delay used (i.e., 12 ms).

Drewing (2013) used more comparable values of auditory feedback delay (0, 15, 30, 45 ms) in tapping experiments. However, they were applied in alternating fashion (i.e., every other tap produced a delay) in an unimanual tapping or in bimanual tapping only one hand got delayed feedback. The current study could augment the findings of Drewing by using feedback delay for every tap with the value of delay varied between trials. If the proposition of the *sensory-goals model* (Drewing & Aschersleben, 2003) is valid, the additional sensory reafferences should decrease timer variance when feedback delay is zero and increase subsequently for higher values of delay.

Since the surrogate feedback in the literature is mostly auditory, the current experiment will use both modalities—audio and tactile, varied within subjects—to offer a direct comparison between the effects of the two. Delayed audio feedback has been used in a considerable number of tapping studies (e.g., Wing, 1977; Drewing & Aschersleben, 2003; Finney & Warren, 2002; Drewing, 2013). According to P. Pfordresher and Palmer (2002), it is often found that the variable error increases with increasing delay of the feedback signal up to 200 ms. Since the values of delay in this study are much lower, it is expected that the variability increases with delay.

The ability to accurately time and synchronize actions is essential for maintaining stability in movement, reacting to unexpected events and interacting with others (Elliott, Wing, & Welchman, 2011). Older adults, however, often show reduced proprioceptional and reduced motor functionality (slower and less precise in comparison to younger adults; Rinkenauer, 2008). If this reduced functionality would be reflected by the measures of the current study, one could conceive of supporting mechanisms specifically tailored for the deficits of older adults.

In continuation tapping (Krampe, Engbert, & Kliegl, 2001) as well as in synchronization tasks (Drewing, Aschersleben, & Li, 2006), no differences related to age were found for the reproduction of isochronous rhythms. It was also shown that in general, older adults retained a good synchronization ability (Repp & Su, 2013). However, Elliott et al. (2011) investigated the effects of age on the integration of multi-sensory feedback on the synchronization performance in a tapping task. They employed an auditory metronome as well as a tactile metronome, consisting of a solenoid based actuator at the non-dominant index finger (thus comparable to the feedback method used in Experiment 1). They varied the reliability of the auditory metronome by introducing jitter to the auditory metronome. When both metronomes were present, the older adults showed a higher variability of their negative mean asynchrony at increasing jitter.

The current study employs not jitter, but delay as a method of signal perturbation. Similar to the afore-mentioned study, the surrogate feedback is offered as a combination of (surrogate) audio and (endogenous) tactile feedback. It will therefore be interesting to see whether the age effect found by Elliott et al. (2011) also shows up during the continuation phase in this experiment—for theoretical reasons, since this would further increase the knowdledge about the mechanisms of sensory integration at older age, but for practical reasons as well, at least when it comes to the implementation of assistive devices for older adults.

7.1 Method

7.1.1 Participants

A total of 40 individuals (all right-handed) participated in the study. A major difference to the previous experiments was, that two age groups were recruited. The mean age of the younger group (11 female) was 25.8 years ($SD = 3.81$, age range = 18–33 years). The mean age of the group of old adults (10 female) was 68.4 years ($SD = 4.81$, age range = 61–78 years).

The younger participants were mostly students recruited by advertisements at the local universities or via social networks, whereas the older participants were recruited by advertisements placed in newspapers and from an internal data base with older adults willing to participate in scientific experiments. In return for their participation, all participants received either €10 or course credits. All participants gave informed consent.

7.1.2 Design

The factorial design of the experiment consisted of the factors Age (young, old) × Modality (audio, tactile) × Delay (0, 12, 24, 48 ms) × Target Interval (250 ms, 500 ms) × Block (1, 2, 3, 4). All factors were within-subjects factors with the exception of age, which was of course a between-subjects factor. Additionally, there was a control condition without any surrogate feedback at all.

The factors Modality and Delay were assigned using a Latin square design, based on the participant id number. The two target intervals were counter-balanced across participants: for each element in the Latin square, participants with an uneven id number started with 250 ms target intervals, follwed by 500 ms target intervals, and vice versa for participants with an even id number. Each target interval in each element of the latin square was repeated two times in succession. This pattern constituted a block and was repeated four times.

The analysis was carried out using complete trials as observations, except for the force analysis and the related correlations, where each tap was used as observation. During the experiment, each completed trial was immediately checked for misses or double taps: each of the collected ITIs had to be at least 0.5×Target Interval long and shorter than 1.5×Target Interval at the same time. If this was not the case, the trial was repeated up to three times. In case it failed for a fourth time, the sequence was accepted and a note was written to the log file. One participant of the older age group met this criterion and was thus excluded from the analysis. To keep the age group balanced, an additional participant was tested and included in the analysis.

7.1.3 Procedure

In this experiment, the procedure was identical to Experiment 4. Additionally, a professional hearing test (Oscilla® USB 350B) was conducted in the beginning. All participants were tested for sufficient hearing abilities up to 2 kHz.

In contrast to all previous experiments, Experiment 5 was conducted on two subsequent days. This was partly due to the increased number of factorial conditions, but also to enable the analysis of possible retention effects. The break was achieved by stopping the experiment after the second block and continuing the experiment on the following day with the third block.

The manipulation of the surrogate tactile feedback could be recycled from Experiment 4. For the auditory feedback, the microcomputer generated the feedback tones (1342 Hz, easily distinguishable from the pacing tones with 1000 Hz) on the fly with submillisecond temporal precision. The duration of the feedback tones depended on the tap duration (about 100 ms, depending on the participants) to mimic endogenous feedback as closely as possible. The feedback tones were mixed into the headphones used for delivering the white noise and the pacing stimuli, at the same volume level as the pacing tones (78 dB).

7.2 Results

7.2.1 Pretests

The same pretests as in Experiments 2, 3, and 4 were conducted. Summary statistics for the two point discrimination test are given in Tables 7.1 and 7.2.

The evaluation of the two point discriminatory ability regarding the effects of age showed a significant difference for both locations, the right index finger ($U = 59$, $Z = 3.83$, $p < .001$, $r = 0.61$) as well as the right big toe ($U = 57$, $Z = 3.87$, $p < .001$, $r = 0.61$).

Table 7.1: Statistics of the two-point discrimination test for the younger participants.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	2.40	3.00	3.50	3.58	4.20	5.80
left index finger	2.00	2.80	3.30	3.26	3.80	4.20
left big toe	5.40	7.95	8.50	8.61	9.15	13.80

Table 7.2: Statistics of the two-point discrimination test for the older participants.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	3.40	4.35	4.50	4.56	4.85	5.60
left index finger	2.80	4.20	4.60	4.44	5.00	6.00
left big toe	8.80	9.75	10.80	10.60	11.40	12.20

The values yielded by the Semmes-Weinstein monofilament test are reported in Tables 7.3 and 7.4. The evaluation of the touch pressure threshold regarding the effects of age using the Mann-Whitney U test showed a significant difference for the right index finger ($U = 96$, $Z = 2.97$, $p < .01$, $r = 0.47$), but not for the toe ($U = 158.5$, $Z = 1.21$, $p = 0.233$, $r = 0.19$).

Table 7.3: Distribution of the touch pressure thresholds of the younger adults at different body locations, measured using the Semmes-Weinstein monofilament test. The column headers represent the markings on the monofilaments, their thickness ascending with the numbers.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	2.36	2.36	2.36	2.48	2.54	2.83
left index finger	1.65	2.36	2.36	2.38	2.54	2.83
left big toe	2.44	3.22	3.22	3.28	3.61	3.61

Descriptive statistics for the results obtained at the finger opposition task are shown in Tables 7.5 and 7.6. A Wilcoxon signed rank test with continuity correction shows that there is a significant difference between the number of correctly executed sequences at the two time points for the younger participants ($W = 11$, $Z = -3.42$, $p < .001$, $r = 0.54$), but only marginally significant for the older group ($W = 35.5$, $Z = -2.06$, $p = 0.052$, $r = 0.33$).

Table 7.4: Distribution of the touch pressure thresholds of the older adults at different body locations, measured using the Semmes-Weinstein monofilament test.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
right index finger	1.65	2.42	2.83	2.85	3.22	3.61
left index finger	1.65	2.36	2.83	2.94	3.22	6.61
left big toe	2.36	3.22	3.42	3.43	3.61	4.17

Table 7.5: Descriptive statistics for the number of correctly and wrongly executed sequences at the FOT for the younger participants. Before/after refers to the point in time of the test relative to the main experiment.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	10.00	14.80	17.50	18.30	22.00	30.00
Correct (after)	11.00	16.50	22.50	21.90	27.00	32.00
Errors (before)	0.00	0.00	1.00	1.45	2.25	5.00
Errors (after)	0.00	0.00	1.00	1.15	2.00	4.00

The number of erroneusly executed sequences instead showed no difference for the younger participants ($W = 64.5$, $Z = 0.46$, $p = 0.461$, $r = 0.07$) compared to a marginally significant difference for the older adults ($W = 22$, $Z = -1.59$, $p = 0.09$, $r = 0.25$).

7.2.2 Constant and Variable Error

Constant error There were 281 outliers removed from a total of 5760 observations (4.88%). There was a main effect on the constant error caused by the factor Delay: $F[2.98,113.11] = 7.54$, $p < .001$, $\eta^2_G = .004$. Means and further statistics are shown in Table 7.7. The constant error was lowest with undelayed feedback, significantly lower than when feedback was delayed for 48 ms ($p < .001$), but also lower than the control condition entirely without feedback ($p < .0001$).

Furthermore, there was a significant main effect of the factor Modality on the constant error ($F[1,38] = 9.25$, $p < .01$, $\eta^2_G = .01$). The mean constant error was smaller (closer to zero) with tactile feedback ($M = -5.72$ ms, $SD = 18.98$ ms) than with audio feedback ($M = -9.49$ ms, $SD = 19.12$ ms). In the control condition without surrogate feedback, the constant error was around the same level of tactile feedback ($M = -5.39$ ms, $SD = 18.03$ ms).

Table 7.6: Descriptive statistics for the number of correctly and wrongly executed sequences at the Finger Opposition Task for the older participants. It is obvious that the older participants in comparison to the younger participants only showed marginal improvements regarding the number of correct sequences before/after. However, the errors also showed a marginal (though negligible) increase.

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Correct (before)	4.00	11.00	15.00	13.70	16.20	21.00
Correct (after)	7.00	12.00	15.00	15.00	18.00	22.00
Errors (before)	0.00	0.00	0.00	0.65	1.00	3.00
Errors (after)	0.00	0.00	1.00	1.10	2.00	4.00

Table 7.7: Main effect of Delay on the constant error. The only non-significant difference between the blocks was between the second and third block.

Delay	Constant Error [ms]	SD	SE	CI
0	-8.80	17.07	0.48	0.94
12	-8.08	17.29	0.48	0.95
24	-7.41	18.02	0.50	0.99
48	-6.12	17.55	0.49	0.96
off	-5.39	16.46	0.65	1.28

There were also a number of interaction effects. First, there was an interesting interaction between Modality and Delay ($F[2.75,104.56] = 4.12$, $p = 0.01$, $\eta^2_G = .002$). The effect is depicted in Figure 7.1. The audio feedback led to a higher constant error than tactile feedback for almost all delay conditions, except when the delay was set to 48 ms ($p = 0.769$). While the influence of tactile feedback remained constant over delays, the effect of audio feedback varied with delay. The constant error was highest without any delay ($M = -11.58$ ms, $SD = 15.62$ ms). With increasing delay, the constant error decreased, ie. approximated zero. The difference between auditive feedback without delay and auditive feedback with 24 ms delay was significant ($p = 0.231$). The difference between 24 and 48 milliseconds was also marginally significant ($p = 0.092$). This effect primarily showed that the above-mentioned main effect is solely due to the audio feedback modality. The length of the produced intervals therefore did not show any influence by the surrogate tactile feedback.

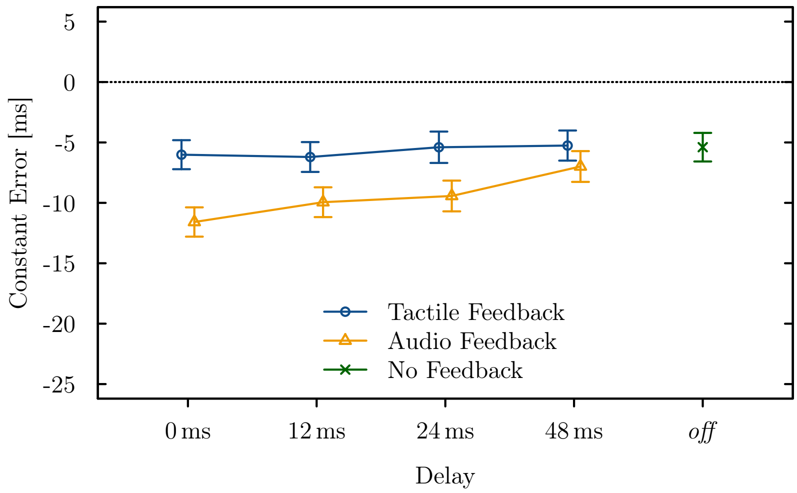
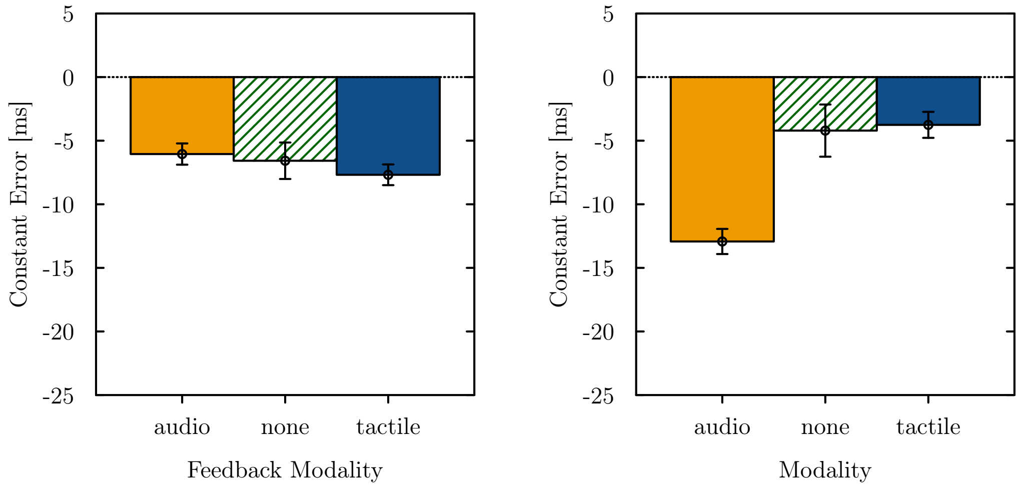


Figure 7.1: Interaction of Delay and Modality on constant error. The constant error differs between modalities. While audio feedback influenced the constant error, tactile feedback did not. Error bars show 95% confidence intervals.

The second interaction effect was caused by the factors Modality and Target Interval. Their combination exerted a significant interaction effect on the constant error ($F[1,38] = 22.82$, $p < .0001$, $\eta^2_G = .03$; see Figure 7.2). The conditions with the short target interval led to low differences within the constant error (Figure 7.2a). There was only one significant difference: between audio and tactile feedback ($p = 0.042$). The differences between both feedback modalities and the absence of surrogate tactile feedback were not significant ($p > .99$, $p = 0.743$).

