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1 Hearing elliptic movements reveals the imprint of

2 action on prototypical geometries

- 3
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15 Abstract

16 Within certain categories of geometric shapes, prototypical exemplars that best characterize the 17 category have been evidenced. These geometric prototypes are classically identified through 18 the visual and haptic perception or motor production and are usually characterized by their 19 spatial dimension. However, whether prototypes can be recalled through the auditory channel 20 has not been formally investigated. Here we address this question by using auditory cues issued 21 from timbre-modulated friction sounds evoking human drawing elliptic movements. Since non-22 spatial auditory cues were previously found useful for discriminating distinct geometric shapes 23 such as circles or ellipses, it is hypothesized that sound dynamics alone can evoke shapes such 24 as an exemplary ellipse. Four experiments were conducted and altogether revealed that a 25 common elliptic prototype emerges from auditory, visual, and motor modalities. This finding 26 supports the hypothesis of a common coding of geometric shapes according to biological rules 27 with a prominent role of sensory-motor contingencies in the emergence of such prototypical 28 geometry.

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29 Introduction

30 Our perceptual system stores and categorizes objects from our surroundings around 31 canonical items, called prototypes, that are the most representative of their category. Geometric 32 prototypes have been viewed as mainly emerging from visual experiences (Rosch, 1973; Rosch 33 & Mervis, 1975; Feldman, 2000; Kalénine et al. 2011; Theurel et al. 2012), via the haptic sensory channel (Theurel et al., 2012; Kalénine et al. 2011) and via a motor restitution 34 (Feldman, 2000; Kalénine et al., 2013). Alternatively, the possibility to recall prototypes 35 through visual and haptic modalities or motor output may suggest common processing of these 36 37 specific shapes. Whether such prototypes only rely on spatial cues that are present in the visual. 38 haptic, and kinetic domains is still questioned. Could such geometric prototypes also be recalled 39 through auditory stimuli that are solely based on dynamic cues? Answering this question is fundamental to understanding the influence of the motor system on human learning, memory, 40 41 and cognition. It is essential both for the language sciences (Sablé-Mever et al., 2021) and for

42 cognitive neuroscience as this is a cornerstone question in these fields (Dehaene et al., 2006).

43 Interestingly, studies revealed the proficient role of the auditory modality to perceive 44 movements and shapes through timbre variations of monophonic sounds (Merer et al. 2008; 45 2013). More strikingly, Thoret et al. (2014) demonstrated that auditors listening to synthesized monophonic friction sounds corresponding to those produced by the pencil of someone drawing 46 47 on a paper, were able to recognize specific kinematics characterizing biological motion, in particular the 1/3 power law linking the tangential velocity of the hand movement to the 48 49 curvature of the drawn shape (Lacquaniti et al., 1983). In addition, they were even able to discriminate geometric shapes, such as a circle, an ellipse, and a line, simply by listening to 50 51 synthetic friction sounds in which timbre variations revealed the velocity profile of the drawing 52 movement. In follow-up studies, we demonstrated that these acoustic variations may even 53 distort the visuomotor coupling of biological motions (Thoret et al, 2016a, 2016b). Taken

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54 together, these studies suggest that simple geometric shapes can be evoked through the auditory 55 channel and that the auditory modality may play a significant role in the perception and 56 production of geometric shapes.

57 Here we investigated the hypothesis that geometrical prototypes can be recalled through 58 the auditory modality employing timbre variations of friction sounds evoking the velocity of 59 biological movements. We focused on a particular shape category, ellipses, that encompass any 60 closed shape of a conic section contained between a line and a circle. From a geometric point 61 of view, an ellipse is principally described by its eccentricity representing its flatness. The 62 eccentricity is a number comprised between 0 and 1: the flatter the ellipse, the higher the 63 eccentricity. The line and the circle are two specific cases which eccentricities equal 1 and 0 respectively. From a dynamic point of view and concerning the 1/3 power law, the accelerations 64 65 of an elliptic movement increase as the distance between the focal points of the ellipse increases (i.e., when the ellipse tends towards a line). Ellipses can be distinguished by ear from circles 66 67 and lines and do not involve discontinuity movements. Hence, this geometric shape has been 68 chosen for the present study.

