Effect of stiffness on tapping performance. Do you rely on force to keep synchronised along with a metronome ?

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Effects of Stiffness on Tapping Performance – Do We Rely on Force to Keep Synchronized along with a Metronome?

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Abstract

Several works have examined the robustness of the sound-action loop to auditory delay, and the effects of delay on performance. In this paper we propose a complementary approach, by modifying the stiffness of the tapped object. Participants had to perform synchronous tapping along with a metronome reference, using a one degree-of-freedom haptic device. Two experimental conditions were tested: with and without sound from the tapped object. Dynamics of the experiment were recorded in order to have a closer look at the dynamic factors affecting performance. Results show that the increase of the stiffness of the tapped object leaded to a decrease of the asynchrony, indicating that the modification of the force dynamics has an effect on performance. On the basis of this observation, an explanation of the negative asynchrony effect is proposed. At last, we show that sound feedback improves performance only when the stiffness is very low.

1. Introduction

Applying repetitive percussions on a sounding object, either with the finger or with another object such as a pen, is commonly called *tapping*. It has been for long an important case of study, because it is not very demanding for human cognition, as almost everybody is able to do this very easily, and because it can reveal low-level features of human sensory-motor skills. We will only provide here a short review of the relevant papers for our work presented here. More information can be found in the recent reviews from Lago and Kon [1], and Mäki-Patola [2].

One important point of studies about tapping involves the perception of delay between sound and gesture, especially when sensory information from two different media should come from the same cognitive object. Levitin et al. [3] reported the perception of simultaneity between a tapping gesture and the so-produced sound. Subjects detected time delay when sound was produced –25 to +42 ms from the tapping event.

This result is somewhat consistent with Adelstein et al. [4], where in a similar experiment subjects were asked to judge whether a hammer tap (performed by the subject) and its corresponding sound were simultaneous or not, when compared to a tapping reference (performed by the subject too) where the sound delay was 7 ms. Results showed a mean Just Noticeable Difference of 24 ms, and a mean Point of Subjective Equality of 4.8 ms (from –25 to 44 ms, depending on the subject). Mäki-Patola and Hämäläinen [5] reported the same kind of experiment, but using the Theremin, a continuous sound instrument involving no tactile or kinesthetic information. Their results showed a JND between 20 and 30 ms, when compared with a reference where no latency was added by the effects processor. The remaining latency with no added delay was however not detailed.

Another aspect of this case study is the maintaining of a regular tapping according to a time reference. When tapping along with an isochronous time reference, such as a metronome, one typical effect is *negative asynchrony*, that is: subjects tend to tap lightly in advance with the isochronous time reference. Aschersleben [6] had subjects tapping with the finger along with a metronome. This experiment showed that subjects systematically tapped in advance of several tens of milliseconds without noticing asynchrony. Mean asynchrony was from –14 ms for skilled musicians vs. –40 to –50 ms (up to –100 ms in extreme cases) for untrained persons.

If it seems possible for some people to maintain a tapping synchronously with a time reference, and that the asynchrony averages one hundreds of milliseconds, it does not seem possible, on the contrary, to maintain a tapping performance when sound information is delayed more than 50 ms from haptic information. Dahl et al. [7] studied the way auditory and tactile feedback more or less influence a player during a musical performance. They had a few subjects performing tapping gestures with a Max Mathews radio-baton (subjects had to hit the radio plate to trigger the sound), following the pulse imposed by a metronome. Delay of auditory feedback was gradually increased from 1 to 127 ms, and it appeared that subjects could manage with this delay up to between 40 and 55 ms, before giving up the tapping movement.

To our knowledge, effects on performance of the material properties of the tapped object have not been studied in the literature: most of the work try to enlighten the sound-gesture relationship by bringing modifications in the sound produced, whether by introducing lag, or by modifying the characteristics of the sound.

We want here to propose another approach, by modifying the properties of the gesture interaction between the subject and the simulated object during the experiment, without modifying the properties of the produced sound, nor modifying the necessary conditions to obtain this sound (e.g. the dynamics of the tapping gesture that could lead to the production of sound).

2. Design of the model

2.1. CORDIS-ANIMA: modeling the matter

The simulation of the tapping situation was designed with CORDIS-ANIMA [8], which is integrated in our real-time multisensorial environment. Two types of elements constitute our models of natural objects:

- Particles of matter; these ones can be understood as inertial material punctual elements.
- Interactions may be established between two particles, and create elastic, viscous or other types of interaction forces. For a given material particle, several interactions with other particle elements may be superimposed.