Within the conditions employing the long target interval, the differences were more pronounced (Figure 7.2b). Audio feedback led to the lowest constant error of all combinations ($M = -12.92$ ms, $SD = 18.03$ ms), which was significantly lower than with tactile feedback ($p < .0001$) or without any surrogate feedback ($p < .0001$). The difference between the latter two was not significant ($p > .99$).

An interaction effect of Delay and Target Interval—similar to Experiment 4—was also present in the analyzed data ($F[2.88,109.40] = 3.08$, $p = 0.03$, $\eta^2_G = .001$). The effect is shown in Figure 7.3. Surrogate feedback generally led to a larger constant error in the slower tapping conditions, except for the condition with 48 ms delay, were no difference was found ($p > .99$) between both tapping speeds. Without feed-



(a) Target Interval: 250 ms (b) Target Interval: 500 ms

Figure 7.2: Interaction effect of Modality and Target Interval on the constant error. Error bars show 95% confidence intervals.

back, there was also no difference between both target intervals ($p > .99$). This was different to the findings from Experiment 4. For instance, the conditions without feedback showed a clear difference in Experiment 4, while the difference found in this experiment was not significant. A possible reason for this could be the subgroup of older adults, causing the difference to blur (the larger standard deviations within the 500 ms condition support this assumption).

The fourth interaction effect on the constant error comprised the factors Modality and Block ($F[2.73,103.76] = 4.11$, $p = 0.01$, $\eta^2_G = .002$). The effect is shown in Figure 7.4. Here, again, the two-day testing pattern became obvious in the conditions with tactile feedback and the control condition without surrogate feedback. The constant error increased on the second block of each day (p's $< .001$), while the first two blocks were at the same level. The control condition without surrogate feedback showed the same pattern. The condition with audio feedback instead showed a constant error, uninfluenced by block and testing day, generally lower than the tactile feedback. Interestingly, there seems to be no retention effect (no differences between the first and third block; $p > .99$), indicating a more stable performance with audio feedback.

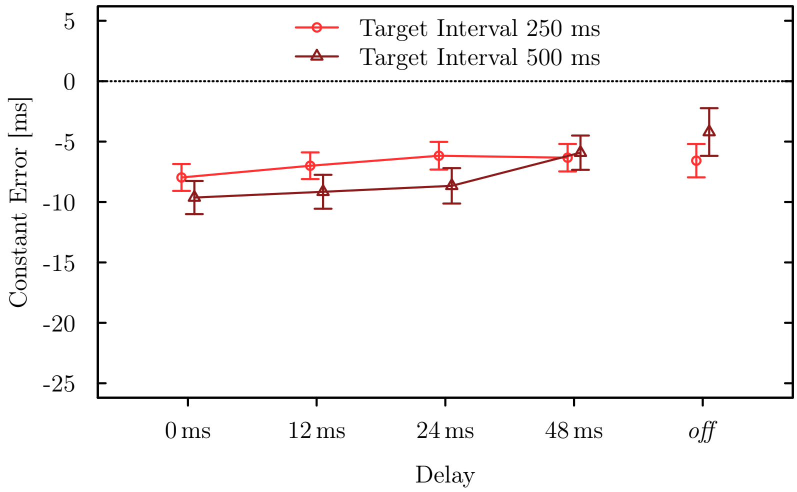


Figure 7.3: Interaction of Delay and Target Interval on constant error. The constant error differs for the two target intervals, except for the 48 ms condition. Error bars show 95% confidence intervals.

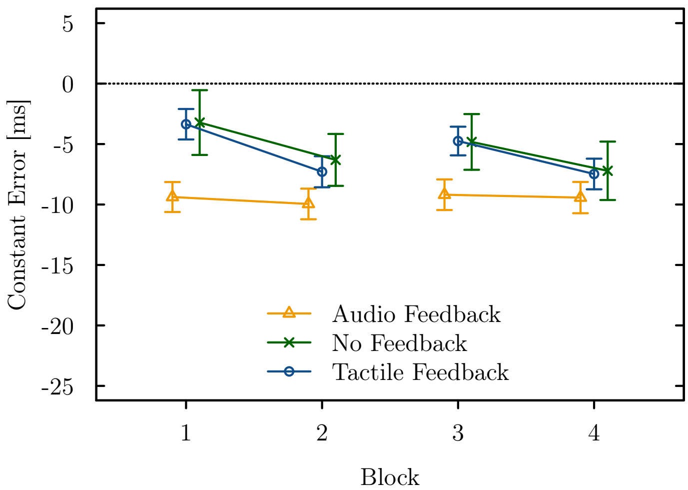


Figure 7.4: Interaction of Modality and Block on the constant error. With audio feedback, the constant error remains constant across blocks. Error bars show 95% confidence intervals.

Variable error There were 247 outliers removed from a total of 5760 observations (4.29%). A main effect on the variable error was induced by the factor Modality: F[1,38] = 10.22, $p < .01$, $\eta^2_G = .008$. With audio feedback, the variable error was significantly lower ($M = 396.37\,\text{ms}^2$, $SD = 310.67\,\text{ms}^2$; $M_s = 18.77\,\text{ms}$, $SD_s = 7.47\,\text{ms}$) than compared with tactile feedback ($M = 428.63\,\text{ms}^2$, $SD = 347.61\,\text{ms}^2$; $M_s = 19.44\,\text{ms}$, $SD_s = 8.23\,\text{ms}$).

The following two main effects were also found in all of the previous experiments. The first of these two is a main effect of Target Interval (F[1,38] = 267.63, $p < .0001$, $\eta^2_G = .50$). As expected, the slower tapping speeds led to a higher variable error ($M = 598.47\,\text{ms}^2$, $SD = 342.49\,\text{ms}^2$; $M_s = 23.84\,\text{ms}$, $SD_s = 6.89\,\text{ms}$) than the faster tapping speeds with the shorter 250 ms intervals ($M = 229.74\,\text{ms}^2$, $SD = 203.37\,\text{ms}^2$; $M_s = 14.44\,\text{ms}$, $SD_s = 5.59\,\text{ms}$).

The second factor which was expected to influence the variable error based on the previous experiments was Block. Within the current study, Block also exerted a significant influence on the variable error: F[2.58,97.90] = 11.65, $p < .0001$, $\eta^2_G = .01$. As can be seen in Table 7.8, the variable error was considerably higher in the first block than in the other three blocks ($p < .001$), which in turn did not differ significantly.

Table 7.8: Variable error (VE and VE_s (SD)) across blocks. Within the first Block, the variable error is significantly higher than all other three block, which in turn did not differ.

Block	VE [ms^2]	SD	SE	CI	VE_s [ms]	SD_s [ms]
1	448.13	316.69	8.35	16.37	20.03	7.32
2	405.24	315.55	8.32	16.31	18.89	7.62
3	417.35	304.75	8.03	15.75	19.28	7.18
4	385.71	312.33	8.23	16.15	18.36	7.58

There were two interaction effects, the first being generated by Modality and Target Interval (F[1,38] = 18.15, $p < .001$, $\eta^2_G = .02$). The data are plotted in Figure 7.5, the standard deviations and other statistics are shown in Table 7.9. Within the faster tapping speed, the variable error did not differ significantly (Figure 7.5a). During the slower tapping speed (see Figure 7.5b), however, the variable error was lowest with audio feedback, significantly lower than both tactile feedback ($p < .0001$) and no feedback ($p < .0001$), which in turn did not differ significantly ($p > .99$).

Table 7.9: Statistics for the variable error (VE_s (SD)) as a result of the interaction between Modality and Target Interval.

Modality	Target Interval	VE_s [ms]	SD_s [ms]	SE	CI
audio	250	14.67	4.49	0.13	0.25
audio	500	22.87	5.37	0.15	0.29
none	250	14.17	4.06	0.23	0.45
none	500	24.61	5.17	0.29	0.57
tactile	250	14.27	4.21	0.12	0.23
tactile	500	24.61	5.15	0.14	0.28

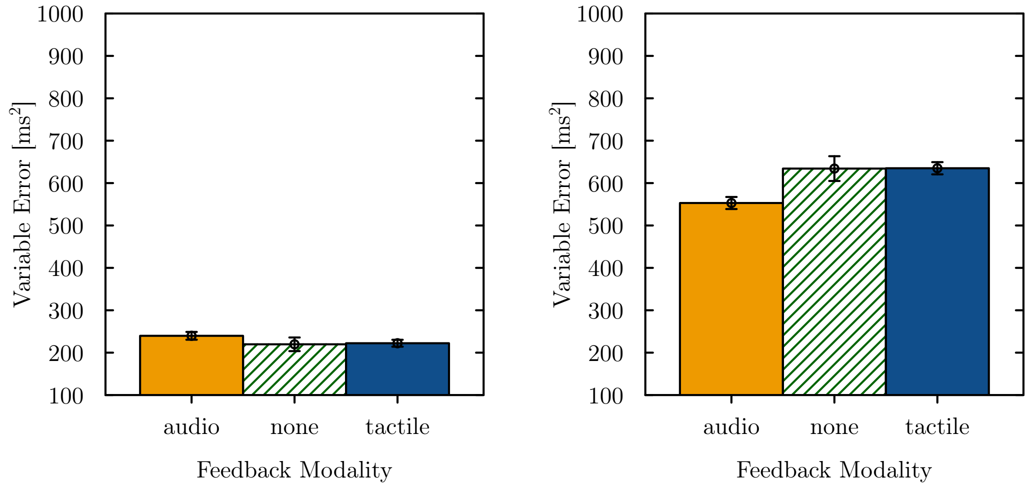
Upon a first glance at this effect, one might be tempted to say that audio feedback reduces the variable error and, hence, increases the precision of the tapping movements. However, it should be kept in mind that the variable error is linked proportionally to the interval length (Stevens, 1886), i.e., the reproduction of longer intervals leads to more variable sequences. As shown by the above-mentioned effect of audio feedback on the constant error (cf. Figure 7.2b on page 126), the mean interval length was shorter for tapping sequences with audio feedback.

To analyze whether the feedback modalities have directly led to different variable errors, the coefficient of variation was computed as follows:

$$\hat{c}_v = \frac{s}{\bar{x}}$$

with $\bar{x}$ denoting the mean inter-response interval of a sequence and s the variable error expressed as standard deviation, thereby offering a correction for interresponse interval length. An ANOVA was computed on the resulting values. Modality did not exert a significant influence on the coefficient of variation: $F[1.58,61.79] = 0.39$, $p = 0.63$, $\eta^2_G = .0006$. Therefore, the reduced variable error was most likely a consequence of the shorter interresponse intervals produced with audio feedback. However, the intercept of $\hat{c}_v$ was 0.05, which significantly differed from zero ($t[39] = 42.17$, $p < .0001$)—theoretically, it should be zero, therefore, the results have to be interpreted with caution.

The second interaction was caused by the factors Age and Modality ($F[1,38] = 4.58$, $p = 0.04$, $\eta^2_G = .003$). The effect is plotted in Figure 7.6, the standard deviations and other statistics are shown in Table 7.10. The variable error was significantly lower



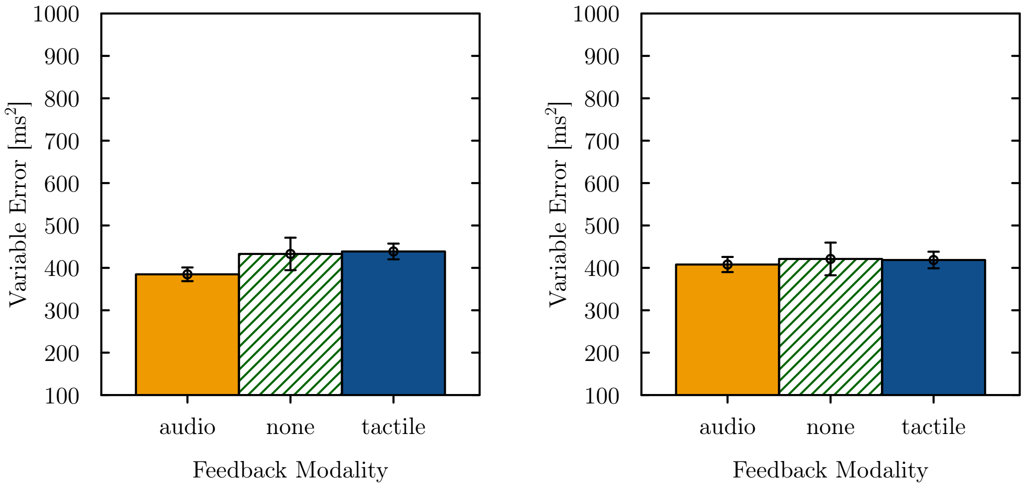
(a) Target Interval: 250 ms (b) Target Interval: 500 ms

Figure 7.5: Interaction effect of Modality and Target Interval on the variable error. Error bars show 95% confidence intervals.

when the surrogate feedback was given via tones rather than tactile signals ($p < .0001$). This effect only showed up in the group of younger adults, older adults showed no significant differences across the different feedback modalities. Contrary to the first interaction effect, this effect has no counterpart in the constant error (i.e., there are no differences in interval length regarding the age group). Therefore, it seems that in this case, the reproduction of the tapping movements was more regular with audio feedback, but only for the younger adults.

Table 7.10: Statistics for the variable error (VE_s (SD)) as a result of the interaction between Modality and Age. Within the first Block, the variable error is significantly higher than all other three blocks.

Age	Modality	VE_s [ms]	SD_s [ms]	SE	CI
old	audio	19.05	7.93	0.22	0.44
old	none	19.30	8.57	0.48	0.94
old	tactile	19.19	8.71	0.24	0.48
young	audio	18.50	6.96	0.19	0.38
young	none	19.48	7.91	0.44	0.87
young	tactile	19.70	7.71	0.22	0.42



(a) Younger adults (b) Older adults

Figure 7.6: Interaction effect of Modality and Target Interval on the variable error. Error bars show 95% confidence intervals.

7.2.3 Wing-Kristofferson Analysis

Central variance There were 201 outliers removed from a total of 5760 observations (3.49%). Neither Age ($p = 0.99$) nor Delay ($p = 0.39$) led to statistically significant differences.

However, there was also a second main effect of Modality ($F[1,38] = 43.92$, $p < .0001$, $\eta^2_G = .04$). The auditive feedback introduced in this experiment generally led to a lower central variance ($M = 271.31\,\mathrm{ms}^2$, $SD = 315.4\,\mathrm{ms}^2$) when compared with the tactile feedback known from the previous chapters ($M = 349.54\,\mathrm{ms}^2$, $SD = 366.62\,\mathrm{ms}^2$).

Finally, there was an expected main effect of Target Interval ($F[1,38] = 365.32$, $p < .0001$, $\eta^2_G = .41$) on the central variance component. The long target intervals led to a higher central variance estimate ($M = 466.94\,\mathrm{ms}^2$, $SD = 419.08\,\mathrm{ms}^2$) than the short target intervals ($M = 153.91\,\mathrm{ms}^2$, $SD = 210.5\,\mathrm{ms}^2$), as predicted by the two-level timing model and found in all previous experiments.