Based on the dynamic model of biological motion described below, four experiments were designed to examine how participants assessed the prototypical ellipse through different modalities. The first three experiments aimed at highlighting the geometric prototype from visual and motor restitutions. The fourth experiment was the cornerstone of this series of experiments and focused on sounds' ability to evoke an elliptic prototype based on the kinematics underlying the drawn ellipse. Consistency between this auditory prototypical ellipse and the visual and motor prototypes would support a common encoding of prototypical shapes.

Before presenting the four experiments, the dynamic model of elliptic motions used in
the four experiments will be described in the following section. The results of these experiments
are presented together.

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79 A model of biological elliptic motor dynamics

Biomechanical mechanisms involved in graphical production as handwriting have been extensively investigated. It has been shown that dynamic and geometric properties of elliptic motions can be modeled by explicit equations. The dynamic approach of movement production supports the idea that planar hand movements can be modeled by two harmonic oscillators (x(t), y(t)) whose frequencies, amplitudes and phases evolve over time (Hollerbach, 1981) with the following system:

86
$$\begin{cases} x(t) = A_x(t)\cos(\omega_x(t) + \phi_x(t)) \\ y(t) = A_y(t)\cos(\omega_y(t) + \phi_y(t)) \end{cases}$$

where A_x and A_y are the amplitudes, and ω_x and ω_y the frequencies, and ϕ_x and ϕ_y the phases of the two oscillators. In the case of periodic elliptic motions, this model can be simplified by equaling the amplitudes and frequencies of the oscillators (A(t) = $A_x = A_y = A$ and $\omega(t) = \omega_x =$ $\omega_y = \omega$):

91
$$\begin{cases} x(t) = A\cos(\omega t) \\ y(t) = A\cos(\omega t + RP) \end{cases}$$
(1)

92 where A is the amplitude, $\omega = \frac{2\pi}{T}$ the frequency with T the period of the motion, and RP = ϕ_x

93 - ϕ_y the relative phase between the oscillators x(t) and y(t).

Hence, this system co-defines the motion dynamics and the geometry, but may also be used to parameterize only the geometry of the entire ellipse whether or not the ellipse is considered dynamically. Practically, the eccentricity *e* of the ellipse and the relative phase RP are linked by the following relations demonstrated in Appendix A:

98
$$\begin{cases} RP = 2 \arctan \sqrt{1 - e^2} \\ e = \sqrt{1 - \tan^2\left(\frac{RP}{2}\right)} \end{cases} (2) \end{cases}$$

99 It should be noted that this model complies with the biological rules, namely the 1/3 power law

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100 (Lacquaniti et al., 1983), as demonstrated in Appendix A.

This model then enables the generation of biological elliptic motions whose trajectory can be continuously morphed from a line ($RP = 0^\circ$) to a circle ($RP = 90^\circ$) by simply acting on RP (see Figure 1). It will be used in the four following experiments in order to generate visual and auditory stimuli complying with biological motion. Motor productions of Experiment 2 will also be analyzed regarding this model.

Finally, the tangential velocity profile was generated according to the equations (1) andcan be explicitly written as follows:

108
$$v(t) = A \frac{2\pi}{T} \sqrt{\sin^2\left(\frac{2\pi}{T}t\right) + \sin^2\left(\frac{2\pi}{T}t + RP\right)}$$
(3)

109 Although the mapping was arbitrarily fixed during the experiment, it is noticeable that it also110 varied according to the period T and the amplitude A of the motion.

111



112

Figure 1. Continuum of different ellipse shapes from a line (left) to a circle (right) with thecorresponding relative phases RP and eccentricities e.

115

116 **Experiment 1 – Static Visual Output**

117 The first experiment aimed to evaluate the prototype of the ellipse from visual restitution (i.e., 118 visual output). To that aim, an adjustment protocol was established. Participants were asked to 119 adjust the eccentricity of static ellipses on a screen to evoke the most representative shape of 120 this geometric category.