Therefore, a CORDIS-ANIMA model can be seen as a network of particle elements, linked one to each other by interaction elements. This type of modeling is very general, and allows for the representation of:

- Various properties of the matter: depending on the type and parameters of the interaction elements, the rheological properties of the matter, such as elasticity, plasticity, viscosity… will be modified.
- Different states of the matter, such as the solid, liquid, gaseous and intermediary states of the matter (paste, powder, sand, etc.).
- Natural interactions between several material objects in a very general way.

An important property of the CORDIS-ANIMA modeling system is that the whole information addressed to the different sensory channels involved is generated *by only one unique model* (Figure 1):

- Sound is produced by transmitting the positions of particular mass elements along time (one of these elements will correspond to one sound channel) to loudspeakers.
- Haptic interaction will involve specific material elements of the model, standing for the haptic device within the model. Forces applied to these elements are transmitted to the haptic device, and position of the haptic device is transmitted back.
- Visual rendering of the model can be performed too, by feeding an external geometrical rendering process with the positions along time of the mass elements constituting the model.

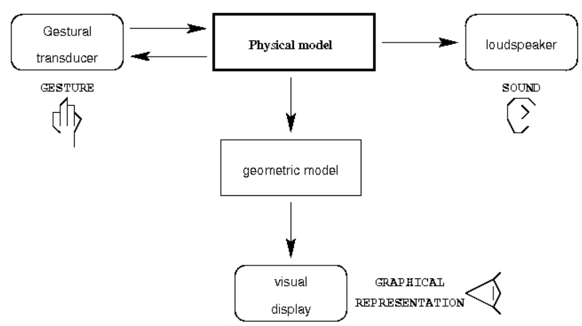

Figure 1. The CORDIS-ANIMA modeling system allows addressing several sensorialities

The model we implemented in our real time simulator tries to imitate the phenomenon occurring in the real world when one performs instrumented tapping on a sounding object (e.g. tapping with a pen on a table). Figure 2 sketches the CORDIS-ANIMA elements used: our model is composed of only five particle elements, including three particle inertia elements (A, B, C), represented by circles on the figure, and two "ground" elements. It also includes four interaction elements, modeling either mechanical stops or visco-elastic links, connecting the particles elements one to the others.

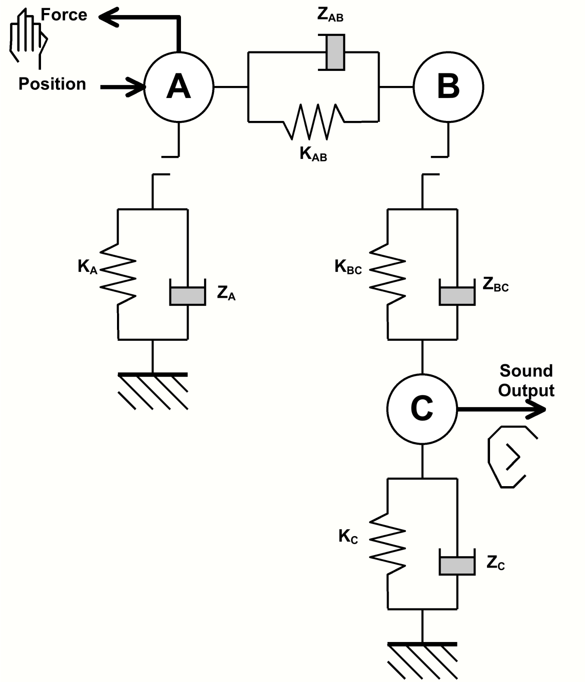

Figure 2. Schematic representation of the simulation model

2.2. Sound from the tapped object: the vibrating structure

Mass C is the particle element generating the sound: its movement is directly transmitted to the sound output of the simulator. The combination of mass C and of the visco-elastic interaction element $\{K_C, Z_C\}$ constitutes an elementary oscillator, whose properties are kept constant throughout the whole experiment; they were designed so that the so-produced sound hears like a small blade of metal. Frequency of the sound is about 630 Hz.

2.3. Manipulation point

Mass A is a specific particle element: it actually represents the point manipulated by the user into the model thanks to the haptic device. The position of the haptic device corresponds to the position of mass A into the model, and forces applied to mass A into the model are applied as well on the haptic device.

A mechanical stop $\{K_A, Z_A\}$ was attached between mass A and the ground to obtain a direct way to modify the rigidity of the tapping phenomenon without having to modify its interaction with the vibrating structure. This could only be possible if the impedances of the mechanical stop $\{K_A, Z_A\}$ viewed from A is important compared to the impedance of the link $\{K_{AB}, Z_{AB}\}$ attached to the rest of the model viewed from A. It allowed us to obtain different situation cases where the haptic interaction could be changed, but where the dynamic phenomenon involved in the sound production could be kept the same.

