Audio-motor Synchronization: the Effect of Mapping Between Kinematics and Acoustic Cues on Geometric Motor Features

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Abstract. This paper presents an experiment dealing with the sensorimotor relation between auditory perception and graphical movements. Subjects were asked to synchronize their gestures with synthetic friction sounds. Some geometrical and dynamical parameters of the motor productions are analyzed according to the different mappings. This experiment provides a formal framework for a wider study which aims to evaluate the relation between audition, vision and gestures.

Keywords: Auditory perception, sensorimotor loop, friction sounds, gestures

1 Introduction

When we are interacting with the material world, we often think that only the visual modality is engaged to guide our actions, like for instance when we are walking, reaching a glass or drawing on a paper. The use of other modalities, like the proprioceptive system or the audition is more subtle and not as well conscious as vision which seems to occupy most of our attention. Nevertheless, several studies have shown our ability to recognize a geometric shape only by touching it [18], or to recognize events only from the sounds they produce [10, 11]. For instance, we are able to recognize and re-enact characteristic walking patterns from listening to the produced footsteps [28]. Other studies have focused on the sounds produced by continuous interactions and showed that we can discriminate rubbing, scratching and rolling sounds from the sounds they produced [6, 7]. Another study focused on the sounds produced by interactions such as squeaking, squeaking or squealing and highlighted specific patterns responsible of their auditory recognition [20]. From rubbing sounds, we are also able to identify biological movements in the case of graphical gestures from sound. More precisely, these studies revealed that we are able to identify a gesture, and to a certain extent the shape, drawn by a human only from the friction sound generated by the pen mine rubbing the paper [19, 21].

The interaction between vision or proprioception and movements has already been studied. In different seminal studies, Viviani and colleagues have largely investigated such relations. For vision, they showed that we are more accurate when we follow a spotlight target which respects the dynamics of biological movements, also called the 1/3 power law. This law links the velocity of a movement to the curvature of its trajectory [24, 14, 25]. The blindfolded manual reproduction of a kinesthetic stimulus has also been studied in another experiment [27] that likewise revealed that subjects based the reproduction of the kinesthetic stimulus on the velocity of the target.

From the auditory point of view, the manual production associated to the timbre variations of an acoustical stimulus has not been studied in the same way. Some studies investigated the relation between a sound and a gesture in specific situations. In particular, the case of musical gesture has been widely studied [16, 15, 12]. Such relations were for instance investigated in an experiment where subjects were asked to imitate a musical excerpt in three dimensions with their hands [5]. This study revealed that the subjects synchronized gesture parameters – mainly the velocity and the acceleration – on specific sound descriptors, mainly the pitch and the loudness. In another study, Caramiaux et al. [4] asked subjects to imitate environmental sounds with their hands, in order to distinguish different behaviors according to the *causality* of the imitated sound event.

In this article, a work in progress about the direct relationship between the auditory system and the graphical motor competency is presented. Our aim is to investigate how audition can guide a graphical gesture in a synchronization task. Moreover, we aimed at investigating the relation between sound and graphical movements with calibrated auditory stimuli which clearly evoked motions. In the case of vision, it is easy to create a calibrated stimulus which evokes a movement and to control its velocity using for instance a moving spot light. In the case of auditory stimuli, the problem is less simple. As mentioned before, the friction sound produced by a mine pen rubbing a paper clearly evokes a movement and has already been used to investigate the gesture evoked by such friction sounds [19]. Here, we used the same kind of sound to create calibrated auditory stimuli as acoustical targets evoking a specific movement. Rather than using recorded frictions sounds of someone drawing, we will use synthesized ones. Synthesis indeed enables to precisely control the friction sound produced by an object rubbing a surface by isolating one aspect, for instance the kinematic, linked to the movements that produced the sound.