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121 Methods

122 Participants. Twenty right-handed participants (8 women) with an average age of 30.6
123 years (SD = 12.8) voluntarily took part in the experiment. All the participants were naive to the
124 purpose of the experiment. As in all the following experiments, participants gave their informed
125 consent before the study, and the experiment was approved by the Aix-Marseille University
126 ethical committee.

127 *Stimuli*. The visual stimuli were white static ellipses displayed on a black background 128 with different sizes and eccentricities according to the dynamic model previously introduced 129 (equations (1)). Three sizes defined by the amplitudes $A_1 = 3$ cm, $A_2 = 5$ cm, $A_3 = 10$ cm were 130 chosen. The ellipses were rotated counterclockwise by 45° to conform to the preferential 131 drawing inclination of an ellipse for right-handed persons (Danna et al., 2011).

Apparatus. The participants sat in front a computer screen (DELL 1907fp) with a resolution of 1280 x 1024 pixels and a frame rate of 60 Hz. The ellipses were displayed at the center of the screen and the interface was programmed with Max/MSP software (<u>http://cycling74.com/</u>). Participants modified the ellipse eccentricities by using a MIDI AKAY MPK keyboard. The experiment took place in a lighted room.

137 *Task.* The participants were asked to adjust the eccentricity of the static ellipse displayed 138 on the screen so as to set the most representative geometric shape of this category. The notion 139 of the most representative ellipse was explained in French to the participants by the following 140 sentences (here translated in English): *Ellipses correspond to any closed shape between a line* 141 and a circle. When you imagine an ellipse, you may have one particular elliptic shape in mind. 142 You will adjust the ellipse on the screen to display the ellipse you think is the most prototypical. 143 The adjustment protocol was based on the one proposed by Carlyon et al. (2010). The ellipse 144 eccentricity was adjusted thanks to 6 different keys defined on the keyboard: "<<<" - "<<" -"<" and ">" – ">>" – ">>>". Depending on the selected key, the ellipse eccentricity was 145

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146 modified with different step sizes. The higher the number of arrows the greater the step size, 147 *i.e.* the modification of the eccentricity. To avoid a possible non-sensorial bias due to the 148 orientation of the arrows (right or left), the action of the keys on the eccentricity differed across 149 participants. Hence, for half of the participants, arrows that pointed to the right increased the 150 eccentricity and for the other half they had the opposite effect. In addition, the step sizes were 151 not the same in both directions. Hence, for a given participant, all the arrows in one direction 152 (right or left) increased for instance the eccentricity by steps of {.01; .02; .03} while the others 153 (left or right) decreased the eccentricity by steps of {-.1; -.001; -.005}. Finally, 11 repetitions 154 for each size starting from 11 different initial eccentricities equally distributed between 0 and 155 1 were executed. The experiment was then composed of 33 trials, i.e. 3 {Sizes} x 11 156 {repetitions}, presented according to two pseudo-random series counterbalanced across the 157 participants. The participants were prompted to explore the whole range of possibilities with 158 the large arrows and to refine their adjustment with the smaller ones. For each participant, 33 159 final eccentricities were collected and the median was computed.

160

161 Experiment 2 – Motor Output

162 The goal of this experiment was to evaluate whether a prototypical eccentricity of an 163 ellipse can be elicited by a motor output. A motor production task was set up during which the 164 participants were asked to draw the ellipse which best represents this geometric shape category.

165 Methods

Participants. Twenty participants (2 left-handed - 5 women) with an average age of 39.6
years (SD = 11.5) voluntary took part in the experiment and were naive to the purpose of the
study. None of them participated in Experiment 1.

Apparatus. The participants sat in front of a Wacom Intuos5 graphic tablet enabling to
 record graphic movements with a spatial precision of 5.10⁻³mm and a sample rate of 129 Hz.

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171 The data were recorded and collected using an interface programmed with the Max/MSP172 software. The experiment was conducted in a lighted room.