Peripheral variance There were 268 outliers removed from a total of 5760 observations (4.65%). Similar to the central variance estimate, there was a main effect of Modality on the peripheral variance ($F[1,38] = 12.44$, $p < .01$, $\eta^2_G = .01$). Contrary to the effect found in the central variance, the auditory feedback generally led to a higher peripheral variance ($M = 52.9\,\mathrm{ms}^2$, $SD = 110.32\,\mathrm{ms}^2$) when compared with the surrogate tactile feedback ($M = 35.81\,\mathrm{ms}^2$, $SD = 114.06\,\mathrm{ms}^2$). The control condition with no surrogate feedback was at the same level as the tactile feedback ($M = 35\,\mathrm{ms}^2$, $SD = 113.95\,\mathrm{ms}^2$; $p = 0.842$).

As known from the previous chapters and contradicting the predictions of the two level timing model, there was an effect of Target Interval on the peripheral variance estimate ($F[1,38] = 10.37$, $p < .01$, $\eta^2_G = .02$). The slow target intervals led to a higher peripheral variance estimate ($M = 54.01\,\mathrm{ms}^2$, $SD = 157.7\,\mathrm{ms}^2$) than the fast target intervals ($M = 34.7\,\mathrm{ms}^2$, $SD = 92.63\,\mathrm{ms}^2$).

Finally, a main effect of Block became apparent: $F[2.24,84.97] = 14.74$, $p < .0001$, $\eta^2_G = .02$. The peripheral variance estimate for the first block was significantly higher than all other three blocks (p's $< .0001$). The effect is depicted in Figure 7.7. The two-day-testing pattern showed a retention effect (difference between the first and third block, which constituted the first block of each testing day) was found to be significant ($p = 0.012$). Between both second blocks of each day (blocks two and four), the peripheral variance did not significantly differ ($p = 0.168$). In the previous experiments, the peripheral variance generally decreased over blocks (with the exception of Experiment 3, i.e., tactile pacing). Thus, this pattern was found in this experiment on each day (p's $< .001$). However, there was also a decay effect, since on the second day, participants required one block to achieve the same result than on block two again ($p = 0.022$).

In contrast to the central variance estimate, the peripheral variance estimate was subject to two three-way-interactions involving the factor Age. The first was an interaction of Age, Modality and Delay: $F[2.79,105.94] = 2.94$, $p = 0.04$, $\eta^2_G = .002$. The effect is depicted in Figure 7.8. The older adults showed a higher peripheral variance when auditory feedback was applied with a delay of 12 ms (p's $= 0.012$). Within the younger subgroup, there was an indication of a comparable difference at a delay of 48 ms. However, the difference there was only marginally significant ($p = 0.054$).

The second three-way interaction effect was an interaction of Age, Target Interval and Block: $F[2.63,99.80] = 3.38$, $p = 0.03$, $\eta^2_G = .004$. The effect showed an interesting pattern. Considering the first testing day, the younger participants showed similar peripheral variance estimates for both target intervals. In the second block, the

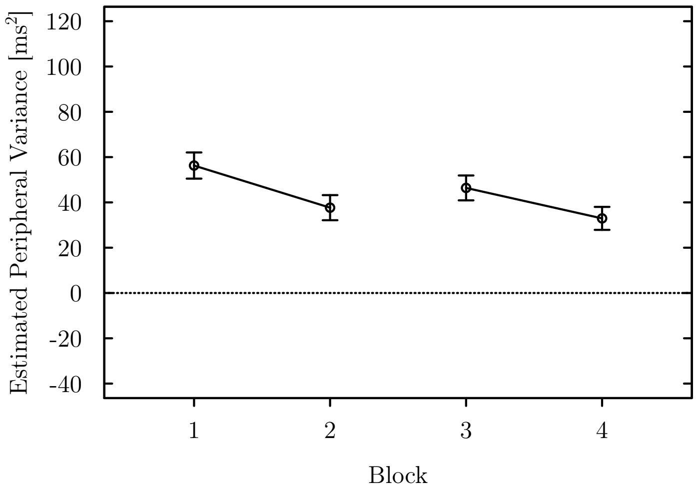


Figure 7.7: Peripheral variance across blocks; two blocks were tested on each day. The only blocks which did not yield significant differences were the second and fourth block. Error bars show 95% confidence intervals.

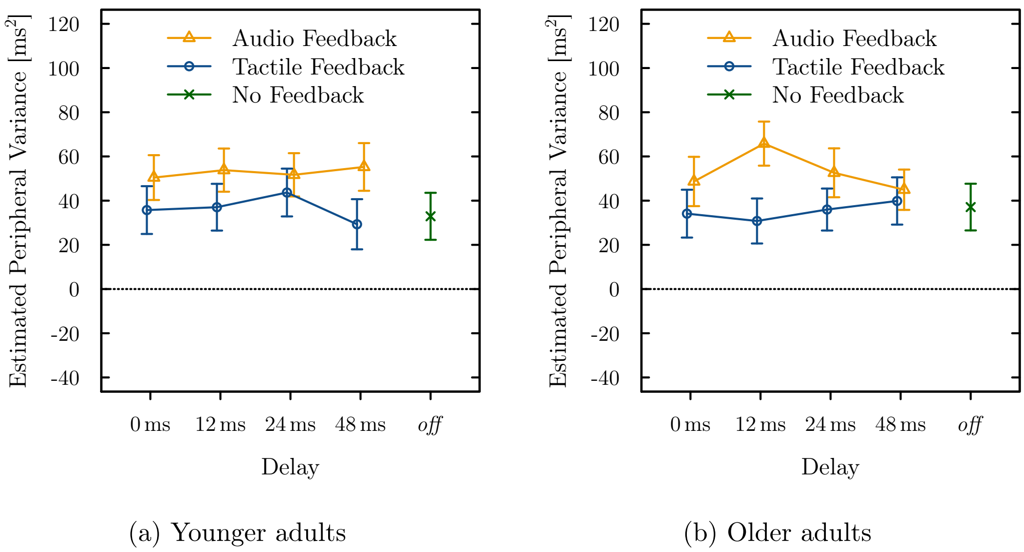
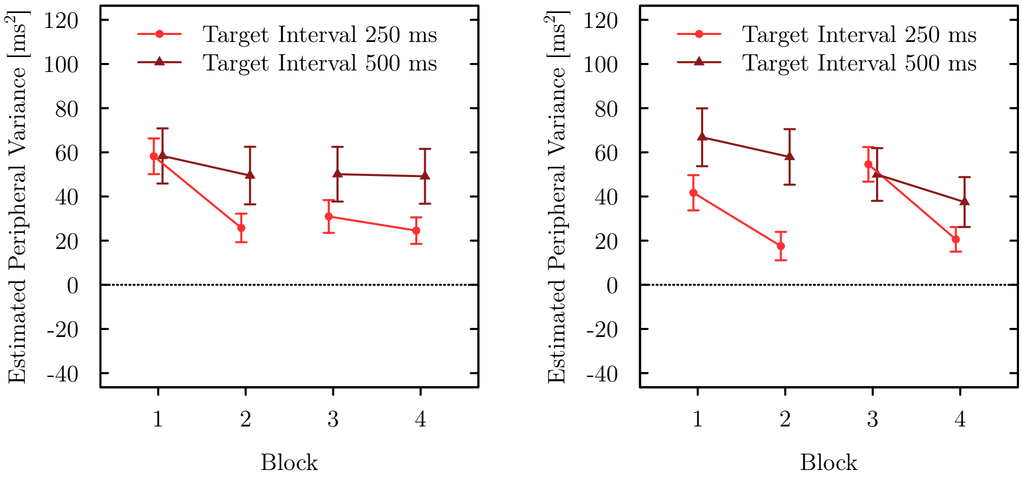


Figure 7.8: Interaction of Modality, Delay and Age on the peripheral variance estimate. Error bars show 95% confidence intervals.

peripheral variance decreased for the 250 ms intervals (p = 0.047) while the estimate for the 500 ms intervals did not show a significant decrease (p > .99). The older participants showed a similar pattern, but at the second day (cf. Figure 7.9). The younger participants instead showed the pattern found in the second block also in both blocks on the second day. This displacement could be an indication for a longer entrainment phase required by the older participants. An alternative explanation would be that older participants show a decay effect, while younger participants retain their skill on the task.



(a) Younger adults (b) Older adults

Figure 7.9: Interaction of Target Interval, Block and Age on the peripheral variance estimate. Error bars show 95% confidence intervals.

Model validity assessment

As can be seen in Figure 7.10, the autocorrelations for lags greater than 1 are not equal to zero, therefore violating the model predictions. There were 3721 (64.6%) valid trials, where $-1/2 \leq \rho_I(1) \leq 0$. The autocorrelations for lags greater than 1 often were not equal to 0. For instance, at lag 4, the mean autocorrelation was $M = 0.05$ ($SD = 0.19$), which significantly differed from zero: t[39] = 9.37, p < .0001. For additional statistics of the autocorrelations at different lags see Table 7.11.

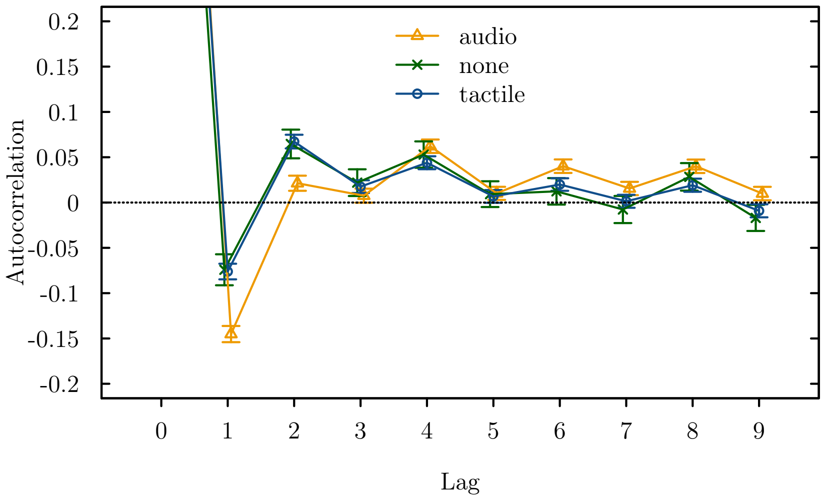
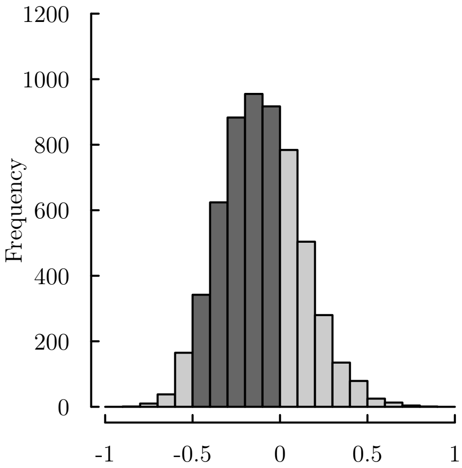
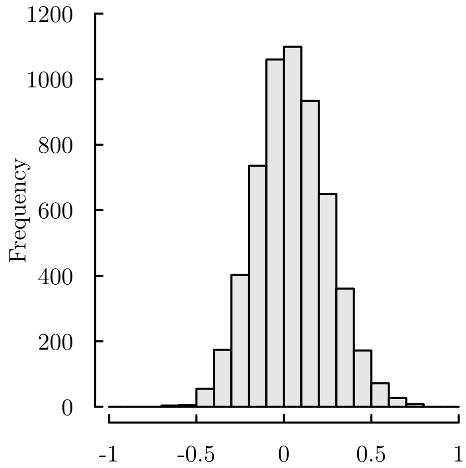


Figure 7.10: Autocorrelation function across lags 0 to 9. Error bars show 95% confidence intervals.



(a) Lag 1 autocorrelation



(b) Lag 2 autocorrelation

Figure 7.11: Histogram and density function of lag 1 autocorrelation (Figure 7.11a) and lag 2 autocorrelation (Figure 7.11b). Lag 1 should be bound between -.5 and 0 (colored in dark grey), Lag 2 should be around zero.

Table 7.11: Test statistics of the autocorrelations at lag 2 to lag 9 (alternative hypothesis: true mean is not equal to 0). Confidence levels are 99%.

	df	t-value	p-value	sample mean	lower CI bound	upper CI bound
lag 2	39	6.10	0.000	0.047	0.026	0.067
lag 3	39	1.79	0.082	0.014	-0.007	0.034
lag 4	39	9.37	0.000	0.053	0.038	0.068
lag 5	39	1.75	0.088	0.009	-0.005	0.022
lag 6	39	5.21	0.000	0.028	0.013	0.043
lag 7	39	1.35	0.186	0.007	-0.007	0.020
lag 8	39	6.07	0.000	0.029	0.016	0.043
lag 9	39	-0.38	0.708	-0.002	-0.013	0.009

7.2.4 Force Analysis

Analogous to Experiments 2 and 4 (Chapters 4 and 6), the force data on this experiment were first parameterized and then analyzed. First, distinct specific elements of each tap were determined (Peaks M1 and M2 as well as points L1, L2 and L3; see Section 2.4.3 on page 45 for details). Subsequently, the areas A1 and A2 were calculated, as well as the time-to-peak (TTP: the time between the beginning of the tap (L1) and the first maximum (M1)).

M1 Amplitude

There were 11922 outliers removed from a total of 254156 observations (4.69%). There was a main effect of Age on the M1 component (F[1,38] = 9.17, $p < .01$, $\eta^2_G = .14$). The younger group of the participants showed lower values for the M1 peak ($M = 4.8$ N, $SD = 3.26$ N) than the older adults ($M = 7.14$ N, $SD = 3.2$ N).

The modality of the surrogate feedback also exerted a significant influence on M1 (F[1,38] = 28.48, $p < .0001$, $\eta^2_G = .02$). For audio feedback, the mean value of the M1 peak was the lowest $M = 5.44$ N ($SD = 2.67$ N), lower than the peaks found with surrogate tactile feedback ($M = 6.36$ N, $SD = 2.62$ N). The highest M1 peaks were measured without surrogate feedback present ($M = 6.58$ N, $SD = 2.54$ N). The differences between all three conditions were significant (p's < .0001).

Analogous to Experiment 4, Target interval had a significant influence on the first maximum (F[1,38] = 13.89, $p < .001$, $\eta^2_G = .01$). The effect showed the same pattern as in Experiments 2 and 4: slower speeds led to increased amplitudes. The mean value of the M1 peak found during the faster target intervals was $M = 5.65$ N ($SD = 2.97$ N), lower than the peaks found during the slower target intervals ($M = 6.3$ N, $SD = 3.19$ N).

In constrast to Experiment 2 and 4, there was no main effect of Block on the M1 amplitude (p = 0.2). However, an interaction between Delay and Block exerted a significant influence on the M1 component (F[7.27,276.34] = 2.16, p = 0.04, $\eta^2_G = .002$). The effect is shown in Figure 7.12. Most prominent seem to be the first block on each day, thus block 1 and 3. The two other blocks remain more or less constant over the different delays. Another finding: On the last block of each day, M1 was noticeably higher than in the first block on each day.