This paper therefore presents an experiment where subjects were asked to synchronize their gestures on different synthesized friction sounds. They were asked to draw ellipses or circles according to the sound, and to translate the evocations of the sounds in their graphical productions. In particular, we investigated the influence of different mapping strategies between the gesture velocity and the sound parameters on the motor production task. The paper is organized in two parts, the synthesis process is firstly presented, in a second time the experiment and the results are presented and discussed.

2 Synthesis of Friction Sounds

In this study, timbre variations of friction sounds will be used as the acoustical target evoking movements. Such sounds naturally evoke movements according to their timbre variations without any spatialization processes. To synthesize such variations, we used a phenomenological model that has been proposed by Gaver [10] and improved by Van den Doel et al. [23]. This model supposed that the sound produced by the friction between a plectrum and a rough surface results from a series of impacts on a resonator. The quicker the plectrum rubs the surface, the higher the number of impacts, and therefore the higher the pitch of the sound. From a signal point of view, the surface can be modeled by a noise[3]. And finally, the friction sound produced by the motion of the plectrum on the surface can be synthesized by low pass filtering the noise with a cutoff frequency proportional to the velocity of the plectrum (see [7] for a recent implementation). The modeling of the resonator is done by filtering the low pass filtered noise with a resonant filter bank tuned to the modal characteristics of the rubbed object [1, 2].

Mapping Strategy. The synthesis process necessitates the determination of a mapping between gesture (velocity) and sound (cutoff frequency of the lowpass filter) parameters. The cutoff frequency of the low pass filter is linked to the velocity of the plectrum by a proportionality coefficient α: $f_c(t) = \alpha v_T(t)$. This

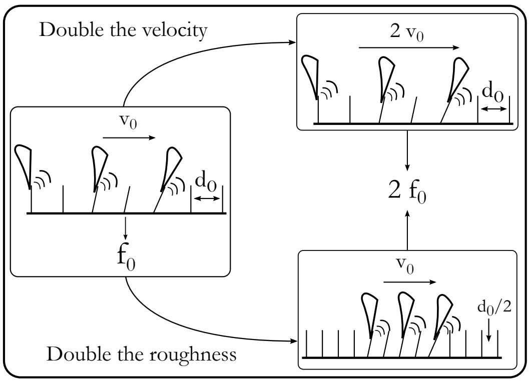

Fig. 1. A simple example of the phenomenological model of friction sounds. The three cases presented illustrate the ambiguity between velocity and roughness in the produced friction sound.

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[3] The more classical model of roughness for a surface is the fractal one, whose spectrum is defined by $S(\omega) = \frac{1}{\omega^\beta}$. When β is null, the noise is white, when β equals 1 the noise is pink. The higher the β the smoother the modeled surface is [23].

coefficient is linked to the surface roughness, and the proposed mapping encompasses two physical effects: the roughness of the surface and the relative velocity of the pen that interacts with the paper. The relationship between these parameters can be illustrated by the following example. We consider a simple surface, with regularly spaced asperities separated from a distance d_0, as presented in figure 1. If the surface is rubbed at a velocity v_0, the pitch of the produced sound will be proportional to v_0 and inversely proportional to d_0. If the surface is now rubbed at a velocity that by two times greater, the pitch of the friction sound produced will be also doubled. In the same way, if the distance d_0 is divided by two, the pitch will be doubled. Finally, when we listen to such a friction sound, there is an ambiguity about the conveyed information. When increasing α, do we imagine that the surface become rougher, or do we imagine that the rubbing is twice as faster?

3 Experiment

The goal of the experiment was to evaluate the characteristics of the evocation induced by a friction sound using a synchronization task between a graphical gesture and a friction sound in visual open loop (i.e. the subjects were blindfolded during the task). It was effectuated in different acoustical conditions corresponding to different mappings between the velocity and the cutoff frequency to evaluate their influence on the produced graphical movements.