173 Task. The participants were asked to repeatedly and continuously draw the most 174 representative ellipse of this geometric shape category on the graphic tablet during 50 seconds. 175 The notion of the most representative ellipse was explained with the same sentence as in 176 Experiment 1. Participants saw their hands during the recording, but no trace was visible on the 177 graphic tablet. The experiment comprised three sessions of 50 seconds. The participants were 178 asked to draw small, intermediate, and large ellipses in two different orders counterbalanced 179 across participants: 1) small -2) intermediate -3) large, or conversely. No template of the 180 ellipses was presented, but the participants could train in advance by drawing the 3 different 181 ellipses on the graphic tablet during a session preceding the experiment.

182 *Data analysis.* For each participant, recordings of the sampled coordinates (x(t), y(t)) of 183 the stylus on the graphic tablet were collected. To eliminate the numerical noise, the raw data 184 were smoothed with a Savitsky-Golay filter (Savitsky and Golay, 1964) with a 43 samples 185 window and a 3rd-order interpolation. This is equivalent to a low-pass filter with a cutoff 186 frequency of 8 Hz. A high-pass filter (Butterworth) with a cutoff frequency of .2 Hz was also 187 applied to eliminate the spatial drift of the participants' hands during their movements.

The geometric characteristics of the drawn ellipses were analyzed according to the relative phase. Computing the Hilbert transforms of x(t) and y(t) enabled to estimate the relative phase RP between two oscillators (Panter, 1965; Smith and Mersereau, 1991) with the following formula: $RP(t) = |\tilde{x}(t) - \tilde{y}(t)|$, where \tilde{x} and \tilde{y} are the unwrapped Hilbert transforms of x and y. The median of the relative phases RP were then computed for each recording and then transformed into eccentricity. For each participant, 3 final eccentricities were collected and the median was computed.

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196 Experiment 3 – Dynamic Visual Output

Here, the Experiment 1 was reproduced with dynamic visual stimuli. The participants
were asked to calibrate the eccentricity of the elliptic trajectory of a moving spotlight to create
the most representative ellipse.

200 Methods

Participants. Twenty participants (1 left-handed; 3 women) with an average age of 32
years (SD = 11.4) voluntary took part in the experiment. None of these participants took part in
Experiments 1 & 2.

Stimuli. The visual stimuli were white spotlights displayed on a black background moving on elliptic paths of different sizes and with different periods according to the dynamic model defined in equation (1). As in Experiment 1, the elliptic paths were rotated counterclockwise by 45°. Three periods of the spotlight motion ($T_1 = 1.2s$, $T_2 = 1.5s$, $T_3 = 1.8s$) inducing different spotlight speeds were chosen.

209 *Task.* The adjustment protocol and the task were the same as in Experiment 1. For each 210 (size) x (period) pair, 11 repetitions were performed starting from 11 different initial 211 eccentricity values equally distributed between 0 and 1. The experiment was composed of 99 212 trials, i.e. 3 (sizes) x 3 (periods) x {11 repetitions}, presented according to two pseudo-random 213 series counterbalanced across the participants. For each participant, 99 final eccentricities were 214 collected and the median was computed.

- 215 *Apparatus.* The apparatus was the same as in Experiment 1.
- 216

217 **Experiment 4 – Auditory Output**

Here, participants were submitted to auditory stimuli generated with the dynamic characteristics of the motor performances recorded in experiment 2 and were asked to modify this dynamic to evoke a friction sound that conveys the the most representative elliptic

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221 movement exclusively from the auditory modality. By using monophonic sounds, only dynamic information was transmitted to the participants, as opposed to the visual cases in which both 222 223 spatial and dynamic cues were contained in the stimuli. Hence, this experiment intended to 224 show whether geometric prototypes could emerge from the auditory stimulations, which would 225 signify that spatial information is not strictly needed to evoke a prototype.

226 Methods

227

Participants. Twenty participants (9 women) with an average age of 32.1 years (SD =

228 9.56) voluntary took part in the experiment.

