Regularity and asynchrony when tapping to tactile, auditory and combined pulses

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ABSTRACT

This research is carried out with the aim to develop assistive technology that helps users following the beat in music, which is of interest to cohchlear implant users. The envisioned technology would use tactile feedback on each musical beat. However, this raises fundamental questions about uni- and cross-modal perception which are not addressed in similar context in the literature. The aim of this study was i) to find out how well users are able to follow tactile pulses. ii) To gain insights in the differences between auditory, tactile and combined auditory-tactile feedback. A tapping experiment was organized with 27 subjects. They were requested to tap along with an auditory pulse, a tactile pulse and a combined auditory-tactile pulse in three different tempi. An evaluation with respect to regularity and asynchrony followed. Subjects were found to perform significantly better in terms of reqularity and asynchrony for the auditory and auditory/tactile condition with respect to the tactile only condition. Mean negative asynchrony (MNA) for auditory and combined (auditory and tactile) conditions were in the range of previous studies. The MNA's for the tactile conditions showed a remarkable dependence on tempo. In the 90BPM condition a clear anticipation (-20ms) was reported, for the 120BPM condition the mean was around zero, the 150BPM condition showed a positive MNA (a reaction vs anticipation). An effect that could be encorporated into the design of an assistive technology.

I. INTRODUCTION

Humans generally are able to track musical beat and rhythm. Synchronizing movement with perceived beats is a process that is natural to most. Both processes develop during early childhood (Hannon and Trehub, 2005). Bodily entrainment with a beat might have biological origins since it promotes group cohesion and could play a role in sexual selection. Dance is often a persuading display of fitness and phenotypic disposition. However, users of cochlear implants that were early-deafened but only implanted during adolescence or later have difficulties following rhythm (Fuller et al., 2013; Timm et al., 2014). This in contrast with post-lingually deafened CI users who perform almost on par with normal hearing persons (McDermott, 2004).

More specifically, this research was carried out after a request of a person which was implanted with a cochlear implant later in life. She wants to be able to dance the tango and has been managing by following the lead of her dance partners. However, she does not want to depend on rehearsed visual cues by specific dance partners and wants be able to switch dance partners freely. Moreover, she has reached a level at which she feels it becomes hard to improve without feeling the beat. This paper aims to be a preliminary step in the design process of an assistive technology. The goal is to gain insights into synchronized tapping performance, in terms of regularity and asynchrony, while following either auditory, tactile or auditory-tactile pulses.

There is a great body of work around tapping to auditory cues. A good overview is given by Repp (2005); Repp and Su (2013). However, much less is known about how multisensory integration can affect sensorimotor synchronization. Elliott et al. (2010) does focus on this topic and finds that multisensory cues can improve synchronization. In the study only a fixed metronome of 120BMP is used. This study includes a wider variation of tempi (90, 120 and 150BMP) and focuses on a single type of multisensory integration: tactile-auditory cues.

II. METHOD

A. Subjects

27 subjects were recruited, 16 female and 11 male. The group contained two professional musicians and three participants with cochlear implants (CI) implanted after language development. All subject had normal motor skills. The three CI users were not included in the main analysis but serve as case studies.

B. Experimental Set-up

The subjects were placed in a soundproof room with dimmed lightning. They were placed at a table with a drum equipped with drums placed below the dominant hand and a vibrating device in the other. Headphones were used to deliver the auditory stimuli. The Ethical Review Committee of Ghent University approved the experimental protocols which also complied with the Declaration of Helsinki.

C. Procedure

Participants were requested to tap along with a) an auditory pulse b) a tactile pulse and c) a simultaneous auditory and tactile pulse at three tempi (90, 120 and 150BPM). Auditory pulses where either discrete (a metronome) or continuous (music). The distinction between discrete and continuous lays in the sound between the events. In the continuous case (music), there is sound information between the beats which can help to predict or anticipate the next beat. For the discrete case (metronome), there is only silence in between the ticks. The intervals between tactile pulses where either rigid (originating from the metronome) or contained small micro timing perturbations (originating from the music). Which makes a total of 18 conditions. Each condition took 35 seconds and between each fragment there was a silent pause for 5 seconds. The total run-through of all tasks was about 15 minutes per participant. The order of the conditions was randomized but with a rule that no two conditions with the same tempo appeared directly in succession.

D. Stimuli and Equipment

A linear resonant actuator (LRA) from Samsung (DMJBRN0832BJ) driven by a haptic motor driver from Texas Instruments (DRV2605) was used to deliver tactile feedback. LRA-motors vibrate on one single axis and have a sharp attack. The LRA was chosen over regular eccentric rotating mass (ERM) actuators. ERM actuators deliver feedback in all directions and are slow to start and stop due to inertia. To register the taps by participants a sensor was built based on strain gauges. The sensor had the look and feel of a regular drum. When hitting the drum, the strain gauges underneath respond quickly to deformation of material. When the deformation is above a certain threshold, a tap is registered.