3.1 Methods

Subjects and Apparatus. 12 participants took part in the experiment: two women and nine men. The average age was 24.17 years (SD=2.55). All the participants were right handed. None of the subjects were familiar with the topic of the study before the test. The subjects were blindfolded in front of a desk. The sounds were played through Sennheiser HD-650 headphones. The graphical gestures were collected through a Wacom Intuos 5 graphic tablet at a time rate of 133 Hz and with a spatial precision of 5.10^{-3} mm.

Geometric Shapes. Two geometric shapes were used. An ellipse of eccentricity 0.9 and semi-major axis of 9.05 cm, and a circle with a radius of 6.36 cm (i.e. an ellipse with null eccentricity and a semi major axis of 3.18 cm). The perimeters equal to 43.86 cm for the ellipse and 40 cm for the circle.

Velocity Profiles. The dynamic along the shapes were defined according to the Lissajous motion:

$$\begin{cases} x(t) = a\cos\left(\frac{2\pi}{T}t\right) \\ y(t) = b\sin\left(\frac{2\pi}{T}t\right) \end{cases} \quad (1)$$

where a and b are respectively the semi-major and semi-minor axis of the ellipse (equal in the case of a circle). The chosen period T was 1.8 seconds, and 19 periods were generated. Thus, the durations of the stimuli were equal to 34.2 seconds. Such a configuration of an ellipse (a fortiori a circle) implies that the motion follows the 1/3 power law (i.e. a biological motion). In the case of the ellipse selected for the experiment, the tangential velocity varies between 13.88 cm.s^{-1} and 31.66 cm.s^{-1}. In the case of the circle, the tangential velocity is constant over the entire trajectory and equals 22.7 cm.s^{-1}.

Acoustical Stimuli. Synthesized friction sounds were generated with the phenomenological model previously presented, and from the velocity profiles defined in the previous paragraph. The role of the mapping coefficient α is here evaluated, we arbitrarily chose 6 different values: 5, 10, 20, 50, 100 and 300 Hz.s.m^{-1}. These values provide friction sounds with very different timbres and influences mainly brightness of the friction sound. The higher the α the brighter the sound. The table 1 presents the minimal and maximal values of the cutoff frequency induced by these different values of α. Finally, 12 stimuli were generated: 2 (shapes) x 6 (mappings).

Table 1. Minimal and maximal values of the low pass filter cutoff frequency in Hertz. In the case of the circle, the cutoff frequency is constant for all the stimuli as the velocity is constant.

	Ellipse		**Circle**
α	f$_{min}$	f$_{max}$	f
5	69	159	111
10	138	318	223
20	276	635	445
50	690	1588	1135
100	1380	3176	2227
300	4140	9528	6681

Task and Procedure. The task consisted in drawing a shape – a circle or an ellipse – while being guided by the friction sound played through the headphones. The subjects were asked to synchronize their movement on the sound variations in the counterclockwise direction during the 34.2 seconds of the friction sound. To investigate the direct relationship between the auditory modality and the evoked gesture, subjects were blindfolded throughout the duration of the experiment (also called in open loop) and encouraged to translate the evocation of the timbre variations in their production. It was explicitly asked to lift the elbow to make sure that the joint used during the movement involved both the shoulder and the elbow, and not the handle as during a handwriting task. The test was preceded by a training phase during which subjects would train on an example of such a circle and an ellipse. It was explicitly stated to the subjects that these two shapes were present. Subjects could also adjust the height of the seat before the beginning of the experiment. Finally, each subject performed 36 trials: 2 (shapes) x 6 (mappings) x 3 (repetitions), which were randomized for all the subjects. The subjects were not aware about the size nor the orientation of the shapes. An experiment lasted about 45 minutes and the subjects were encouraged to make a break when they felt the need.

Data Analysis. Recorded data correspond to the coordinates of the stylus position on the tablet over time. Data analysis focuses on the geometric and kinematic characteristics of the motor performance. A data preprocessing is performed prior to the study of these two characteristics in order to overcome from the digital artifacts that appears when calculating the first and second derivatives of the data. The methods for calculating the different descriptors have been established in various articles of Viviani and colleagues [26, 27, 17].