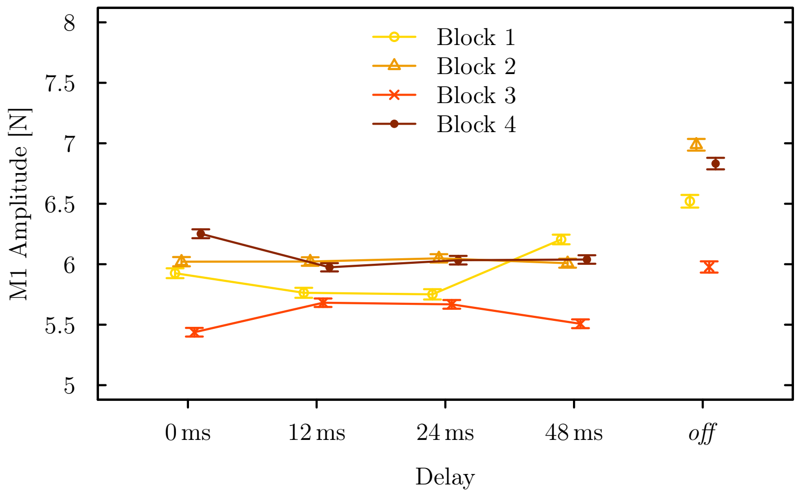


Figure 7.12: M1 Amplitude as a function of Delay, splitted by Block. Error bars show 95% confidence intervals.

In contrast to Experiment 4, there was no main effect of Delay (p = 0.68). Instead, the factor Age was part of an interaction effect in combination with Delay. Together, both factors exerted a marginally significant influence on the M1 amplitude (F[2.34,89.09] = 2.54, p = 0.08, $\eta^2_G = .0007$). The effect is shown in Figure 7.13. Post-hoc analyses showed that the differences between the two age groups were significant for all levels of Delay, even for the 12 ms condition (p = 0.041). The curve was only vaguely V-shaped like in Experiment 4 (cf. Figure 6.5 on page 109), but only in the younger subgroup, where both outmost ends (0 ms delay and the control condition without feedback) were higher than the middle part (delays of 12, 24 and 48 seconds). This was not the case with the older subgroup, who instead showed the lowest M1 amplitude at zero delay.

There was also an interaction between Target Interval and the modality of the surrogate feedback (F[1,38] = 5.73, p = 0.02, $\eta^2_G = .0007$). The effect is shown in Figure 7.14. Again, post-hoc analyses showed that all differences between each of the combinations were significant. Although the differences between each of the feedback modalities persist under both target intervals, their relative size remains constant. The main difference is that during the longer target intervals, the M1 amplitude is higher in general (as shown by the main effect of Target Interval mentioned above).

M2 Amplitude

There were 12949 outliers removed from a total of 254156 observations (5.09%). Similar to the M1 amplitude, the modality of the surrogate feedback also exerted a significant influence on the M2 amplitude (F[1,38] = 23.64, $p < .0001$, $\eta^2_G = .03$). With audio feedback, the mean value of the M2 peak was the lowest $M = 2.28$ N ($SD = 1.28$ N), lower than the peaks found without any surrogate feedback ($M = 2.74$ N, $SD = 1.25$ N, $p < .0001$). The M2 amplitude with audio feedback was also lower than with tactile feedback present ($M = 2.71$ N, $SD = 1.24$ N, $p < .0001$). The difference between tactile feedback and no feedback was also significant ($p < .0001$).

The factor Delay also exerted a significant influence on the second force amplitude (F[2.81,106.78] = 2.97, p = 0.04, $\eta^2_G = .0008$). Means and additional statistics are shown in Table 7.12. The pattern found was comparable to the one found in Experiment 4, the lowest amplitude was measured at a delay of 12 ms.

Target interval had a significant influence on the second maximum (F[1,38] = 23.68, $p < .0001$, $\eta^2_G = .02$). The M2 peak values found during the shorter target intervals had a mean of 2.33 N ($SD = 1.37$ N), lower than the peaks found during the longer target intervals ($M = 2.72$ N, $SD = 1.55$ N).

There was a marginally significant interaction effect involving the factors Age and Target Interval, which in combination influenced the M2 component (F[1,38] = 3.31, p = 0.08, $\eta^2_G = .003$). The effect is shown in Figure 7.15. Post-hoc analyses showed that all differences between each of the combinations were significant. Comparable to the M1 component, both age groups showed a higher M2 amplitude during the slower

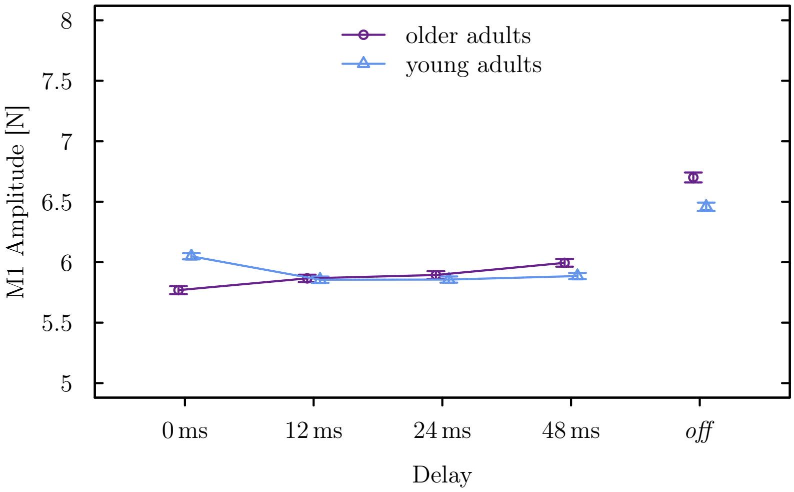
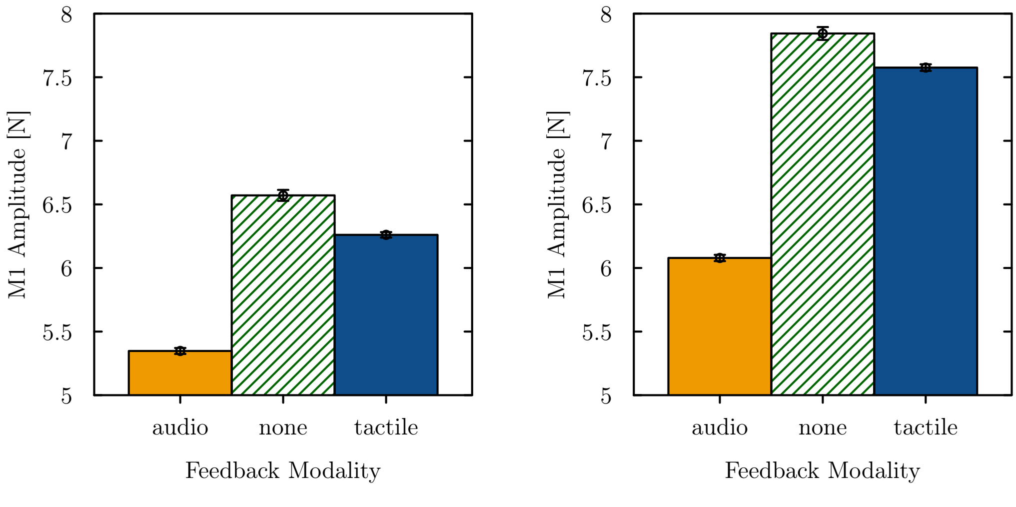


Figure 7.13: Interaction of Delay and Age on the M1 amplitude. The V-shape known from the previous experiment seems only to apply for younger participants and is not as pronounced. Error bars show 95% confidence intervals.



(a) Target Interval: 250 ms

(b) Target Interval: 500 ms

Figure 7.14: Interaction effect of Modality and Target Interval on the M1 amplitude. All differences were significant. Error bars show 95% confidence intervals.

Table 7.12: M2 amplitude across Delay. The delay is slightly lower in the 12 ms condition. Only the 24 ms and zero delay conditions did not differ, all other differences were significant.

Delay	M2 Amplitude [N]	SD	SE	CI
0	2.53	1.186	0.005	0.010
12	2.44	1.149	0.005	0.009
24	2.52	1.195	0.005	0.010
48	2.50	1.163	0.005	0.010
off	2.74	1.139	0.007	0.013

tapping speed as compared to the faster tapping speed (p's $<$ .0001). However, the gap between both target intervals was larger for the group of older adults ($\Delta = 0.54$ N) than for the group of younger adults ($\Delta = 0.24$ N, $p = 0.078$).

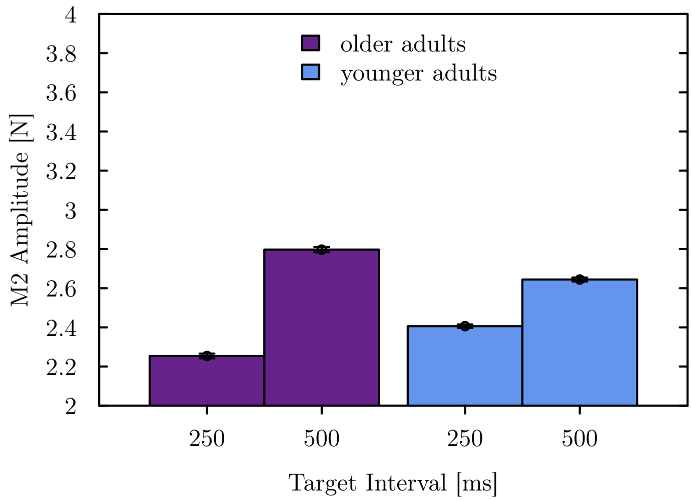


Figure 7.15: Interaction effect of Age and Target Interval on the M2 Amplitude. Error bars show 95% confidence intervals.

Correlations To further examine the assumption that the M1 and M2 are the result of different neuronal origins (cf. discussion of Experiment 2), correlations between both were computed for each tapping trial. Prior to submitting them to the ANOVA, they were z-transformed and outliers were replaced as described in the general methods. There were 137 outliers removed from a total of 2880 observations (4.76%).

The main effect of Block found in Experiment 4 was not significant in this experiment ($p = 0.42$). However, the feedback modality significantly influenced the correlation between the M1 and M2 amplitudes ($F[1,38] = 15.81$, $p < .001$, $\eta^2_G = .008$). For audio feedback, the correlation between the M1 and the M2 amplitudes was the highest $M = 0.58$ ($SD = 0.27$), higher than the correlation found with surrogate tactile feedback ($M = 0.54$, $SD = 0.27$). The control condition without feedback lay between the two feedback modalities ($M = 0.56$, $SD = 0.26$).

Time to Peak (TTP)

There were 11304 outliers removed from a total of 254156 observations (4.45%). There was a main effect of Age on the TTP ($F[1,38] = 8.50$, $p < .01$, $\eta^2_G = .13$). The younger group of the participants showed higher values for the TTP ($M = 4.81$ ms, $SD = 1.09$ ms) than the older adults ($M = 4.22$ ms, $SD = 0.94$ ms).

The modality of the surrogate feedback also had a significant influence on the TTP: $F[1,38] = 28.80$, $p < .0001$, $\eta^2_G = .02$. For audio feedback, the mean value of the TTP was the highest ($M = 4.65$ ms, $SD = 1.03$ ms), higher than the TTP found without any surrogate feedback ($M = 4.38$ ms, $SD = 0.87$ ms) or with surrogate tactile feedback present ($M = 4.41$ ms, $SD = 0.91$ ms). The differences between all three conditions were significant (p's $< .0001$).

As also found in Experiments 2 and 4, Target Interval exerted a significant influence on the TTP ($F[1,38] = 6.81$, $p = 0.01$, $\eta^2_G = .007$). The TTP found during the shorter target interval was $M = 4.58$ ms ($SD = 1.14$ ms), longer than the TTP at the longer interval ($M = 4.45$ ms, $SD = 1.09$ ms).

The factor Age was part of an interaction effect in combination with the factor Delay, which exerted a significant influence on the TTP ($F[2.84,107.79] = 3.41$, $p = 0.02$, $\eta^2_G = .001$). The effect is shown in Figure 7.16. Post-hoc analyses showed that nearly all of the differences between the two age groups were significant for all levels of Delay, even for the 24 ms condition ($p = 0.05$). Only in the control condition without feedback ($p = 0.089$) and the condition with undelayed feedback ($p = 0.115$), the young adults showed a longer TTP than the older adults.

Finally, there was an interaction between Target Interval and the modality of the surrogate feedback ($F[1,38] = 7.37$, $p = 0.01$, $\eta^2_G = .0008$), shown in Figure 7.17. The

TTP was lowest without any feedback during the long target interval. Post-hoc tests showed that all differences were significant, even the difference between no surrogate feedback and surrogate tactile feedback during longer target intervals (p's $< .01$).

There was a strong correlation between TTP and the following force peak (M1), $r(38) = -0.72$, $p < .0001$. This means that on a short TTP, a large peak followed and vice versa.

Momentum (A1 and A2)

A1 There were 10517 outliers removed from a total of 254156 observations (4.14%). Similar to Experiment 4, there was no significant effect of Delay on the first momentum ($p = 0.54$).

However, there was a main effect of age on the first momentum: $F[1,38] = 9.44$, $p < .01$, $\eta_G^2 = .16$. Younger adults tapped with less momentum ($M = 18.83$ N ms, $SD = 10.07$ N ms) than older adults ($M = 26.74$ N ms, $SD = 10.01$ N ms).

There was also a main effect of Modality on the first momentum: $F[1,38] = 20.13$, $p < .0001$, $\eta_G^2 = .02$. The first momentum was lower with audio ($M = 21.48$ N ms, $SD = 7.62$ N ms) than with tactile feedback ($M = 23.73$ N ms, $SD = 7.28$ N ms) or without any surrogate feedback ($M = 21.48$ N ms, $SD = 7.62$ N ms; $p < .0001$).

Finally, like in Experiment 4, the momentum differed between both target intervals. At shorter intervals, participants applied a lower momentum ($M = 21.93$ N ms, $SD = 8.49$ N ms) compared to the longer 500 ms target intervals ($M = 23.64$ N ms, $SD = 8.84$ N ms; $F[1,38] = 17.43$, $p < .001$, $\eta_G^2 = .008$).

A2 There were 12950 outliers removed from a total of 254156 observations (5.1%). Analogous to the first momentum, there was a main effect of Modality on the second momentum: $F[1,38] = 25.12$, $p < .0001$, $\eta_G^2 = .03$. Similar to A1, the second momentum was lower with audio feedback ($M = 142.5$ N ms, $SD = 128.48$ N ms) than with tactile feedback ($M = 182.62$ N ms, $SD = 138.87$ N ms) or without any surrogate feedback ($M = 142.5$ N ms, $SD = 128.48$ N ms; $p < .0001$).

A significant influence on the A2 momentum was exerted by the tapping speed. At shorter intervals, participants generally applied a lower momentum ($M = 127.05$ N ms, $SD = 123.18$ N ms) compared to the longer 500 ms target intervals ($M = 202.3$ N ms, $SD = 169.95$ N ms; $F[1,38] = 71.67$, $p < .0001$, $\eta_G^2 = .08$).