Stiffness values for K_A were chosen to cover a wide range of possible contacts: from almost no stiffness (K_1) to hard stiffness (K_3) (Table 1). Experiencing stiffness K_1, most of the subjects of the pilot experiment complained about the lack of reference when there was no sound feedback from the tapped object, because in this case stiffness was such low that it was almost impossible to feel the elastic contact with the object at movement speeds required by the experiment. We however decided to keep a low value for K_1 to observe the possible effects of loosing the haptic reference for tapping contact.

2.4. Hammer

The ideal model would be to have mass A directly colliding mass C, without any intermediary. Although very interesting because of its simplicity, this design solution couldn't lead to perfectly stable cases, because the maximum stiffness required was important. Another limitation of this solution was due to the computation of mass A at 3 kHz, whereas the rest of the model was computed at 15 kHz. A direct contact of mass A with the vibrating structure (mass C) would have generated some transients due to the over-sampling, thus increasing the instability of the model.

In order to provide a simulation situation sufficiently close from the real tapping situation, we therefore had to add an intermediary mass between masses A and C, playing the role of a hammer (mass B): it is linked to mass A through a visco-elastic interaction element. It plays at first the role of a filter for mass A under-sampling, and mass C is this way excited by another mass computed at 15 kHz.

Physical parameters of the visco-elastic interaction element between A and B were chosen so that its rigidity could be as high as possible, but leaving the so-produced oscillator in its non-oscillatory domain. This way, from the point of view of the subject, the added mass B could not be perceived as an added oscillator at the end of the manipulated point. Furthermore, weight of mass B was chosen sufficiently low so that it was

Table 1. Stiffness for the three possible values of K_A during the experiment

Parameter K_A	Stiffness [$N.mm^{-1}$]
K_1	0.17
K_2	1.7
K_3	17

imperceptible compared to the natural inertia of the haptic device.

However, adding a striker element introduced some delay between the haptic percussion due to the collision into stop $\{K_A, Z_A\}$ and the sound produced by the hitting of mass B into the vibrating structure, since mass B is attached to mass A through a viscous spring: the mean added delay we measured was about 11 ms (between 10 and 13 ms depending on the movement performed); it is the time between the generation of haptic feedback, and the generation of the sound. Adding this delay to the time necessary for the generation of a sound at headphones (3 ms, due to the sound board), we obtain an overall delay of 15 ms, between the haptic event and the sound event, for a same tapping event inside the simulated model. This delay falls below the thresholds for the perception of simultaneity [3,4,5], and was therefore not considered as a disturbance for our experiment.

2.5. Metronome

The metronome is not represented on Figure 2, but it was included inside the model to have a recording of its movement for post-analysis, and to be sure that its recorded dynamics would be perfectly synchronized with the dynamics of the tapping model. The metronome model is based on the use of a mass oscillating between two stops, and striking a vibrating structure such as the couple mass C and the interaction element $\{K_C, Z_C\}$. Viscosity of the interactions was set sufficiently low so that the loss of energy of the striking mass wouldn't lead to a perceptible decrease in the metronome frequency along the length of the trial.

$\{K, Z, M\}$ parameters of the vibrating structure were set such that the frequency of the produced sound would be: $f_{metronome} = 100$ Hz. This frequency is very different from the sounding frequency of the tapped object, so that no confusion could be possible between these two sounds.

3. Gesture interaction: the haptic device

3.1. Functional characteristics

When performing taps on an object, the simplest situation is obtained by making linear movements. That is, a minimal situation can be obtained using a one degree-of-freedom haptic interface between the user and the multisensory simulator.

We therefore have chosen among the ERGOS panoply [9] a simple stick, fixed on one slice of our force-feedback keyboard. The stick is 4 cm long, and a ball of 1.5 cm diameter is fixed at its extremity to provide a suitable finger grip. This way, a vertical movement of about 22 mm range allows performing taps on the simulated sounding object. The functional characteristics of the haptic device are presented in Table 2, and a picture of the device is presented Figure 3.