Pre-processing. A smoothing of the data is performed by using Savitzky-Golay filters. Moreover, since subjects were blindfolded during the task, their graphic productions are not spatially accurate during the entire movement, and a low frequency deviation appears. In order to avoid the deflection of the center of gravity over time, a high-pass filtering is performed at 0.5 Hz on the recorded coordinates.

The recordings lasted 34.2 seconds for each trial. Since it took some time for the subjects to produce a regular and synchronous movement with the sound (in the case of ellipses), the first six periods were excluded from the analysis, which corresponds to the first 10.8 seconds. Finally, the following 12 periods were selected, which corresponds to 21.6 seconds.

Geometric and Kinematic Characteristics:

- *The eccentricity.* Eccentricity of an ellipse is defined with the following formula: $e = \sqrt{\frac{a^2-b^2}{a^2}}$, where a and b are respectively the semi major and minor axis of the ellipse. To determine the average eccentricity of the drawn shape, we used a method proposed by Viviani [26]. We considered each recording as a group of pointlike unitary masses and we computed the inertial tensor. It is well known in classical mechanics that the inertial tensor of a two-dimensional structure can be modeled by an ellipse whose characteristics are linked to the eigenvalues of the inertial tensor. The precise method will not be described here, but we refer to the Viviani studies and to the Goldstein book for more details [13].

- *The tilt.* Tilt of an ellipse corresponds to its inclination relative to a horizontal axis. It is well known that when we draw an ellipse, the preferred coordination pattern corresponds to a an ellipse inclined of 45 degrees [9]. It can easily be calculated by using a similar method than for the eccentricity in diagonalizing the inertial tensor, the tilt corresponds to the angle between the eigenvectors with the horizontal axis.

- *The perimeter.* This is calculated from the recorded trace on the twelve analyzed periods.
- *The mean velocity.* This is computed from the 10 recorded cycles of movement.

3.2 Results

All the results are summarized in the table 2. For each descriptor and each geometrical shape, a repeated measures ANOVA is performed to evaluate whether the mapping has affected the geometric and kinematic characteristics of the performances. Each significant effect is widely analysed with a Newman-Keuls post-hoc test to highlight interactions between the different mapping conditions.

Table 2. Marginals means and standard errors for the three geometrical descriptors.

	α	$\bar{e}$	*Perimeter* (cm)	*Tilt* (degrees)	$\bar{v}$ (cm/s)
	5	.72 ±.044	7.4±1.11	55.4 ±7.23	4.26 ±0.991
	10	.63 ±.030	7.0±.92	47.9 ±5.78	4.06 ±0.817
Circle	**20**	.63 ±.047	7.4±1.03	50.7 ±8.46	4.36 ±1.013
	50	.63 ±.042	6.9±1.03	38.7 ±6.69	4.34 ±1.178
	100	.59 ±.029	7.6±1.10	47.6 ±6.28	4.5 ±1.067
	300	.55 ±.032	5.3±1.23	48.9 ±7.08	3.42 ±1.324
	5	.93 ±.016	15.7±1.82	37.9 ±6.20	8.74 ±1.981
	10	.93 ±.011	15.8±1.37	32.9 ±5.20	8.63 ±1.487
Ellipse	**20**	.94 ±.009	15.9±1.57	39.4 ±6.27	8.84 ±1.693
	50	.94 ±.013	16.1±1.62	32.7 ±7.28	9.00 ±1.773
	100	.95 ±.010	15.9±1.45	24.9 ±5.17	8.87 ±1.592
	300	.94 ±.013	16.4±1.89	35.2 ±7.77	9.19 ±2.102

- *Eccentricity.* The eccentricity was significantly affected by the mapping for circles but not for the ellipses, $F(5,55) = 5.907, p < .001$ and $F(5,55) = 2.295, p = .0576$ respectively. In the case of circles, post-hoc tests revealed that the mapping $\alpha = 5$ provided significantly flatter circles than the five others conditions ($p < .05$ for all comparisons). Moreover, $\alpha = 20$ provided significantly flatter circles than $\alpha = 300$, see figure 2.