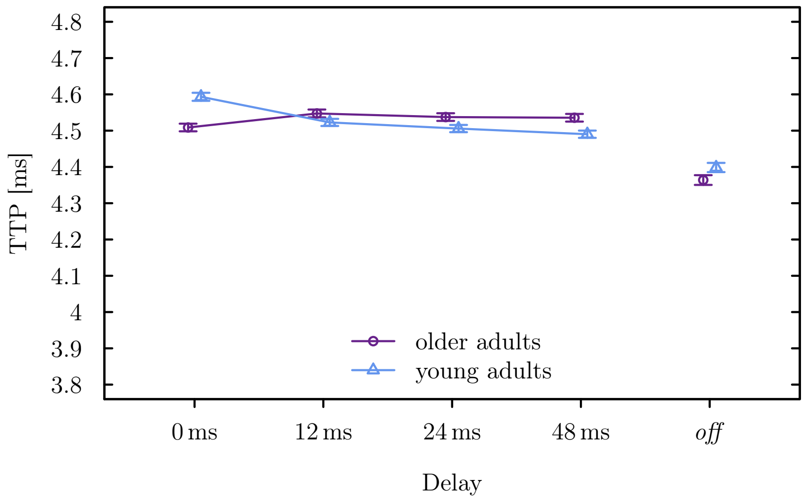
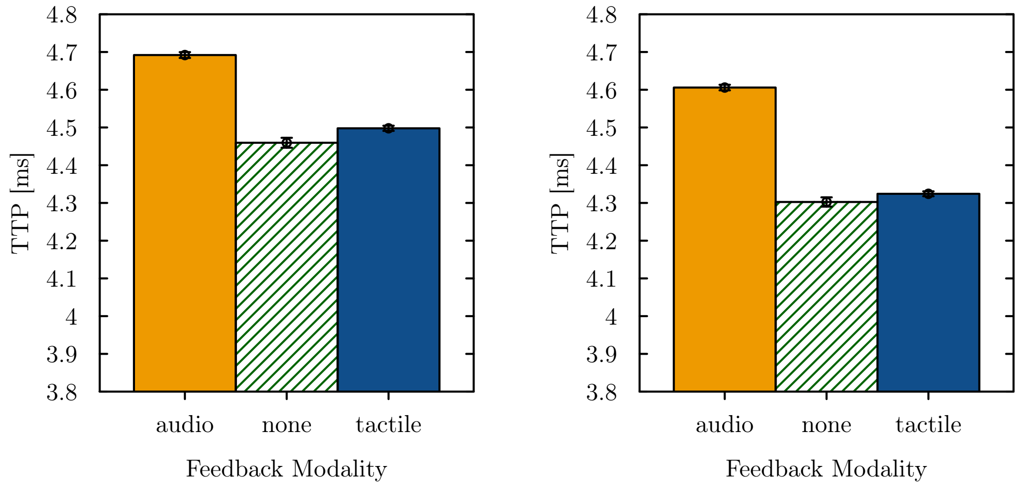


Figure 7.16: Interaction of Delay and Age on the TTP. Only in the control condition without feedback and with undelayed feedback, the young adults showed a shorter TTP than the older adults. Error bars show 95% confidence intervals.



(a) Target Interval: 250 ms

(b) Target Interval: 500 ms

Figure 7.17: Interaction effect of Modality and Target Interval on the time to peak (TTP). Error bars show 95% confidence intervals.

Contrary to the first momentum, there were also two interaction effects. The first interaction effect was caused by Delay and Modality (F[2.65,100.85] = 3.17, p = 0.03, $\eta^2_G = .001$). The effect is shown in Figure 7.18. Almost all differences were significant (p's < .0001)).

In contrast to the first momentum, the main effect of Age on the A2 momentum was not significant. However, there was an interaction of Age and Target Interval (F[1,38] = 8.47, p < .01, $\eta^2_G = .01$). The effect is shown in Figure 7.19. Post-hoc analyses showed that all differences between each of the factorial combinations were significant (p's < .0001). Comparable to the main effects found in the A1 component, both age groups showed a higher momentum during the slower tapping speed as compared to the faster tapping speed. However, the gap between both target intervals was larger for the group of older adults ($\Delta = 101.58$ N ms) than for the group of younger adults ($\Delta = 48.89$ N ms).

Correlations The correlations between both momenta A1 and A2 were also analyzed using the same procedure as described for both amplitudes. There were 128 outliers removed from a total of 2880 observations (4.44%).

There was a significant effect of Age on the correlation coefficient (F[1,38] = 4.16, p = 0.05, $\eta^2_G = .01$). Older adults showed a slightly higher correlation between A1 and A2 ($M = 0.37$; $SD = 0.26$) compared to the younger adults ($M = 0.31$; $SD = 0.25$).

Furthermore, Target Interval also exerted a significant influence on the correlation coefficient (F[1,38] = 4.71, p = 0.04, $\eta^2_G = .008$). The correlation between A1 and A2 was higher for longer target intervals $M = 0.36$ ($SD = 0.33$) compared to shorter target intervals ($M = 0.31$; $SD = 0.35$).

7.2.5 Mental Effort

After each condition resulting from the factorial design, participants had to fill in the Rating Scale of Mental Effort (RSME). There were 219 outliers removed from a total of 3024 observations (7.24%). The ratings were used to get a further perspective on the application of surrogate tactile feedback. There was a marginally significant main effect of Age on the ratings: F[1,39] = 4.03, p = 0.05, $\eta^2_G = .06$. Older participants' effort ratings for the tapping task were generally higher ($M = 44.15$, $SD = 27.84$) than the effort ratings made by the younger group ($M = 31.95$, $SD = 17.71$).

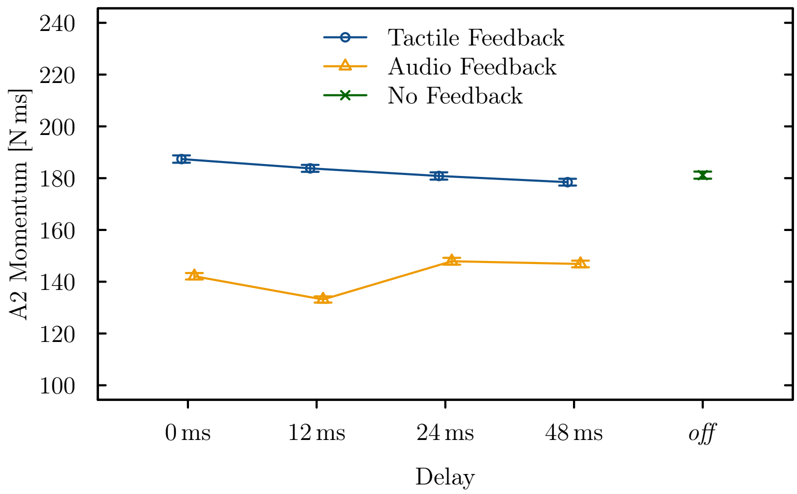


Figure 7.18: Interaction of Delay and Modality on the second momentum. Almost all differences were significant, except between 12 ms tactile feedback and no feedback. Error bars show 95% confidence intervals.

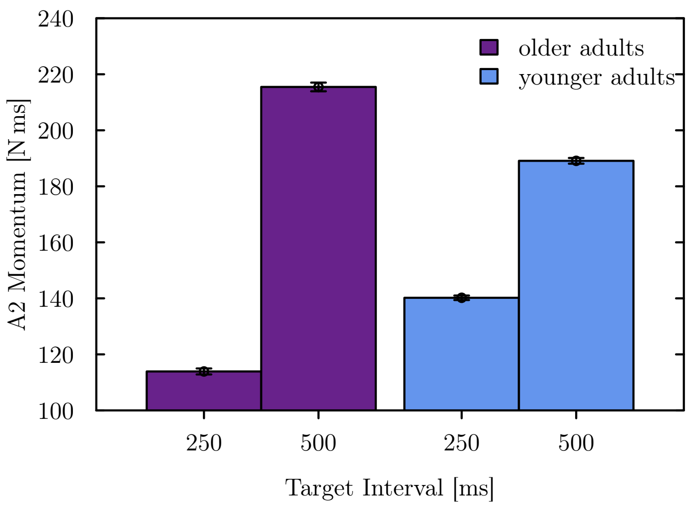


Figure 7.19: Interaction effect of Age and Target Interval on the A2 momentum. Error bars show 95% confidence intervals.

There was also an effect of Block on the mental effort ratings: F[1.99,77.60] = 10.39, p < .001, $\eta^2_G = .03$. Descriptive statistics are shown in Table 7.13. There was a drop in the effort ratings between the second and third block (p < .0001). Blocks 1 and 2 (p < .0001) as well as 3 and 4 do not differ from each other (p < .01).

Table 7.13: Main effect of Block on the ratings of mental effort. There is a drop in the effort ratings between the second and third block. Blocks 1 and 2 aswell as 3 and 4 do not differ from each other.

Block	Rating	SD	SE	CI
1	40.54	19.30	0.70	1.38
2	43.67	16.42	0.60	1.17
3	33.36	14.55	0.53	1.04
4	35.79	15.30	0.56	1.09

There were also interaction effects on the effort ratings—the first one emerged from a combination of Block and Target Interval (F[2.29,89.24] = 3.95, p = 0.02, $\eta^2_G = .0009$). The effect is shown in Figure 7.20. Again, the two days of testing are clearly visible as a large gap between the second and third block. On the second day, ratings were significantly lower than on the first day (p's < .0001). However, on both days, the second block with the 500 ms conditions were rated higher than the first block (p's < .001) on the resp. day. This was not the case for the 250 ms conditions.

There was also an interaction of Modality and Delay: F[2.30,89.78] = 2.99, p = 0.05, $\eta^2_G = .0010$. The effect is shown in Figure 7.21. At zero delay, audio feedback was rated as more effortful than tactile feedback (p = 0.024). At a delay of 12 ms and higher, the differences were not significant (p's > .99).

7.3 Discussion

In Experiment 4, there were no delay-related differences found within the two-level timing model components, neither in the central, nor in the peripheral variance estimate. Therefore, one of the main aims of this experiment was to check whether this is also the case when the surrogate feedback is cross-modal (i.e., audio beeps as surrogate feedback with a tapping task). Therefore, both surrogate feedback modalities were tested at the same levels of delay already used in Experiment 4. Additionally,

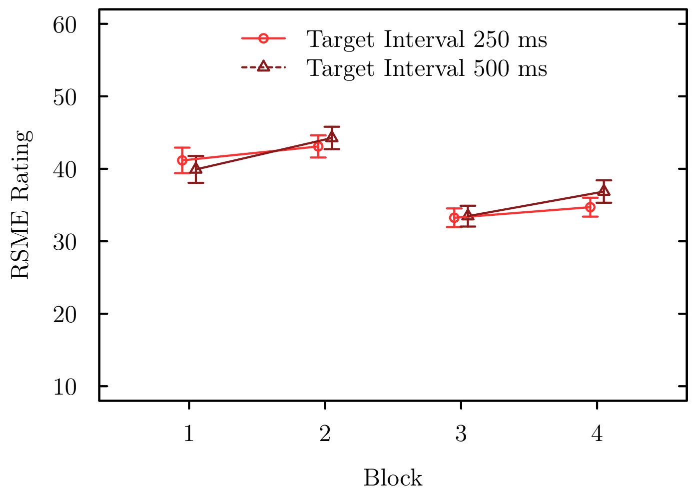


Figure 7.20: Interaction of Target Interval and Block on the ratings of mental effort. Error bars show 95% confidence intervals.

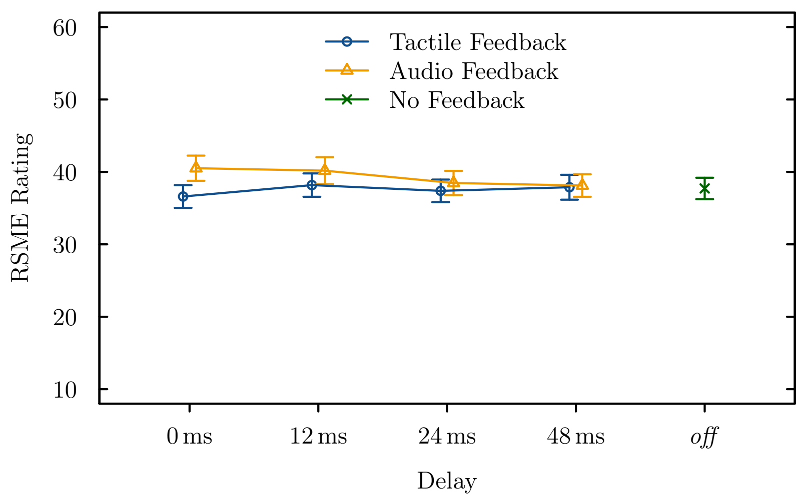


Figure 7.21: Interaction of Delay and Modality on the effort ratings. Error bars show 95% confidence intervals.

two age groups (younger and older adults) were tested and compared to see whether both surrogate feedback modalities show different influences depending on age. The dependent variables were the same as in the previous experiments (two-level timing model estimators, constant and variable error, force measures).

7.3.1 Constant and Variable Error

In Experiment 4, the feedback did exert an influence on the constant error, but only during slower tapping speed. In this experiment, the findings were comparable: while the constant error at faster tapping speed was not influenced by the different levels of delay, the intervals at slower speed showed a decreased constant error to a level comparable to the short intervals, but only at a delay of 48 ms—in the previous study, this was already the case at a delay of 12 ms. The auditory modality was most likely responsible for this effect, since it led to a large increase of the constant error at the long target intervals.

This assumption receives support by the interaction effect of delay and feedback modality, which showed that the tactile feedback in general did not influence the constant error at all. Across all levels of delay, it was comparable to the control condition without surrogate feedback. The auditory feedback instead showed a much stronger influence, strongest at zero delay and then decreasing with higher delay values, until at the 48 ms delay condition, it does not differ anymore from the no feedback control condition and the surrogate tactile feedback. Therefore, it seems likely that the surrogate audio feedback at acceptable rates of delay was incorporated into the timing mechanisms of the motor system, but otherwise ignored. In contrast, the surrogate tactile feedback seems to have been completely ignored.

Additional evidence for the suppression of the surrogate tactile feedback comes from the found interaction of feedback modality in combination with Block, showing a drop in constant error, with similar values for both testing days. On the second block of each day, the participants produced slightly shorter intervals than in the first block with tactile feedback. The no feedback conditions showed a similar pattern. In contrast, this was not the case for the audio feedback, which led to a regular undershoot of about 10 ms for all blocks on both days.

Further additional evidence for this assumption comes from the ratings of mental effort, which showed no difference between tactile feedback and no surrogate feedback.

The audio feedback conditions, however, were rated as generating more effort. This difference decreased with increasing feedback delay, thus inversely proportional to the constant error. Increased effort ratings may be due to the increased amount of cognitive control contributing to generating precise inter-tap-intervals.

The magnitude of the constant error was about −5 ms for 500 ms target intervals, collapsed across all feedback and delay conditions. Repp (2010) found that for non-musicians, 10 ms is a typical value for the constant error during a continuation phase with a target interval of 500 ms, while musisicans are able to reach a constant error close to zero under the same circumstances. The current experiment did not explicitely control for musical proficiency, but the experience and proficiency of the participants with musical instruments was queried after the experiment. The results from the questionnaire showed that about one third of the participants had musically experiences (one year or more experience with an instrument). Therefore, the negative mean constant error fits to the literature and to the previous experiments.