Table 2. Functional characteristic of the ERGOS device

Size of workspace	22 mm
Maximum force level	200 N per slice
Max **continuous** force exerted	60 N per slice
Weight (active compensation of weight)	300 g per slice

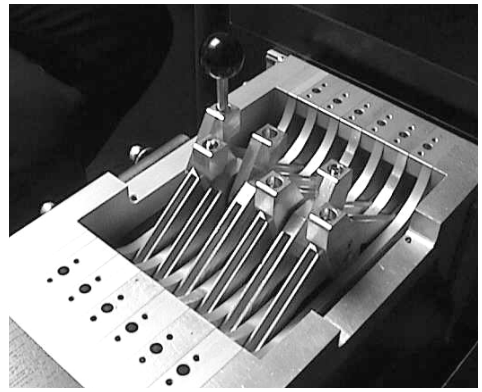

Figure 3. Picture of the ERGOS device equipped with a 1-dof mechanical interface

The haptic device works in impedance mode: forces applied to the manipulation point that are calculated inside the model are applied by the haptic device on the user, and the position of the manipulated point inside the model is mapped to the measured position of the haptic device.

One can note the relatively small range of movement available. Up to now, this has not been considered as a limiting factor for the experiment, since even in a real situation, we often perform tapping in a very limited range of movements (a few centimeters only). This is especially true for fast repetitive taps.

At last, the weight of the moving part is 300 g (weight of one slice), but it was compensated during the experiment by applying an opposite constant force equal to the weight of the slice; however, the subject still had to do with the remaining inertia of the device.

3.2. Simulation frequency

The simulation of the model was performed at 15 kHz to allow the generation of vibrations in the audio domain. However, due to technical limitation, exchange of data between the simulator and the haptic device is limited at 3 kHz. Therefore, the dynamics of the particle element related to the haptic device (mass A in Figure 2) had to be computed at 3 kHz.

3.3. Dynamic recording of the experiments

To allow post-analysis of the dynamics involved in the studied phenomenon, we recorded positions and forces applied to the particle elements constituting the model. All data were recorded at a sampling frequency of 3 kHz.

4. Method and experimental protocol

4.1. Participants

Nine men and three women participated in the experiment. They were from 22 to 32 years old (mean 26 yrs), all of them were right handed and free of neuromotor or auditory impairments. All were naïve to the details of the experiment and its hypothesis.

4.2. Apparatus

Subjects were seated in a darkened room to left side of the haptic device. The haptic device was manipulated with the right hand as when holding a pen, the right arm reposing on the table, leaving the wrist free of movement. During the experiment, participants wore headphones for sound feedback and for isolating them from external noise.

4.3. Method

The whole experiment was conducted in two successive phases: synchronous tapping along with a metronome, and fast tapping without time reference. Each half of the participants began alternatively with one of the two phases. The overall experiment was about 15 minutes maximum for a participant.

Once all the trials were passed, impressions of the participants were recorded during a short interview.

Six subjects participated to a pilot test before the presented experiment. These six subjects did not participate to the final experiment. As some of these subjects experienced fatigue during the pilot experiment, we reduced the length time of each trial to about 20 s to be sure that the fatigue factor would not impair the performance.

4.4. Task A. Fast tapping

In this experimental situation, subjects were asked to perform regular taps as fast as possible, but keeping the pulse as regular as possible. Three stiffness values {K_1, K_2, K_3} were used (Table 1). For each participant, a series of three trials was passed in random order under the two following conditions: (1) with sound from the tapped object; (2) without sound feedback. These conditions were combined with the three different stiffness values, thus providing six trials (Table 3 and Figure 4). They received sound from the tapped object binaurally; frequency of the produced sound was about 620 Hz.

Half of the subjects did the series in reverse random order. Each trial followed this procedure: the participant had first as much time as wanted to experiment the situation (generally a few tens of seconds were sufficient); then, when the participant was ready, it began the fast tapping sequence. About 5 s after the beginning of the fast tapping sequence, the experimenter stopped the trial. After each trial, participants had at least 30 s for rest.

Table 3. Synthesis of the six experimental conditions for the fast tapping task

Trial N°	Stiffness	Conditions
1	K_1	Haptics only
2	K_2	Haptics only
3	K_3	Haptics only
4	K_1	Haptics and sound
5	K_2	Haptics and sound
6	K_3	Haptics and sound

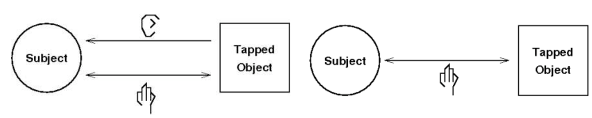

Figure 4 – The two experimental situations for the fast tapping task

4.5. Task B. Synchronous tapping

In this experimental situation, subjects were asked to perform repetitive taps synchronously along with the pulse imposed by a metronome. They received sound from the tapped object on the left headphone, and sound from the metronome on the right. Moreover, frequencies of the tapped object and of the metronome were chosen sufficiently different to avoid confusion: $f_{\text{metronome}} = 622$ Hz and $f_{\text{tapped object}} = 100$ Hz.