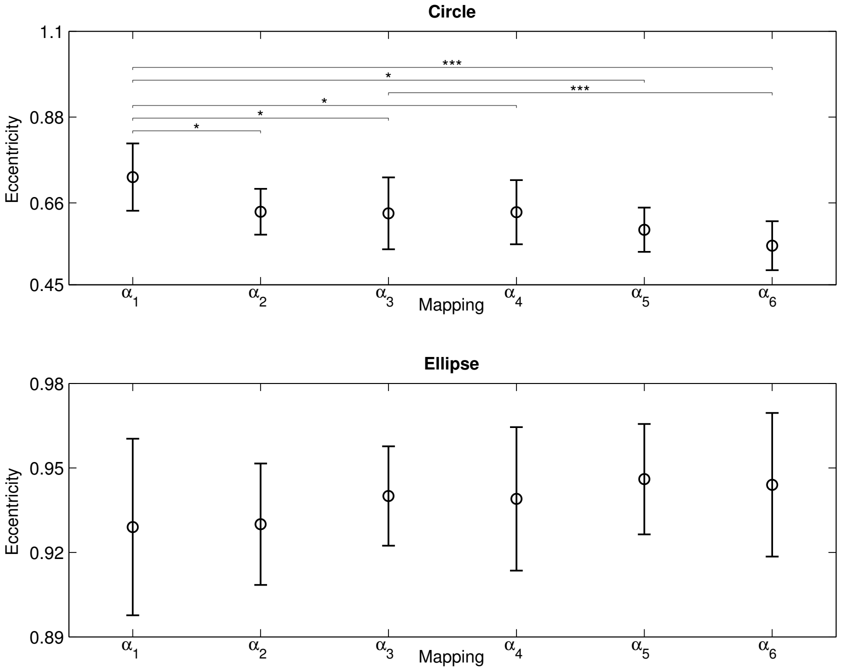

Fig. 2. Eccentricities: Marginal means and 95% confidence intervals

- *Tilt.* The orientation wasn't significantly modified both for circles and ellipses, $F(5,55) = .854, p = .52$ and $F(5,55) = 1.695, p = .151$ respectively, see figure 3. It is noticeable that the orientation of the shape was higher for circles than for ellipses.

- *Perimeter.* As for the tilt, no significant effect of the mapping was observed both for the circles and the ellipses, $F(5,55) = 1.642, p = .16$ and $F(5,55) = .569, p = .72$, see figure 4. These results reveal that whatever the mapping, the size of the drawn shape wasn't affected, it's really interesting because it supports the hypothesis that in this task of synchronization, the mapping is not perceived as a change of velocity but as a change of the surface roughness, higher the mapping, higher perceived roughness is.

- *Mean Velocity.* No significant effect of the mapping was observed both for the circles and the ellipses, $F(5,55) = 1.604, p = .17$ and $F(5,55) = .581, p = .71$, see figure 5. These results confirm the previous ones, for each shape, a change in the mapping is not perceived as a change in the velocity but as a change of roughness.