Interestingly, there was no effect of delay on the variable error. However, the audio feedback led to a significantly lower variability, but only in the slower tapping conditions. Considering the dependency on the length of the produced inter-tap-intervals (which were significantly shorter, as shown by the effect found in the constant error), it was assumed that the lower variability was a consequence based on the linear relation between interval length and variability Stevens (1886), and not due to the feedback modality. The analysis of the coefficient of variation showed no indications that the decrease with audio feedback was higher than to be expected based on interval duration alone. Hence, the variable error seems not to have been directly influenced by the feedback modality, but instead indirectly moderated via the effect of feedback modality on the interval length.

7.3.2 Two-level Timing Model Estimators

In this experiment, the tactile variant of the surrogate feedback did not show an effect on the components of the two-level timing model. The audio feedback, instead, led to a general reduction of the central variance estimate, thereby supporting the notion of Drewing and Aschersleben (2003) that the central timing mechanism is able to increase its precision by incorporating additional sensory reafferences from multiple modalities. The delay of the feedback signal seems to be of minor importance for this effect, as it did (again) not exert any significant influence on the central variance. Considering the findings of Finney and Warren (2002), it might be the case that a larger delay is required to significantly distort the variance estimates—or a variable delay instead of a constant delay, as suggested earlier in this thesis.

Both age groups showed the expected differences in the pretests (lesser sensitivity as well as slower movement in the finger opposition task for the older adults). Nevertheless, the older adults did not yield differences in the model estimators compared to the younger participants—except for an interesting interaction of modality on the peripheral variance. In this interaction, at a delay of 12 ms, the peripheral variance estimate was higher than all other conditions, but only with audio feedback. The effect was not present for the younger adults. Since it was also not found in Experiment 4, it seems to be confined to the older population. The puzzling nature of this effect may be linked to the violated assumption of independence between both variance estimators of the two-level timing model. The original model predictions assume independence between both estimates, which should result in stationarity, viz. a mean autocorrelation of 0 for lags greater than 2. This was clearly not the case (Figures 7.10 and 7.11b). The issue of possible violations of the assumption stationarity was already discussed in Experiment 3. According to Vorberg and Wing (1996) nonstationarity can lead to totally misleading results of the autocovariances and hence, the central and peripheral variance estimates.

Another notable finding is the retention- resp. decay-effect of Block on the peripheral variance. Decreasing peripheral variance during the course of a tapping experiment was also found in the previous experiments (except in Experiment 3) and is regarded as a sign of familiartity with the task (Drewing & Aschersleben, 2003). Here, this result could also be confirmed. However, because the current experiment was divided on two subsequent days, the effect also persisted for the duration of 24 hours. Since the peripheral variance in the third block (i.e., the first block on the second day) was higher than the second, but lower than the first block, this could qualify as a retention effect. Interestingly, this varied with age: older adults showed this decrease of the faster intervals at the second day, while younger adults showed the same effect already at the first day. This could be interpreted as increasing amount of practice needed by the older adults, since they showed the same (learning) pattern on the second day that the younger adults showed on the first day.

7.3.3 Force Measures

Age was also found to influence the force movement characteristics, specifically the TTP and the M1 amplitude. The TTP as measure to estimate the speed of movement showed that in general, the downward movement of the index finger was faster for older adults than the movements by younger adults. Correspondingly, the M1 amplitude values were higher for the older adults. Considering the economic aspect of force regulation, this seems to fit to the general notion that force control decreases with age (Lindberg, Ody, Feydy, & Maier, 2009).

The M2 amplitude also showed a relation between age and tapping speed. Slower tapping speed generally led to higher force amplitudes (found in the previous experiments and by Vardy et al. (2009)). Here, it was shown that increasing age also increases the strength of this relation, which fits to the findings of greater force variability with increasing age (Lindberg et al., 2009).

As in Experiments 2 and 4, all force-related measures again showed an influence of tapping speed. A possible cause could be differences in earlier antagonist activation at higher movement speeds. Evidence for different muscular acitivity comes from Zallinger (1998), who found that in leg-tapping, different muscle activation patterns were employed depending on the target frequency (Birklbauer, 2006).

The modality of the surrogate feedback also exerted different influences on both force components. Generally, the amplitude was lowest with audio feedback, followed by tactile feedback and highest for tapping without surrogate feedback. Considering the notion of generalized motor programs (Schmidt, 1988), the differences in produced force at the M1 depending on the modality of the surrogate feedback could be explained in terms of adjustments of dynamic parameters of a specific program. For instance, one could assume that audio feedback influences gain parameters, which then results in different outcomes in terms of measured force at the movement endpoint.

Furthermore, in a synchronization study by Keller, Dalla Bella, and Koch (2010), the amplitudes of finger movements were found to be larger in experimental conditions where taps did not trigger tones than in conditions where taps did trigger tones. Keller et al. interpreted this increase in movement amplitude to reflect an attempt to enhance tactile feedback by increasing the force with which keys were struck in the absence of auditory feedback (Keller, Ishihara, & Prinz, 2011).

This notion would fit to the results of DiFranco, Beauregard, and Srinivasan (1997), who studied the influence of different auditory feedback on perceived stiffness of virtual surfaces. Their findings were confirmed and extended by other studies, specifically that auditory feedback can modulate tactile perception (Bresciani et al., 2005) and vice versa (Bresciani & Ernst, 2007). Bresciani et al. (2005) demonstrated that the number of perceived taps on a fingertip can be influenced by the number of beeps when both are presented in conjunction. Furthermore, they concluded that the auditory beep must necessarily present sufficient similarity with the tactile stimulus for a successful modulation. This conclusion fits to the interaction of delay, modality and target interval on the constant error in the current study. Here, the delay decreased the similarity between the tactile reafference and the surrogate audio feedback and hence the meaning, resulting in a reduction of constant error to the levels of no feedback.

In contrast to the effect of delay on the first momentum A1 in Experiment 4, there was no such effect found in the current study. However, the delay affected the second momentum in interaction with the modality. This is most certainly due to the modality of the feedback. The tactile feedback showed no great influence compared to the audio feedback conditions, which show large variations across the different levels of delay, while the effort was nearly the same in the tactile feedback conditions, close to the control conditions without feedback. That this effect manifested in the second momentum in place of the first momentum seems to qualify the assumption that both momenta reflect processes at different neurological levels. Still, both show quite different effect patterns and were again weakly correlated, which seems to offer an interesting perspective for future research, but cannot be answered within the limits of the current thesis.

Chapter 8

General Discussion

This final chapter is organized into the following sections. First, the findings of all experiments as well as their accompanying interpretations are summarized. Subsequently, limitations of the applied research methods are addressed. The chapter concludes with implications for future research and considerations regarding the practical relevance.

8.1 Summary of Findings and Interpretations

The influence of tactile feedback on the coordination of sequential movements has been subject to many studies using synchronization and continuation tapping tasks (Repp, 2005; Repp & Su, 2013). As dependent measures, researchers often employed the negative mean asynchrony or the inter-tap-interval (ITI) variability. Wing and Kristofferson (1973a) offered a widely accepted approach for the decomposition of the ITI variability into two assumed processes, timing and motor variability. In terms of the variance decomposition by means of the autocovariance structure, the model gained broad empirical support (Drewing et al., 2002). However, the actual processes modeled by both estimates seem to differ from the original assumptions made by Wing and Kristofferson (1973b)—as demonstrated, for instance, by the *bidigital advantage* found by Helmuth and Ivry (1996).

Originally assumed to be an open loop process, the central timing structure was soon found to be influenced by additional sensory feedback (Wing, 1977). The peripheral variance, initially conceived as a mere transfer delay, also seems to reflect more sophisticated processes, e.g. active error correction processes (Drewing et al., 2002). The increasing evidence for the contribution of sensory reafferences to the timing precision of movements (Drewing et al., 2002; Drewing & Aschersleben, 2003; Goebl & Palmer, 2008) was the primary reason to assess whether the influence of surrogate sensory feedback on the timing precision can be modelled by means of the two-level timing model. In Experiments 1–5, additional measures of timing precision and force application were also evaluated.

8.1.1 Influence of Feedback Location

Experiment 1 was conducted with the aim to investigate the effects of additional surrogate tactile feedback on the temporal coordination of sequential motor actions. This was achieved by examining the effects of the additional sensory reafferences created by the surrogate tactile feedback on the central and peripheral variance components, but also the constant and variable error. Additionally, tapping force was evaluated.

Based on the notion of the *sensory-goals model* (Drewing & Aschersleben, 2003), it was expected that the additional tactile reafferences corresponding to the tapping movements would decrease the central variance. This could be confirmed.

Furthermore, the surrogate tactile feedback was applied at two locations of the body. The amount of sensory sensitivity of the feedback application site was assumed to affect the amount of contribution to the temporal precision of the cognitive system, analogous to the assumptions of Keller et al. (2011). Therefore, the palmar side of the toe was chosen as a less sensitive site—however, there was still a good amount of sensitivity, as shown by the two-point discrimination pretest. Both locations were found to elicit comparable influence on the measures of temporal performance and the central variance estimate. This was in line with the findings of Panarese, Edin, Vecchi, Carrozza, and Johansson (2009), who studied force regulation of a prosthesis at the toe. Therefore, it was concluded that despite the differences in nerve conduction, the foot is suitable as a location for the surrogate tactile feedback and was used in all subsequent experiments.

It was also found that the peripheral variance was influenced by the target interval. While the central variance is expected to increase with longer target intervals, the peripheral variance component should remain constant across different target intervals (Vorberg & Wing, 1996). Furthermore, there was no significant influence on the force measures, except for an effect of Target Interval on force variability. These issues were addressed in Experiment 2.

8.1.2 Contact-free Tapping

Experiment 2 varied the endogenous tactile feedback by introducing a new tapping device, which made it possible to execute tapping movements without surface contact (comparable to the one Drewing et al. (2002) used). Therefore, the tactile reafferences from the finger-surface contact could be omitted. The aim was to test whether the sensory reafferences of the surrogate tactile feedback could be used as a surrogate for the missing endogenous reafferences. Also, Experiment 2 introduced a new tactile stimulator, since the first version was found to generate a delay due to its inertia.

The contact-free tapping condition led to a higher central variance estimate, thereby augmenting the results of Drewing et al. (2002). Furthermore, in conditions with contact-free tapping and surrogate feedback, the central variance decreased to the level of classical tapping with surface contact (though only during slower tapping speeds). Hence, the surrogate tactile feedback could, at least partially, compensate the missing endogenous sensory reafferences.

The faster tapping speeds (target interval 250 ms) were assumed to be too fast to effectively integrate the additional sensory reafferences. This assumption seems to be supported by an effect of surrogate feedback on the constant error, where additional tactile sensory reafferences in combination with slower tapping speeds led to shorter intervals, while at faster tapping speeds, the constant error was reduced (Experiment 1) or did not differ significantly (Experiment 2).

Since the peripheral variance in this experiment also increased with target interval, a different strategy was tested to handle trials which violate the model assumptions of the two-level timing model. The original policy was to ignore the trials yielding $\rho_I(1) \leq -1/2$ or $\rho_I(1) \geq -1/2$ and include them into the analysis anyways. An alternative account suggests to exclude them from the analysis (O'Boyle et al., 1996). This method was applied and analyzed via linear mixed-effects modeling. The influence of target interval on the peripheral variance remained, thus an exclusion of violators did not significantly change the outcome, which fits to the conclusions of O'Boyle et al. (1996). Henceforth, the original policy was used within the remaining experiments.

The force data were analyzed using a more sophisticated algorithm than in Experiment 1. Since the taps were essentially composed of two components, their amplitudes were extracted separately. Furthermore, the duration was used to compute the impulse as a measure of effort. It was found that all extracted features showed influence of the target interval. However, the other factors only manifested in the first part of the tap. It was assumed that the first part, the initialization of the tap, was of central origin, which would explain the influence of Feedback and Block. The second part was assumed to be controlled from a lower level, probably by a long loop reflex.

8.1.3 Tactile Pacing

Experiment 3 was conducted based on the findings of Experiment 2—it was speculated that the surrogate tactile feedback was not salient enough to be properly integrated. In Experiment 3, it was tested to cue the sensory modality of the feedback by using the surrogate tactile feedback as pacing method.

The results were not as expected. The peripheral variance was the only measure which showed a significant difference due to the pacing modality, yielding a lower variance for the tactile pacing method than for the audio pacing method used in all other experiments in this thesis. However, the analysis by means of the two-level timing model seemed to be problematic, since 52.28% of the trials yielded negative estimates for the peripheral variances. It was assumed that a violation of the assumption of stationarity was the cause for the negative variance estimates. However, most precautions were already taken: the data were tested for drift, the tapping sequences were not too long and in Experiment 2, only valid trials were analyzed.

Since both pacing methods also showed nearly equal proportions of negative estimates, the large amount of model prediction violating trials could not be attributed to a specific pacing modality. Instead, the contact-free tapping was suspected to be problematic for the analysis with the two-level timing model and the following two experiments again used the classical tapping method, requiring participants to tap on a solid surface.

8.1.4 Effects of Delayed Feedback

Experiment 4 was conducted to assess the effects of systematically varied delay of the surrogate feedback signal. Contrary to the expectations, there was no influence of the surrogate feedback on the central variance. It was assumed that the delay decreased the subjective reliability of the feedback signal, which led to a decrease in relevance for the temporal coordination.

There was an influence of delay on the constant error, but only in the slower target intervals. This added further evidence to the notion that the faster tapping speed was problematic and probably too fast for the surrogate tactile feedback to be integrated properly. Additionally, it was confirmed that a delay of 12 ms can already yield differences in temporal coordination. Yet, these were not very pronounced.

The force measurements (amplitudes and momenta) were generally influenced by target interval. Both amplitudes were also influenced by delay, in a comparable manner. There was an interesting V-shape found for both with the applied force being lowest at a delay of 12–24 ms. Considering the notion that lesser force constitutes a more economic movement (e.g., the efficient regulation of grasping force when lifting an object; Johansson & Westling, 1987), this could be an indication that surrogate tactile feedback is best integrated when offered with a certain delay. A possible cause for this could be that delayed feedback signals allow for a better isolation and processing by minimizing interference with endogenous feedback signals.

The momenta of both tap components instead showed different influences: the first momentum, in contrast to the second momentum, was influenced by Delay, thereby supporting the earlier made assumption that both components reflect different neurological origins. Additional evidence came from the correlations between both components, which were quite low.

8.1.5 Effects of Modality and Age

Experiment 5 was conducted for two main reasons: first, to compare the findings from the delayed surrogate feedback with the auditory modality, and second, to investigate potential influences of age in combination with surrogate feedback. Because of the complexity, the experiment was splitted and conducted on two consecutive days.

As in Experiments 1 and 2, the central variance estimate was lower with surrogate feedback. However, this was only the case with the auditory feedback; the tactile feedback did not elicit significant differences as in Experiment 4. At least in terms of auditory feedback, this could be seen as support for the notion of a *sensory-goals* model, as proposed by Drewing et al. (2002). However, this conclusion has to be treated carefully, since there was a lot of evidence that the model assumptions were violated (in terms of the assumed stationarity). Since the model is mathematically identical to the original two-level timing model, the same restrictions apply and, as Vorberg and Wing (1996) put it, nonstationarity can lead to totally misleading results.