The auditory feedback was done using a closed headphone, the HD 215 by Sennheiser. The stimuli were equalized for perceptual loudness using a replay gain algorithm in Audacity to -89dB. The volume was kept stable during the experiment. During the tactile feedback condition noise was used to mask the sound made by the participant while hitting the drum. It was colored using the spectrum of the sound produced by tapping the drum. The perceptual loudness of the noise was also fixed at -89dB.

Tactile feedback, registering taps and auditory feedback was done by a microcontroller. The main advantage of using a microcontroller is the precision in time. Here, a Teensy 3.2 (by PJRC) microcontroller was programmed to perform these tasks. Since all timing critical tasks are performed by a device that is capable of low-latency, sub-millisecond guarantees can be made for timing measurements between feedback (auditory, tactile) and input (tapping). The Teensy was equipped with an Audio Adapter Board (also by PJRC) to store and play audio.

During the experiment, the obtained data was sent to a laptop (a late 2010 Macbook Air) for storage and analysis over a serial port. On the laptop a script in the Ruby programming language instructed the Teensy microcontroller of which condition to perform and stored the tapping data in a text file with a descriptive name.

E. Data

The resulting experimental data consists of two lists of timestamps in milliseconds. A list for the reference (beats or tactile feedback pulses) and a list for the received taps. With the first list, the regularity of the inter tap intervals can be determined. Using both lists, the asynchrony between taps and beats - or tactile pulses - can be analyzed.

After the session each participant was requested to fill out a questionnaire with basic personal data and musical background. Also they were asked to subjectively describe the difficulties during trails. To detect irregularities after the experiment, the trails were videotaped.

Since participants need a few seconds to adjust to a tempo at the beginning of a 35 seconds trail, four seconds were removed at the beginning. One second was removed at the end to prevent that the fade-out present in the music trails had any effect. This trimming operation ensured 30 seconds of usable data. Extreme values were also removed from the dataset. The underlying reasoning being that the task was not correctly executed in these cases. Values are deemed extreme if 1.5 times the standard deviation of the inter tap intervals is larger than half of the expected Inter Beat Interval. Only four of the total of 432 trails were removed.

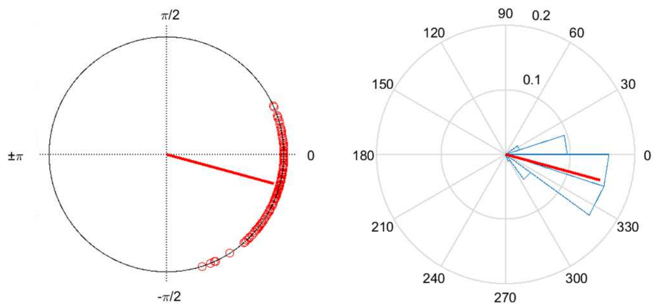

Figure 1. The data from one trail visualized as a series of dots (left) and in a histogram (right). Each Inter Beat Interval is mapped to 0 to 360 and each tap contributes to the position and size of the mean. The position determines the mean negative asynchrony. The size determines the regularity: closer to the unit circle means more regular.

F. Analysis

Regularity is defined by a list of Inter Tap Intervals (ITI) for a trail. The standard deviation of the ITIs was used as a proxy for regularity end is expressed in milliseconds. Regularity was used to check if participants executed the task correctly. Also an univariate ANOVA analysis was done using SPSS 23 looking for effects of three factors:

1. **Stimulus**, it is either auditory, tactile or combined auditory-tactile.
2. **Sound**, which is either music, or metronome. Music contains small micro timing variations while the metronome is perfectly stable.
3. **Tempo**, which is either slow, medium, or fast. Respectively 90, 120 and 150 beats per minute (BPM).

Table 1. Effect of the factors on regularity. Stimulus has the biggest significant effect, followed by Sound and Tempo.