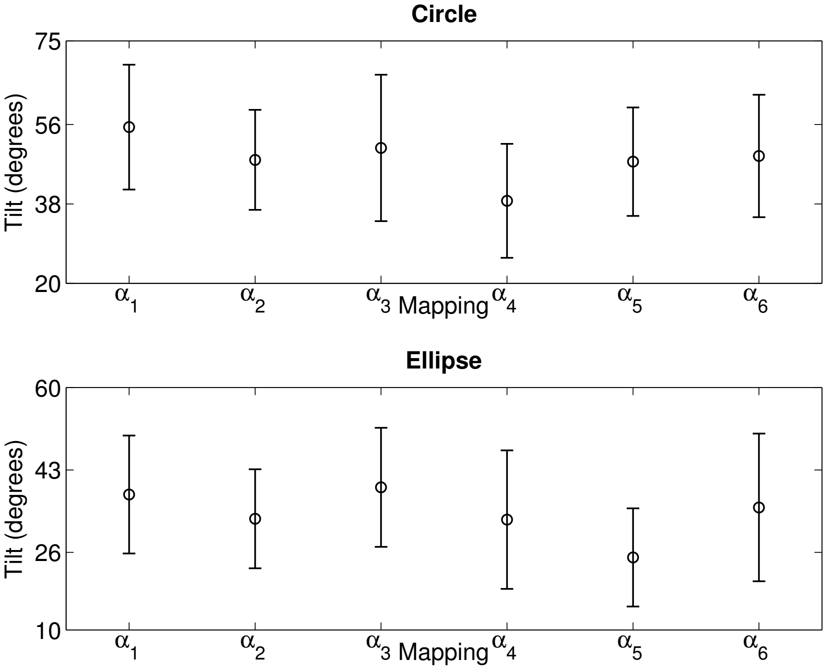

Fig. 3. Tilts (in degrees): Marginal means and 95% confidence intervals

3.3 Discussion

The goal of the experiment was to evaluate the influence of the mapping on the evoked movement and more precisely, to evaluate the extent to which the manipulation of the mapping coefficient α – informing either on the roughness of the rubbed surface or on the velocity of the evoked movement – modifies the movement produced by synchronization. The investigated descriptors, tilt, perimeter, and mean velocity, did not differ between mappings for both shapes, meaning that the subjects were guided by the temporal variations of timbre rather than the intrinsic sound texture to synchronize their gestures with the sounds. In particular, results showed that the mapping effect was perceived as a modification of a surface roughness rather of gesture velocity. Nevertheless, in the case of drawn circles, for which friction sounds contained no timbre variations and had a uniform sound texture, the eccentricity was significantly lower for high values of the mapping. This observation is interesting regarding the fact that mean velocities have not been affected, this indeed revealed that when the sound evoke any velocity variations, the changes in the geometry are not linked to the relation between velocity and curvature. This should be investigated further to better explain this, a possible hypothesis is that as the velocities are very low (about 4 cm/s for each mapping) it is more difficult to produce a regular