Two parameters were tested: the frequency of the imposed pulse (three possible values), and stiffness of the tapped object (three possible values), thus making nine trials to be tested under the two conditions (1) no sound from the tapped object, and (2) with sound from the tapped object and sound from the metronome (Table 4 and Figure 5). Half of the subjects did the

Table 4. Synthesis of the six experimental conditions for the synchronous tapping task

Trial N°	Stiffness	Metronome ppm
1	K_1	67
2	K_2	67
3	K_3	67
4	K_1	135
5	K_2	135
6	K_3	135
7	K_1	202
8	K_2	202
9	K_3	202

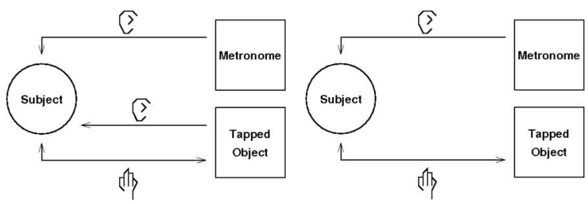

Figure 5 – The two experimental situations for the synchronous tapping task

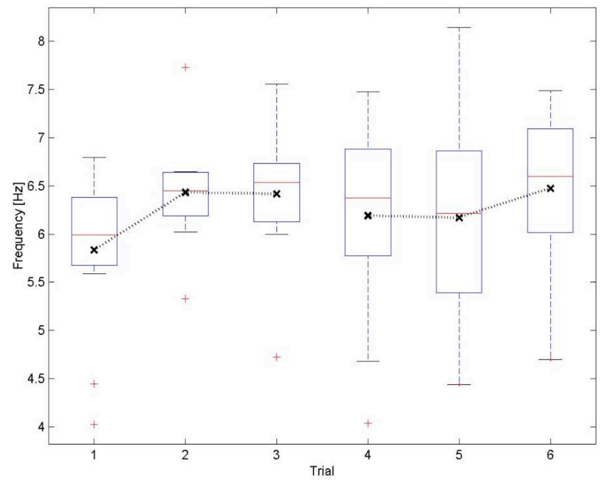

Figure 6. Box and whisker diagram for the fast tapping task, indicating frequency values obtained for each trial; column numbers correspond to the trials numbers; line inside the box represents median values, star-dotted line represent mean values. Cross points represent outliers.

series in reverse random order. Each trial was 20 s long, and between each trial, participants were given 5 to 10 s for rest.

5. Analysis of the results

5.1. Fast tapping task

We extracted the tapping frequency of each trial from the recorded data. The tapping frequency was obtained by detecting the maximum value in the spectrum power of the manipulated point movement (mass A in Figure 2), thus indicating the mean frequency of the tapping during one trial. Mean frequency values observed during fast tapping are around 6 Hz; considering the relatively important inertia of the moving part of the haptic device (300 g, weight compensated) for this kind of gesture, these frequencies are relatively high, and do correspond to the task asked to the subjects, which was to perform taps as rapidly and as regularly as possible.

Analysis of variance did not provide any significant result however: neither the effect from stiffness ($p < 0.25$), nor the addition of sound feedback from the tapping object ($p < 0.8$) seemed to bring significant modification into performance results. Two-way analysis of variance shows that there is no interaction effect between stiffness and the addition of sound feedback ($p < 0.5$).

Qualitative analysis of the results nevertheless shows that there is a soft increase of the tapping frequency with the increase of stiffness (Figure 6). However, mean frequencies obtained for trials 2 and 3, and for trials 4 and 5 are almost equal, and the large distribution obtained in our results induces us to take into account this factor only with precautions. Comparing the two experimental conditions, one can note an increased distribution of the results with sound feedback, compared to the haptics only condition. This indicates the possibility that the addition of sound in this phase had a disturbing effect on fast tapping.

5.2. Synchronous tapping

The instant of subject's tapping was determined by the instant of contact between the point manipulated by the subject and the mechanical stop $\{K_A, Z_A\}$; time difference between subject tapping time and metronome onset time were measured. This way of measuring asynchrony is usual for such studies on tapping. We call this measurement method *position-based*. The so-obtained results are represented in Figure 7.