For the auditory modality, the constant error showed a clear influence of delay. The tactile modality instead showed comparable values across all levels of delay and the control condition without feedback. The conclusion was that it seemed to have been ignored by the participants, at least in terms of temporal precision. Support from this assumption came from the ratings of mental effort, which showed decrease in effort across the levels of delay, proportional to the effect of constant error. For the tactile feedback, the ratings did not differ from the control condition.

The variable error at first showed a significant decrease in the conditions with auditory feedback—however, this could be traced back almost completely to the lowered constant error by computing the coefficient of variation. Therefore, the variable error was most likely not influenced by the feedback but instead by the shorter interval length produced in conjunction with the auditory feedback. This explanation received support from the fact that the variable error was not influenced by the surrogate feedback in any of the previous experiments, except for a small effect in Experiment 1.

The force measurements showed various influences. Here, the complexity of the factorial design made it difficult to clearly identify patterns between the results. Age for instance had an effect on all force measures, indicating the application of higher force in general, perhaps to compensate reduced sensory performance which was measured by the pretests. Additionally, it was concluded that this effect fits to the notion of declining force control with age.

Furthermore, audio feedback generally led lower values for both amplitudes and momenta, which seems to fit to the notion of multisensory integration (Ernst & Banks, 2002; Ernst & Bülthoff, 2004). The tactile feedback led to a lower force and effort as well, but not of the same magnitude as the audio feedback.

However, the pattern of effects was different for both parts of the tap. Additionally, the correlations between both parts were again low, which could be seen as support for the assumption that both reflect different neurological processes.

8.2 Comparisons Across Experiments

The effect of surrogate feedback was not consistent over the experiments. Within the first two experiments, the constant error decreased in combination with surrogate feedback, but only in the slower conditions. In the faster conditions instead, the pattern was inverted: with surrogate feedback, the constant error increased. In the last two experiments, this effect was not the found: the slower conditions always led to larger constant errors, independent of surrogate feedback.

The variable error was influenced by the surrogate feedback in none of the experiments, except in Experiment 1 (a marginal reduction when feedback was applied at the hand, but only between-subjects) and in Experiment 5, where the reduction of the variable error could be traced back to the shortening of the intervals, as measured by the constant error. In all experiments, the variable error increased with Target Interval.

The absence of feedback effects on the variable error was interesting, since there were significant effects of feedback on the estimated central variance. However, these were not consistent. In the first two experiments, a lower central variance was estimated under surrogate feedback conditions (in the second experiment only in combination with contact-free tapping). In Experiments 3 and 4, there was no sign of a lower central variance, and in Experiment 5, only the surrogate audio feedback led to a lower central variance. This could be due to the problems with the estimation of the two variance components according to Wing and Kristofferson (1973b), which was found to be questionable—if not unappropriate—in all experiments. The trials which fitted to the original model assumptions ranged from 51.11% (Experiment 3) to 64.6% in Experiment 5. This seemed not to be unusual, as it has been reported to happen in about 30% of all practical cases (Kampen & Snijders, 2002)—however, it seems to be problematic in the present context due to the unsystematic behavior of the estimators.

An interesting consistent effect found in the Wing-Kristofferson estimators was a reduction of the peripheral variance with each block, which was also reported in the literature and presumed to constitute a learning effect of the tapping movement (Drewing & Aschersleben, 2003). Here, it was found in all experiments except Experiment 3, where the same effect was found in the central variance instead (thereby again highlighting the unsystematic behavior of the estimators).

All of the force measurements in Experiments 2, 4, and 5 showed a significant influence of tapping speed: slower speeds lead to higher force. The surrogate feedback also was responsible for a number of effects, however, these were inconsistent across experiments. Tendentially, surrogate feedback leads to decreased force peaks and momenta; audio feedback seems to have a greater impact than tactile feedback. A different neurological origin was assumed between both peaks and momenta (A1 and

M1 vs. A2 and M2) based on the pattern of effects and only modest correlations between them—however, this remains speculative and has to be assessed specifically by further research to gain more insight.

8.3 Limitations

The first limitation to be mentioned is, as in all laboratory studies, the compromise between a highly controlled environment and a limited generalizability of the findings. One might argue that tapping is quite an artificial task—which is true, but necessary for the use of variability as dependent measure. Furthermore, great care has been taken to maximize internal validity, while still considering aspects of external validity.

The use of between-subject comparisons is another point which makes the analysis of fundamental mechanisms as in this thesis difficult. Hence, it was tried to minimize the number of between-subject comparisons. Experiment 1 was of exploratory nature, which is why feedback location was integrated with a second sample of participants. The only other between-subject factor in this thesis was Age in Experiment 5, which is difficult to realize within-subject.

Age itself is always a difficult factor, since the inter-individual differences of general motor ability increases with age (Krampe, 2002; Rinkenauer, 2008). The problem with older adults participating in psychological experiments is then that they are often from the upper half of the ability spectrum. The question whether the adults were "too healthy" therefore mostly remains open. However, since the pretests in this thesis showed clear differences between both age groups, the preconditions were good.

Finally, as already mentioned, the assumption of stationarity is crucial for the correct estimation of central and peripheral variance in the context of the two-level timing model. In the context of the tasks employed within this thesis, this assumption was often violated. Although the trials have been screened for drift, it may be nevertheless possible that there was an undetected influence of drift. Fluctuating drift patterns for instance would not have been detected by the applied drift test—using models incorporating trend estimators could help in this case. The violation of the assumptions of stationarity limits the interpretability of the model estimators regarding the effects of surrogate sensory feedback. The interpretation of these effects therefore should be based on global measures of temporal performance and force measures, at least in the context of this thesis.

8.4 Practical Implications

There are a number of practical implications considering the development of sensorimotor assistance systems, which could be derived from the findings of the current thesis.

First of all, it was shown by Experiment 1 that artificial, surrogate sensory feedback can be integrated into the body scheme to increase timing performance. The location at the body therefore has been found to be of relatively little importance, despite the difference in nerve conduction. In the context of sensorimotor assistance systems, this is relevant because it supports the idea of integrating feedback at the foot, which in turn is attractive for several reasons, including improved usability and practicability, thereby making a system suitable for daily use.

Another aspect to consider during the development of surrogate feedback is the delay of the feedback signal. Experiments 4 and 5 yielded important results regarding the effects of force regulation: it was shown that tactile as well as auditory surrogate feedback can enhance force regulation. For both modalities, it was shown that the applied force was most economic when the feedback was delayed within a range of 12–24 ms. Perhaps, this particular amount of delay could be optimal because the delay was long enough to reduce online interferences with the endogenous sensory feedback and simultaneously short enough so that the central nervous system can still cope with it. Even longer delays would eventually lead to distortions (cf. Lee, 1950). Hence, a built-in delay depending of surrogate feedback in sensorimotor assistance systems could be an improvement in the context of supporting economic grip force control.

A third important finding is that, although there were age-related differences found by common tests of motor and sensory discrimination ability, older adults did show almost no differences compared to younger adults regarding the integration of feedback on the temporal coordination of movements. Instead, the influence of surrogate feedback on the force regulation differed between age groups. In summary, the effects suggest that prolonged training might be required for older adults, but generally permit good prospects for the use of sensorimotor assistance systems by older adults.

8.5 Future Research

An interesting topic to investigate would be the assumed different neurological origins of the tapping force components. Since both effort measures, momenta A1 and A2, continuously showed different effect patterns, this assumption seems tenable. For instance, the first momentum showed in all three experiments (2, 4, and 5) an influence of Block, which could be comparable to the one often found in the peripheral variance. If systematical assessment turns out that these components indeed reflect different neurological mechanisms, this could mean a new approach to modeling the mechanisms of motor control in the context of repetitive movements.

Furthermore, a path worth exploring, which was not pursued in this thesis, is an inclusion of the skin sensitivity (two-point discrimination, SWMF, or both) into the analysis of the performance measures, possibly as covariate. This could help to further elucidate the influence of surrogate sensory feedback.

Finally, a possible future research topic could be a replication of Experiment 4, but with the reliability manipulation of the surrogate feedback signal as variable error with different levels of variability in place of a constant delay as independent variable. It would be interesting to see wether the reliability of the surrogate feedback would be reflected by the central variance when it is manipulated using variable rather than constant errors as perturbation.

8.6 Conclusions

The primary aim of this thesis was to investigate whether and how the timing of motor behavior as measured by repetitive movements can be influenced via surrogate feedback. It could be shown that the motor system integrates surrogate feedback at the central level, thereby supporting the notion that the central and peripheral components originally thought to be open-loop are far more complex than originally conceived. For instance, throughout most of the experiments, a learning effect was found in the peripheral variance estimate, congruent with the conclusion of (Drewing & Aschersleben, 2003).

However, the general applicability of the two-level timing model as suggested by Wing and Kristofferson (1973a) in this context has to be questioned, due to the frequent violations of the model assumptions found in all experiments. One of the model assumptions is that central and peripheral variance can be estimated independent of each other, which would be true if they are of open-loop nature—which seems not to be the case.

Since these assumptions are crucial for the proper interpretability of the estimators, it was not possible to support the notion of a *sensory-goals model* as proposed by Drewing et al. (2002) based on the current results. Nevertheless, beneficial effects of surrogate feedback on timing as well as force control were found across all experiments, which highlights the importance of this issue as a research topic.

Bibliography

Adams, M., & Hicks, A. (2005). Spasticity after spinal cord injury. *Spinal cord*, *43*(10), 577–586.

Andersen, R. A., Snyder, L. H., Bradley, D. C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annual review of neuroscience*, *20*(1), 303–330.

Antfolk, C., Björkman, A., Frank, S.-O., Sebelius, F., Lundborg, G., & Rosen, B. (2012). Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin. *Journal of rehabilitation medicine*, *44*(8), 702–707.

Antfolk, C., D'Alonzo, M., Controzzi, M., Lundborg, G., Rosen, B., Sebelius, F., & Cipriani, C. (2013). Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile versus mechanotactile sensory feedback. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *21*(1), 112–120.

Aschersleben, G., Gehrke, J., & Prinz, W. (2001, Feb). Tapping with peripheral nerve block - a role for tactile feedback in the timing of movements. *Experimental Brain Research*, *136*(3), 331–339.

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

Bach-y-Rita, P., Webster, J., Tompkins, W., & Crabb, T. (1987). Sensory substitution for space gloves and for space robots. *Workshop on Space Telerobotics*, *2*, 51–57.

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior research methods*, *37*(3), 379–384.

Barnes, M. P., & Good, D. C. (2013). *Neurological rehabilitation: Handbook of clinical neurology* (Vol. 110). Elsevier.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and* *language*, *68*(3), 255–278.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). lme4: Linear mixed-effects models using Eigen and S4 [Computer software manual]. Retrieved from `https://CRAN.R-project.org/package=lme4` (R package version 1.1-9)

Bell-Krotoski, J. A. (2011). Sensibility testing: History, instrumentation, and clinical procedures. In T. M. Skirven, A. L. Osterman, J. Fedorczyk, & P. C. Amadio (Eds.), *Rehabilitation of the hand and upper extremity* (pp. 132–151). Elsevier.

Biddiss, E. A., & Chau, T. T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and orthotics international*, *31*(3), 236–257.

Billon, M., Semjen, A., Cole, J., & Gauthier, G. (1996). The role of sensory information in the production of periodic finger-tapping sequences. *Experimental Brain Research*, *110*(1), 117–130.

Birklbauer, J. (2006). *Modelle der motorik: eine vergleichende analyse moderner kontroll-, steuerungs-und lernkonzepte* (Vol. 5). Meyer & Meyer Verlag.

Bresciani, J.-P., & Ernst, M. O. (2007). Signal reliability modulates auditory–tactile integration for event counting. *Neuroreport*, *18*(11), 1157–1161.

Bresciani, J.-P., Ernst, M. O., Drewing, K., Bouyer, G., Maury, V., & Kheddar, A. (2005). Feeling what you hear: auditory signals can modulate tactile tap perception. *Experimental brain research*, *162*(2), 172–180.

Burchiel, K. J., & Hsu, F. P. (2001). Pain and spasticity after spinal cord injury: mechanisms and treatment. *Spine*, *26*(24S), S146–S160.

Capa, R. L., Audiffren, M., & Ragot, S. (2008). The interactive effect of achievement motivation and task difficulty on mental effort. *International Journal of Psychophysiology*, *70*(2), 144–150.

Carlton, L. G., Carlton, M. J., & Newell, K. (1987). Reaction time and response dynamics. *The Quarterly Journal of Experimental Psychology*, *39*(2), 337–360.

Chase, R. A., Harvey, S., Standfast, S., Rapin, I., & Sutton, S. (1959). Comparison of the effects of delayed auditory feedback on speech and key tapping. *Science*, *129*(3353), 903–904.

Cong-Khac, D. (2012). *Basic timing concepts for the execution of multiple motor tasks: Coordination of periodic tapping with discrete tasks* (Unpublished doctoral dissertation). München, Univ. der Bundeswehr, Diss., 2012.

Cornsweet, T. N. (1962). The staircase-method in psychophysics. *The American* *journal of psychology*, 485–491.

Davis-King, K. E., Sweeney, M. H., Wille, K. K., Steenland, K., & Arezzo, J. C. (1992). Reference values for amplitudes and conduction velocities obtained from a cohort of middle-aged and retired workers. *Scandinavian journal of work, environment & health*, 24–26.

Delignieres, D., Lemoine, L., & Torre, K. (2004). Time intervals production in tapping and oscillatory motion. *Human Movement Science*, *23*, 57–103.

Dellon, A. L., Mackinnon, S. E., & Brandt, K. E. (1993). The markings of the semmes-weinstein nylon monofilaments. *The Journal of Hand Surgery*, *18*(4), 756–757.

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in cognitive sciences*, *4*(11), 423–431.

DiFranco, D. E., Beauregard, G. L., & Srinivasan, M. A. (1997). The effect of auditory cues on the haptic perception of stiffness in virtual environments. In *Proceedings of the asme dynamic systems and control division* (Vol. 61, pp. 17–22).

Dittmer, D. K., Buchal, R. O., MacArthur, D. E., et al. (1993). The smart wrist-hand orthosis (who) for quadriplegic patients. *JPO: Journal of Prosthetics and Orthotics*, *5*(3), 73.

Drewing, K. (2013). Delayed auditory feedback in repetitive tapping: A role for the sensory goal. *The Quarterly Journal Of Experimental Psychology*, *66*(1), 51–68.

Drewing, K., & Aschersleben, G. (2003). Reduced timing variability during bimanual coupling: A role for sensory information. *The Quarterly Journal of Experimental Psychology: Section A*, *56*(2), 329–350.

Drewing, K., Aschersleben, G., & Li, S.-C. (2006). Sensorimotor synchronization across the life span. *International Journal of Behavioral Development*, *30*(3), 280–287.

Drewing, K., Hennings, M., & Aschersleben, G. (2002). The contribution of tactile reafference to temporal regularity during bimanual finger tapping. *Psychological Research*, *66*(1), 60–70.