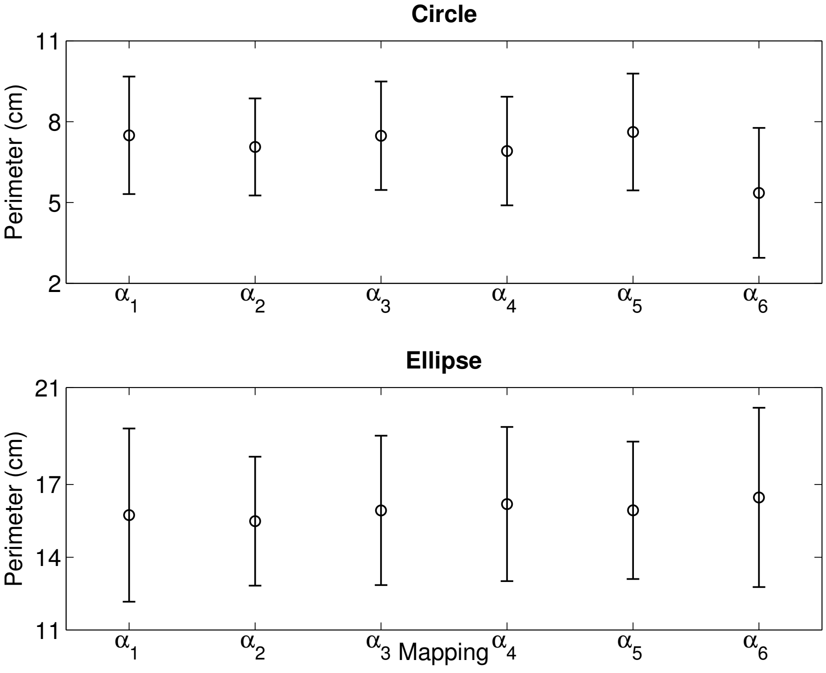

Fig. 4. Perimeters (in cm): Marginal means and 95% confidence intervals

movement than when the velocity is higher. This could be investigated by asking subjects to draw circles more or less slowly without sounds to evaluate whether it should modify the geometrical regularity. Finally, these results revealed that in a synchronization task, the temporal variations of timbre contained in the ellipses dominated over the absolute information given by the sound texture. Another interesting point to highlight is the average eccentricity value of .93 observed for the drawn ellipses. This result confirms classical results about preferred coordination patterns observed in different studies that have highlighted that ellipses of .91 eccentricities were the easiest to draw [3, 8]. It shows that the mapping and the synchronization task do not influence such motor attractors.

4 Conclusion and Perspectives

This experiment enables to conclude that the mapping – expressed by the proportionality coefficient α – between the sound parameter and the velocity of a rubbing plectrum modifies the produced synchronized movements only if there are no slower timbre variations as in the case of the ellipses. It enables to conclude that, from a perceptual point of view, the α coefficient is more related to the roughness of the rubbed surface than to the velocity of the gesture. Further

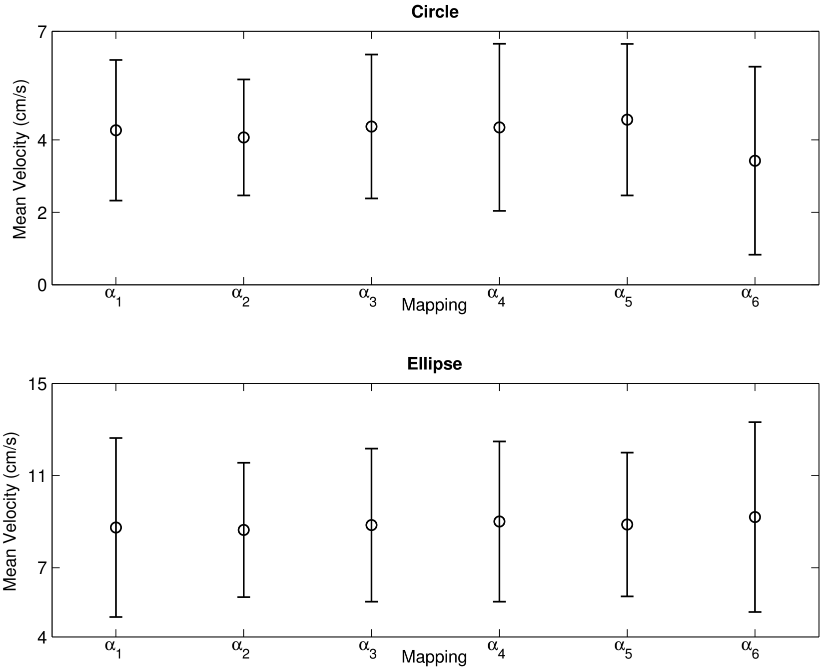

Fig. 5. Mean Velocities (cm/s): Marginal means and 95% confidence intervals

analysis should be conducted to completely assess the results presented here. In addition, the analysis of asynchrony between the gestures and the acoustical sound parameters might reveal whether there are mappings that provided better synchronizations. An analysis by subject should also enable to evaluate whether intrinsic personal strategies have been used.

This preliminary study tackles the problem of the sensorimotor relation between an auditory input and a produced movement which has never been done before in such a formal approach. The obtained results will also help us to choose the adequate mapping strategy for friction sound synthesis model in further experiments. Such a framework should enable to evaluate the influence of the sound on the produced gesture in a multimodal context. Potential multisensory conflicts are currently being evaluated in different experimental conditions [22].

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