Haptics only condition. Mean asynchrony values indicate that the increase of stiffness reduced subjects' asynchrony. Variance analysis of the mean values confirms this observation ($F = 2.316$, $p = 0.1145$ for 67 ppm, $F = 3.16$, $p = 0.0555$ for 135 ppm, $F = 12.74$, $p < 10^{-4}$ for 202 ppm), and further indicates that this

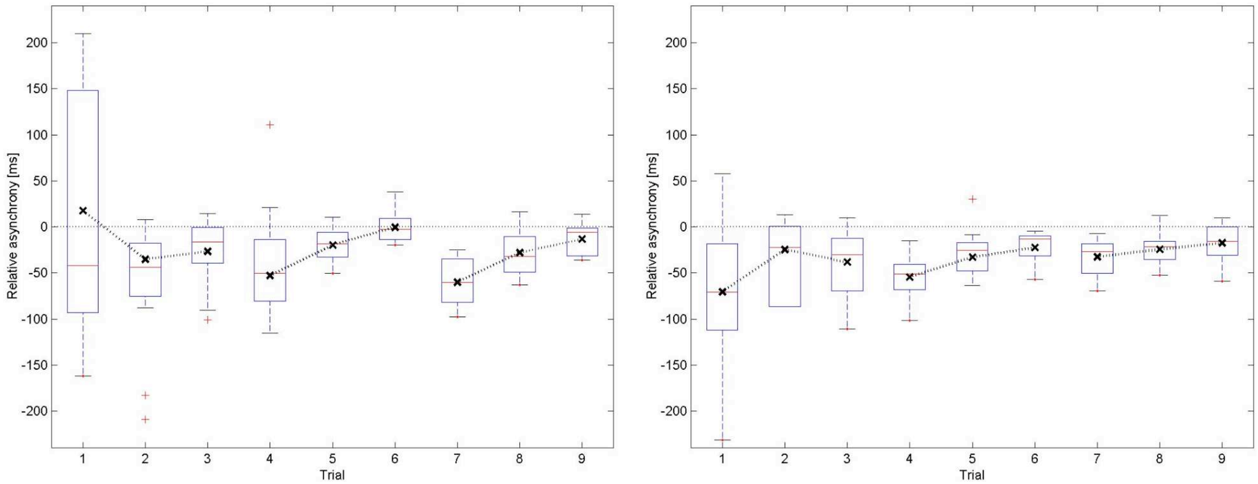

Figure 7. Synchronous tapping task; box and whisker diagrams representing the relative asynchrony in the haptics only condition (left), and in the sound and haptic condition (right). Star-dotted lines represent mean values (outliers not taken into account), and gather trials with the same metronome frequency value. Trial numbers are those detailed in Table 4.

differences in asynchrony become stronger as the pulse frequency increases.

Comparing the effects of metronome frequency on trials with the same stiffness value, variance analysis tends to show that metronome frequency factor had an effect on synchronization ($F = 2.509$, $p < 0.1$ for K_1; $F = 3.217$, $p < 0.06$ for K_2; $F = 3.316$, $p < 0.05$ for K_3). This was mainly due to cases with stiffness K_1 (i.e. trials numbers 1,4 & 7): further variance analysis, this time comparing two-by-two trials with stiffness K_2 and K_3 for the same frequency shows that metronome frequency has merely no effect when the object is stiff ($p = 0.2802$, $p = 0.3988$, $p = 0.0759$ respectively for the comparison of trials 4 & 7, 5 & 8, 6 & 9).

Results of the trial 1 were significantly poorer than the others; this seems to be mainly due to the absence of reference (spatial or temporal) for the moment where the percussion would be produced. During the interview after the experiment, most of the subjects complained for the lack of feedback for the lowest stiffness cases in absence of sound feedback, and thus reported that the task was really difficult in these cases. The very large distribution of the results on this trial confirms the fact that subjects had great difficulties to keep a synchronous tapping along with the metronome.

Sound and haptics condition. Here again the effects of stiffness are significant when the metronome frequency was 135 or 202 ppm ($p < 0.003$ and $p < 0.1$ respectively), but not when it was 67 ppm ($p > 0.5$). However, these results are not as much significant as for the haptics only condition. As for the haptic only condition, effect of the metronome frequency was not very significant too here ($p < 0.15$, $p < 0.20$, $p < 0.14$ respectively for 67, 135 and 202 ppm).

Effects of the addition of sound feedback from the tapped object were not very easy to analyze. Significant effects of sound feedback addition were only found for trial 1 ($p < 0.06$), trial 6 ($p < 0.005$) and trial 7 ($p < 0.008$); furthermore, sound feedback had a negative effect on trial 6, by increasing asynchrony. Variance analysis did not show significant results for the other trials ($p > 0.3$). The significant effect of the addition of sound feedback on trial 1 is relatively easy to explain: in the haptics only condition, subject expressed a lack of reference to fulfill the task, and we observed very poor results in this conditions; the addition of sound feedback has improved their sensory feedback from the task, and thus helped to improve the task performance. We could explain on the same manner the differences on trial 7 between the two experimental conditions, but unexpectedly this is not observed for trial 4 ($p > 0.4$). One can however note that the dispersion of the results was reduced with the addition of sound: standard deviation was 60 ms in the haptics only condition, against only 24 ms for the sound and haptic condition.