Source	Type III Sum of Squares	D.f.	Mean Square	F	Sig.	Pct (%)	Cum Pct
Model	373429.5	18	20746.1	70.3	< 0.001		
Stimulus	7816.4	2	3908.2	13.2	< 0.001	33.2	33.2
Sound	3805.7	1	3805.7	12.9	< 0.001	32.3	65.5
Tempo	4206.2	2	2103.1	7.1	0.001	17.8	83.3
Stimulus * Sound	1859.7	2	929.9	3.2	0.044	7.9	91.2
Stimulus * Sound	1614.4	4	403.6	1.4	0.245	3.4	94.6
Stimulus * Tempo Sound	1292.1	4	323	1.1	0.359	2.7	97.4
Tempo * Sound	622.1	2	311	1.1	0.35	2.6	100
Error	104473	354	295.1				
Total	477902.5	372					

Asynchrony was measured by comparing the reference with the actual tap. The asynchrony can be expressed using an angle. The expected inter beat interval is mapped to a circle, and each tap can be seen as a point on this circle. Figure 1 shows the data of one trail, tap instants are mapped onto a unit circle in the left part of the figure. The circular mean is shown as a vector (red) where the angle, in degrees, between zero and the vector is the mean asynchrony. In this case it shows a mean negative asynchrony which suggests anticipatory behaviour: the tap happens before the beat. Conversely, a positive angle would mean a delay between (responsivatory) the actual event and the response, while zero means perfect synchronization. The size of the vector determines how regular the participant tapped. A value of 1 would mean perfect regularity. For data analysis, circular statistics and the circular statistics matlab toolbox (Berens et al., 2009) is used. A circular statistics ANOVA was done using the same factors as explained above: Stimulus, Sound and Tempo.

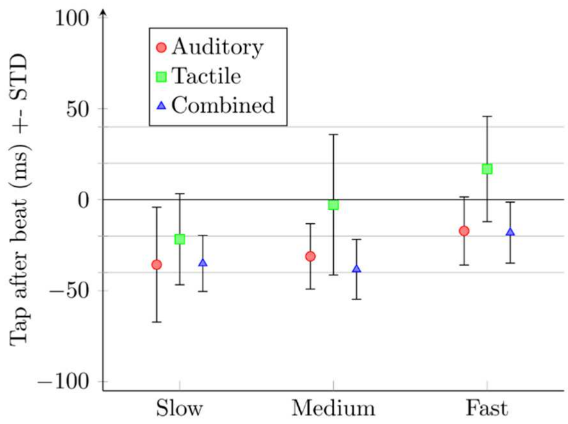

Figure 2. The asynchronies for slow medium and fast tempi while tapping to auditory, tactile or combined pulses..

III. RESULTS

In terms of regularity, subjects performed significantly better for the auditory and auditory/tactile condition with respect to the tactile only condition. As shown by an ANOVA (see Table 1) followed by a post-hoc Tuckey test. The standard deviation of the inter tap intervals increases from 25.9 ms and 29.5 ms to 37.0 ms in the tactile case. The data is also suggests that adding tactile pulses to an auditory stream improves regularity, but the data is not conclusive. The ANOVA showed a significant main effect for factors Tempo (90, 120 and 150BPM), Sound (music or metronome) and Stimulus (tactile, auditory or tactile/auditory). Modifying these parameters, in other words, changes tapping behavior.

In terms of asynchrony, performance changes were also induced mainly by a change in from auditory to tactile feedback. A circular statistics ANOVA (see Table 2) showed significant effects for Stimulus and Tempo but the model only explained 18% of the variance. The data showed a similar performance for the auditory and tactile-auditory condition and worse performance for the tactile only condition in terms of synchronization.

In Figure 2 the mean ascynchrony is plotted for all trails, grouped by Tempo and Stimulus. In the slow condition it hints at a more stable asynchrony for the combined versus the auditory case. While in the fast condition adding tactile information to the auditory stream helps less to improve asynchrony. For the tactile condition there seems to be a striking dependence on tempo. In the slow tempo anticipation is recorded, while in the fast condition hits are registered, on average, too late.

IV. CONCLUSION

It is possible to follow a tactile pulse however regularity and synchronization both suffer compared to auditory queues. Mean negative asynchrony (MNA) for auditory and combined (auditory and tactile) conditions were in the range of previous studies. The MNA's for the tactile conditions showed a remarkable dependence on tempo. In the 90BPM condition a clear anticipation (-20ms) was reported, for the 120BPM condition the mean was around zero, the 150BPM condition showed a positive MNA (a reaction vs anticipation). If both tactile and auditory queues are present at the same time our data suggest that tapping performance increases slightly (in terms of both regularity and synchronization).

It is hard to attribute changes in synchronization behavior between tactile or auditory conditions to a specific cause. In the current experimental design it is not possible to separate effects of feedback processing time, anticipatory behavior, motor control delay/problems or reaction times. Further research is needed for a better understanding of the underlying processes.

Table 2. Effect of the factors on asynchrony. Stimulus has the biggest significant effect, followed by Tempo.

Source	D.f.	SS	MS	F	Sig.	Pct	Cum
Stimulus	2	9.2	4.6	26.7	< 0.001	11	11
Tempo	2	3	1.5	8.7	< 0.001	3,6	15
Interaction	4	2.5	0.6	3.4	0.009	3	18
Residual	379	69	0.2			82	100
Total	387	84					

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