Duchek, J. M., Balota, D. A., & Ferraro, F. R. (1994). Component analysis of a rhythmic finger tapping task in individuals with senile dementia of the alzheimer type and in individuals with parkinson's disease. *Neuropsychology*, *8*(2), 218.

Elliott, M. T., Wing, A., & Welchman, A. (2010). Multisensory cues improve sensorimotor synchronisation. *European Journal of Neuroscience*, *31*(10), 1828–1835.

Elliott, M. T., Wing, A. M., & Welchman, A. E. (2011). The effect of ageing on multisensory integration for the control of movement timing. *Experimental brain research*, *213*(2-3), 291–298.

Eriksson, L., Sebelius, F., & Balkenius, C. (1998). Neural control of a virtual prosthesis. In *Icann 98* (pp. 905–910). Springer.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*(6870), 429–433.

Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in cognitive sciences*, *8*(4), 162–169.

Finney, S. A., & Warren, W. H. (2002). Delayed auditory feedback and rhythmic tapping: Evidence for a critical interval shift. *Perception & Psychophysics*, *64*(6), 896–908.

Gallace, A., Tan, H. Z., & Spence, C. (2007). The body surface as a communication system: The state of the art after 50 years. *Presence: Teleoperators and Virtual Environments*, *16*(6), 655–676.

Goebl, W., & Palmer, C. (2008). Tactile feedback and timing accuracy in piano performance. *Experimental Brain Research*, *186*(3), 471–479.

Harrington, D. L., Haaland, K. Y., & Hermanowitz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology*, *12*(1), 3.

Harrington, D. L., Lee, R. R., Boyd, L. A., Rapcsak, S. Z., & Knight, R. T. (2004). Does the representation of time depend on the cerebellum? *Brain*, *127*(3), 561–574.

Held, R. (1961). Exposure-history as a factor in maintaining stability of perception and coordination. *The Journal of nervous and mental disease*, *132*(1), 26–hyhen.

Helmuth, L. L., & Ivry, R. B. (1996). When two hands are better than one: reduced timing variability during bimanual movements. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 278.

Hope, R. M. (2013). Rmisc: Ryan miscellaneous [Computer software manual]. Retrieved from `http://CRAN.R-project.org/package=Rmisc` (R package version 1.5)

Hoschouer, E. L., Basso, D. M., & Jakeman, L. B. (2010). Aberrant sensory responses are dependent on lesion severity after spinal cord contusion injury in mice. *Pain*, *148*(2), 328–342.

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal*, *50*(3), 346–363.

Hothorn, T., Hornik, K., van de Wiel, M. A., & Zeileis, A. (2008). Implementing a class of permutation tests: The coin package. *Journal of Statistical Software*, *28*(8), 1–23. Retrieved from `http://www.jstatsoft.org/v28/i08/`

Inui, N., Ichihara, T., Minami, T., & Matsui, A. (1998). Interactions: timing and force control of finger-tapping sequences. *Perceptual and motor skills*, *86*(3 suppl), 1395–1401.

Ivry, R. B., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience*, *1*(2), 136–152.

Johansson, R., & Westling, G. (1987). Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. *Experimental Brain Research*, *66*(1), 141–154.

Kampen, J. K., & Snijders, T. A. (2002). Estimation of the wing-kristofferson model for discrete motor responses. *British Journal of Mathematical and Statistical Psychology*, *55*(1), 159–168.

Kandil, F. I., Diederich, A., & Colonius, H. (2014). Parameter recovery for the time-window-of-integration (twin) model of multisensory integration in focused attention. *Journal of vision*, *14*(11), 14–14.

Keele, S. W., Ivry, R. I., & Pokorny, R. A. (1987). Force control and its relation to timing. *Journal of Motor Behavior*, *19*(1), 96–114.

Keller, P. E., Dalla Bella, S., & Koch, I. (2010). Auditory imagery shapes movement timing and kinematics: Evidence from a musical task. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(2), 508.

Keller, P. E., Ishihara, M., & Prinz, W. (2011). Effects of feedback from active and passive body parts on spatial and temporal parameters in sensorimotor synchronization. *Cognitive processing*, *12*(1), 127–133.

Koch, I., Keller, P., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance. *International Journal of Sport and Exercise Psychology*, *2*(4), 362–375.

Korman, M., Doyon, J., Doljansky, J., Carrier, J., Dagan, Y., & Karni, A. (2007). Daytime sleep condenses the time course of motor memory consolidation. *Nature neuroscience*, *10*(9), 1206–1213.

Krampe, R. T. (2002). Aging, expertise and fine motor movement. *Neuroscience & Biobehavioral Reviews*, *26*(7), 769–776.

Krampe, R. T., Engbert, R., & Kliegl, R. (2001). Age-specific problems in rhythmic timing. *Psychology and aging*, *16*(1), 12.

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and anovas. *Frontiers in psychology*, *4*, 863.

Larkin, D., & Cermak, S. A. (2002). Issues in identification and assessment of developmental coordination disorder. In D. Larkin & S. A. Cermak (Eds.), *Developmental coordination disorder* (pp. 86–102). Delmar, Albany, NY.

Lee, B. S. (1950). Effects of delayed speech feedback. *The Journal of the Acoustical Society of America*, *22*(6), 824–826.

Leuthardt, E. C., Schalk, G., Moran, D., & Ojemann, J. G. (2006). The emerging world of motor neuroprosthetics: a neurosurgical perspective. *Neurosurgery*, *59*(1), 1–14.

Lindberg, P., Ody, C., Feydy, A., & Maier, M. A. (2009). Precision in isometric precision grip force is reduced in middle-aged adults. *Experimental brain research*, *193*(2), 213–224.

Liu, W., Forrester, L., & Whitall, J. (2006). A note on time-frequency analysis of finger tapping. *Journal of motor behavior*, *38*(1), 18–28.

Long, C., & Schutt, A. (1986). Upper limb orthotics. *Occupational Therapy, J B. Lippincott Company, Philadelpia*, 258–271.

Miall, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural networks*, *9*(8), 1265–1279.

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to cousineau (2005). *reason*, *4*(2), 61–64.

Mulcahey, M., Betz, R., Kozin, S., Smith, B., Hutchinson, D., & Lutz, C. (2004). Implantation of the freehand system® during initial rehabilitation using minimally invasive techniques. *Spinal Cord*, *42*(3), 146–155.

Nowak, D. A., Glasauer, S., & Hermsdörfer, J. (2004). How predictive is grip force control in the complete absence of somatosensory feedback? *Brain*, *127*(1), 182–192.

Nowak, D. A., Hermsdörfer, J., Glasauer, S., Philipp, J., Meyer, L., & Mai, N. (2001). The effects of digital anaesthesia on predictive grip force adjustments during vertical movements of a grasped object. *European Journal of Neuroscience*, *14*(4), 756–762.

O'Boyle, D. J., Freeman, J. S., & Cody, F. W. (1996). The accuracy and precision of timing of self-paced, repetitive movements in subjects with parkinson's disease. *Brain*, *119*, 51–70.

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods*, *8*(4), 434–447.

Osborne, J. W., & Overbay, A. (2004). The power of outliers (and why researchers should always check for them). *Practical assessment, research & evaluation*, *9*(6), 1–12.

Panarese, A., Edin, B. B., Vecchi, F., Carrozza, M. C., & Johansson, R. S. (2009). Humans can integrate force feedback to toes in their sensorimotor control of a robotic hand. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *17*(6), 560–567.

Pastor, M., Jahanshahi, M., Artieda, J., & Obeso, J. (1992). Performance of repetitive wrist movements in parkinson's disease. *Brain*, *115*(3), 875–891.

Pfordresher, P., & Palmer, C. (2002). Effects of delayed auditory feedback on timing of music performance. *Psychological research*, *66*(1), 71–79.

Pfordresher, P. Q. (2006). Coordination of perception and action in music performance. *Advances in Cognitive Psychology*, *2*(2-3), 183–198.

R Core Team. (2016). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria. Retrieved from `https://www.R-project.org/`

Raspopovic, S., Capogrosso, M., Petrini, F. M., Bonizzato, M., Rigosa, J., Di Pino, G., ... others (2014). Restoring natural sensory feedback in real-time bidirectional hand prostheses. *Science translational medicine*, *6*(222).

Repp, B. H. (2005). Sensorimotor synchronization: a review of the tapping literature. *Psychonomic bulletin & review*, *12*(6), 969–992.

Repp, B. H. (2010). Sensorimotor synchronization and perception of timing: effects of music training and task experience. *Human movement science*, *29*(2), 200–213.

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: a review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452.

Resnik, L., Klinger, S. L., Etter, K., & Fantini, C. (2014). Controlling a multi-degree of freedom upper limb prosthesis using foot controls: user experience. *Disability and Rehabilitation: Assistive Technology*, *9*(4), 318–329.

Rigoli, L. M., Holman, D., Spivey, M. J., & Kello, C. T. (2014). Spectral convergence in tapping and physiological fluctuations: coupling and independence of 1/f noise in the central and autonomic nervous systems. *Frontiers in Human Neuroscience*, *8*, 1-10.

Rinkenauer, G. (2008). Leistungsfähigkeit und Mobilität im alter. In B. Schlag (Ed.), (p. 239-254). TÜV Rheinland.

Rossini, P. M., Micera, S., Benvenuto, A., Carpaneto, J., Cavallo, G., Citi, L., ... others (2010). Double nerve intraneural interface implant on a human amputee for robotic hand control. *Clinical neurophysiology*, *121*(5), 777–783.

Rupp, R. (2008). *Die motorische rehabilitation von querschnittgelähmten mittels elektrostimulation: ein integratives konzept für die kontrolle von therapie und funktioneller restitution.* Verlag Dr. Hut.

Schmidt, R. A. (1988). *Motor control and learning.* Champaign, IL: Human kinetics.

Schöner, G. (2002). Timing, clocks, and dynamical systems. *Brain and cognition*, *48*(1), 31–51.

Schröder-Schetelig, J., Manoonpong, P., & Wörgötter, F. (2010). Using efference copy and a forward internal model for adaptive biped walking. *Autonomous Robots*, *29*(3-4), 357–366.

Shadmehr, R., Smith, M. A., & Krakauer, J. W. (2010). Error correction, sensory prediction, and adaptation in motor control. *Annual review of neuroscience*, *33*, 89–108.

Singmann, H., Bolker, B., & Westfall, J. (2015). afex: Analysis of factorial experiments [Computer software manual]. Retrieved from `http://CRAN.R-project.org/package=afex` (R package version 0.14-2)

Stein, J., Narendran, K., McBean, J., Krebs, K., & Hughes, R. (2007). Electromyography-controlled exoskeletal upper-limb–powered orthosis for exercise training after stroke. *American journal of physical medicine & rehabilitation*, *86*(4), 255–261.

Sternad, D., Dean, W. J., & Newell, K. M. (2000). Force and timing variability in rhythmic unimanual tapping. *Journal of motor behavior*, *32*(3), 249–267.

Stevens, L. T. (1886). On the time-sense. *Mind*(43), 393–404.

Stich, H. L., & Baune, B. T. (2011). Increasing prevalence of motor impairments in pre-school children from 1997-2009: results of the bavarian pre-school morbidity survey. *Educational Research (ISSN: 2141-5161)*, *2*(8), 1409–1416.

Studenka, B. E., Zelaznik, H. N., & Balasubramaniam, R. (2012). The distinction between tapping and circle drawing with and without tactile feedback: an examination of the sources of timing variance. *The Quarterly Journal of Experimental Psychology*, *65*(6), 1086–1100.

Sullivan, J. E., & Hedman, L. D. (2008). Sensory dysfunction following stroke: incidence, significance, examination, and intervention. *Topics in stroke rehabilitation*, *15*(3), 200–217.

Tiwana, M. I., Redmond, S. J., & Lovell, N. H. (2012). A review of tactile sensing technologies with applications in biomedical engineering. *Sensors and Actuators A: physical*, *179*, 17–31.

Ulrich, R., & Wing, A. M. (1991). A recruitment theory of force-time relations in the production of brief force pulses: The parallel force unit model. *Psychological Review*, *98*(2), 268.

Ungerleider, L. G. (1995). Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature*, *377*, 155–158.

Ursino, M., Magosso, E., & Cuppini, C. (2011). Sensory fusion. In *Perception-action cycle* (pp. 23–62). Springer.

Van der Linden, D., Frese, M., & Meijman, T. F. (2003). Mental fatigue and the control of cognitive processes: effects on perseveration and planning. *Acta Psychologica*, *113*(1), 45–65.

Vardy, A., Daffertshofer, A., & Beek, P. (2009). Tapping with intentional drift. *Experimental brain research*, *192*(4), 615–625.

von Holst, E., & Mittelstaedt, H. (1950). Das Reafferenzprinzip. *Naturwissenschaften*, *37*(20), 464–476.

Vorberg, D., & Wing, A. (1996). Chapter 4 modeling variability and dependence in timing. In H. Heuer & S. W. Keele (Eds.), *Motor skills* (Vol. 2, p. 181 - 262). Academic Press. Retrieved from `http://www.sciencedirect.com/science/article/pii/S1874582206800071` doi: doi: http://dx.doi.org/10.1016/S1874-5822(06)80007-1

Weber, E. H. (1835). Über den Tastsinn. *Archiv für Anatomie, Physiologie und Wissenschaftliche Medicin*, *52*, 152.

Weinstein, S. (1993). Fifty years of somatosensory research: from the semmes-weinstein monofilaments to the weinstein enhanced sensory test. *Journal of Hand Therapy*, *6*(1), 11–22.

Welch, B. L. (1947). The generalization of Student's' problem when several different population variances are involved. *Biometrika*, *34*(1/2), 28–35.

Wing, A. M. (1977). Perturbations of auditory feedback delay and the timing of movement. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(2), 175.

Wing, A. M., Doumas, M., & Welchman, A. E. (2010). Combining multisensory temporal information for movement synchronisation. *Experimental brain research*, *200*(3-4), 277–282.

Wing, A. M., & Kristofferson, A. B. (1973a). Response delays and the timing of discrete motor responses. *Perception & Psychophysics*, *14*(1), 5–12.

Wing, A. M., & Kristofferson, A. B. (1973b). The timing of interresponse intervals. *Perception & Psychophysics*, *13*(3), 455–460.

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *nature neuroscience*, *3*, 1212–1217.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science-AAAS-Weekly Paper Edition*, *269*(5232), 1880–1882.

Zallinger, G. (1998). *Das zyklische zeitprogramm als koordinative grundlage für die leichtathletische sprinttechnik – eine elektromyographische analyse* (Unpublished doctoral dissertation). University of Salzburg.

Zijlstra, F. R. H. (1993). *Efficiency in work behaviour: A design approach for modern tools* (Unpublished doctoral dissertation). TU Delft, Delft University of Technology.

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Hiermit versichere ich **schriftlich** und **eidesstattlich** gemäß §11 Abs. 2 PromO v. 08.02.2011/08.05.2013:

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Dortmund, den 19. Januar 2018

Andreas Bremer

3. Weiterhin erkläre ich **schriftlich** und **eidesstattlich**, dass mir der „Ratgeber zur Verhinderung von Plagiaten" und die „Regeln guter wissenschaftlicher Praxis der Technischen Universität Dortmund" bekannt und von mir in der vorgelegten Dissertation befolgt worden sind.

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