Speed at tapping time was extracted from our data recordings. Manipulation speeds at tapping time were calculated by discrete derivation ($v_n = x_n - x_{n-1}$) of the position of the manipulated point. Mean results and standard deviation comparing the two experimental conditions for each trial are depicted on Figure 8. One hypothesis was that the speed of the manipulated point (mass A) at tapping time would linearly vary with the

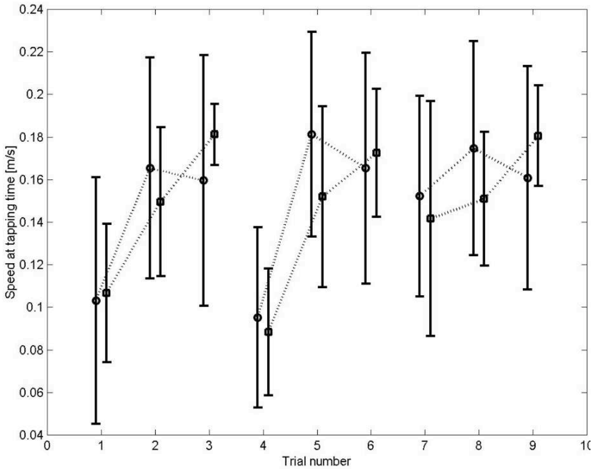

Figure 8. Mean and standard deviation for the speed of the manipulated point at tapping time. Circles represent the haptic only condition, squares the sound and haptic condition.

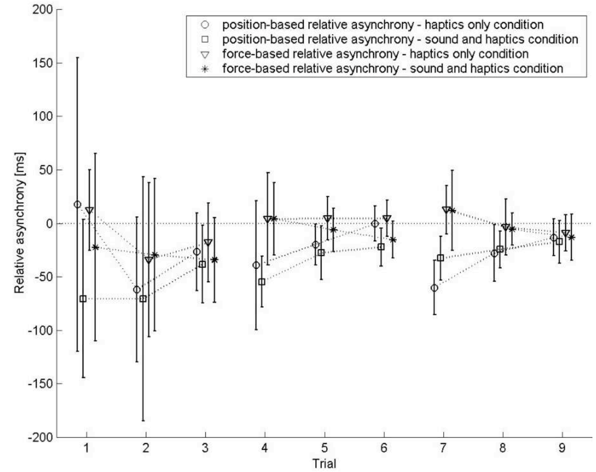

Figure 9. Comparison of the mean and standard deviation values of the relative asynchrony obtained with position-based or force-based methods.

frequency of the imposed pulse if the tapping movement resulted from a sustained oscillation movement. Observation of the results indicate that tapping speed depends on the stiffness of the tapped object ($p < 0.000$ in the two experimental conditions) but not on the tapping frequency imposed by the metronome in the haptics only condition ($p < 0.25$), whereas metronome frequency had an effect on tapping speed in the sound and haptic condition ($p < 0.05$). The difference between the two experimental conditions may be explained by the model design itself, because the mechanical stop responsible for the collision of the hammer element into the vibrating structure was positioned a little behind the mechanical stop responsible for the haptic interaction: it was necessary to penetrate slightly into the tapped object before colliding the vibrating structure. The energy required to penetrate sufficiently in the object depended on its stiffness and thus, the energy required to produced sound increased with the stiffness, hence the speed at tapping time. Conversely, no significant differences can be seen between stiffness K_2 & K_3 in the haptics only condition ($p < 0.35$). The differences between the two experimental conditions show that the absence of sound feedback from the tapped object modified the dynamics of the movement.

Force-based measurement of asynchrony. We have shown that position-based asynchrony depends on the stiffness of the tapped object, which means that asynchrony actually depends on the force dynamics of the visco-elastic interaction. We introduce here a *force-based* measurement of asynchrony, which we obtained by measuring the time delay between the metronome onset and the moment where the visco-elastic interaction force at the manipulation point reached its maximum.

Figure 9 compares the results obtained by position-based and force-based measurements of asynchrony, and shows that asynchrony values obtained by a force-based measurement method provide results closer to a null asynchrony compared to results obtained with a position-based measurement method, especially for trials 4 to 9. Figure 10 plots the delay between the collision time (that we used for position-based measurements) and the time force reaches its maximum. We observe that this delay strongly decreases as the stiffness increases, and that it is relatively important, as it exceeds 5 ms in all the cases. Therefore, one can explain the difference in the two asynchrony measurement methods on figure 9 by the

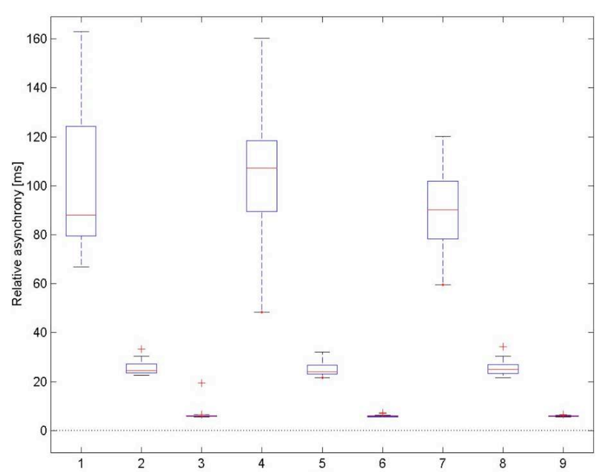

Figure 10. Box and whiskers diagram for the time delay between the collision time and the maximum interaction force time

existence of this time interval between the effective collision and the moment the force reaches its maximum.

6. General discussion

The main goal of this study was to determine if the physical parameters of the tapped object, such as stiffness, would play a role in tapping performance. First observation is that the tap onset preceded the stimulus onset in almost all conditions. These results are consistent with the negative asynchrony generally observed in other studies [6], [10]. Same orders of magnitude were observed here than in previous studies: negative asynchrony was usually measured between –10 and –80 ms, up to –200 ms in extreme cases (without considering outliers); this is consistent with the –35 to –45 ms observed in [11], and with –20 to –80 ms in [6] quoting previous studies. But we found out that the stiffness of the tapped object plays an important role in the timing of synchronization: the relative asynchrony decreased as the stiffness increased. Furthermore, it seems that stiffness has an effect on performance in very fast asynchronous tapping, by increasing the maximum frequency attainable.

Assuming the fact that a perceptible effect of the variation of stiffness is the variation of the interaction forces among the different trials, modifications of the force dynamics of the task have an effect on tapping performance. It was already discussed by Aschersleben [6] that the amplitude of the force applied to the key exerts a strong influence on the size of the negative asynchrony, and by Hommel et al. [12] quoting [13] [14], where effects of the force of the tap have been observed for the standard tapping task and for isometric force pulses. Furthermore, it was observed in our experiment that, when basing asynchrony measurements on force criteria, results are not so likely depending on stiffness as compared to results obtained with measurements based on position criteria. This could indicate that subjects synchronize their taps on the basis of force information, and it could be a possible explanation of the usual negative asynchrony observation, as the asynchrony measurements usually take position into account instead of force.

It is sometimes assumed that the more sensory feedback you can get from a task, at best you can achieve it. We however found that sound feedback could be a disturbance in fast tapping, by increasing the distribution of asynchrony results. In the synchronous tapping task, we found that sound feedback had only a benefit effect on performance in the very low stiffness case; that is, sound feedback had a benefit effect when no sufficient cues could be found in the gesture sensory feedback to correctly achieve the task. Furthermore, the very low stiffness but sound feedback case was judged easy by the subjects whereas the situation with very low stiffness and no sound feedback was judged very difficult. When stiffness was sufficient, sound didn't improve performance, and even deteriorated asynchrony in one condition (trial n°6). These results go along with previous works of Dahl et al. [7] where synchronous tapping couldn't be performed if auditory feedback exceeded 50 ms. Mates and Aschersleben [10] have shown that the increase of auditory feedback delay increased asynchrony, but that negative displacements of sound feedback (i.e. putting sound feedback before the tapping event) had no effect on performance. Mates and Aschersleben explained this by the fact that in our everyday life, sound feedback always follows our action, and never precedes it; if sound feedback should precede the action, the sensory-motor system would not interpret it as feedback providing from the tap and thus would ignore it.

The observation of speed at tapping time has shown too that the addition of sound feedback modified the motor dynamics of the task: when sound feedback could be obtained from the tapped object, tapping speed varied linearly with the stiffness of the tapped object due to a particular artifact of the simulated model; conversely, this effect was not noticed in the haptics only condition, showing that the addition of sound feedback on the task leaded to a modification of the task dynamics.

In addition to the results found on the effects of stiffness, these observations lead us to assume that sound has to be considered as an entry of the sensory-motor system when performing tapping, but that sound information may not be taken into account when other cues are sufficient to perform the task. Moreover, haptic sensory information seems to be prevailing sound information in a tapping task.

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8. References

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