229 Stimuli. Stimuli were monophonic synthetic friction sounds simulating the motion of a 230 pencil on a rough surface, e.g., a piece of paper. A physically based model which simulates the 231 physical sound source as the result of successive impacts of a plectrum, here a pencil nail, on 232 the asperities of a surface, was used (Conan et al., 2014). The surface roughness is modeled by 233 a noise reflecting the different heights of the surface asperities. Movements on this surface is 234 then simulated processing this noise according to the velocity profile of the movement: the 235 faster the movement the more impacts there are. From a signal processing point of view, such 236 an operation is equivalent to a low-pass filter on the noise with a central frequency directly 237 linked to the movement velocity. The filtered noise is finally convolved with an impulse 238 response simulating the resonance of an object such as a table. To control the synthesis model, 239 we used the 60 motions (3 recordings x 20 participants) recorded in the motor experiment 240 (Experiment 2).

241 *Task.* The participants were asked to modify the sound to evoke an elliptic motion for 242 which the trajectory was the most representative of an ellipse. They were implicitly adjusting 243 the delay between the recorded oscillators which implicitly modify the ellipse's roundness. For 244 each of the 60 movements to adjust, 4 periods of the initial recording were used to generate the 245 stimuli. The participants were informed when they reached limits, i.e. 0 or 1 eccentricity, and

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246 the adjustment protocol was inspired on one proposed by the on proposed Carlyon and 247 colleagues (Carlyon et al., 2010). The eccentricity of the ellipse could be modified either with a large or a small modification of the actual eccentricity by using top-down and left-right-248 249 arrows respectively, by steps of .10/.3 and .05/.2 respectively. In order to avoid an experimental 250 bias, for each opposite key, e.g., left/right, the roundness was modified with a different step so 251 that participants could not count the number of taps to adjust the friction sound. The participants 252 were prompted to explore the whole range of possibilities with the large arrows and to refine 253 their adjustment with the smaller ones.

Apparatus. Sounds were presented through Sennheiser HD650 headphones and the
sample rate of the soundcard was 44100 Hz with 16-bit resolution. The friction sounds were
real-time synthesized with MATLAB software. The experiment was carried out in a quiet room.
The sound was modified by the participants using the keyboard of the computer.

258 *Data analysis.* For each participant, 60 eccentricities values were collected and their
259 median was computed to characterize the prototypical ellipse.

260 Results

The results first revealed that an elliptical prototype can be determined in each modality. More strikingly, a coherence between the motor, the visual - static and dynamic - and the auditory prototypes was observed (Non-parametric Friedman test with modality as a factor: df=3; $\chi^2=1.26$; p=.73) (Figure 2). They all converge toward a common eccentricity, each one is not significantly different from .91 (t-test vs. .91: all not significant, Bonferroni corrections, for each experiment, df=19) (motor: Mdn=.89, iqr=.067 – auditory: Mdn=.88, iqr=.049 – visual static: Mdn=.91, iqr=.062 – visual dynamic: Mdn=.91, iqr=.121).

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Figure 2. Averaged eccentricities obtained from the four experiments. The boxplot represents the median (dot), the 25th and 75th percentiles (the bottom and top edges of the box). The whiskers (vertical dashed line) extend to the most extreme data points below 1.5 the interquartile range.. The dashed line indicates the value .91 corresponding to the elliptic movement attractor. These results reveal a coherent averaged eccentricity close to .91.

274

275 General Discussion

In this study, we aimed at investigating whether common prototype of elliptic shapes elicited across modalities, especially from auditory stimuli, could be identified. We compared the restituted geometry through different outputs (visual, motor and auditory) across a series of four experiments. A common elliptic prototype characterized by an eccentricity of .91 was uncovered, hence demonstrating the common encoding of this prototype.

281

This complements knowledge from previous studies on the existence of prototypical
geometric shapes (Rosch, 1973, 1975; Feldman, 2000; Kalénine et al., 2013). This is also in

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284 line with those from Wamain et al. (2011), who highlighted that the ellipse drawn 285 spontaneously has a relative phase close to 45°, i.e. an eccentricity of .91, and with those from 286 pure motor experiments aiming at revealing the preferentially drawn ellipse (Dounskaia et al., 287 2000; Sallagoïty et al., 2004; Danna et al., 2011) corresponding to stable states, so-called motor 288 attractors (Kelso, 1986) (cf. Figure 2). Interestingly, when superimposing the prototypical 289 ellipse obtained in the present study with the prototypical rectangle highlighted by Kalénine et 290 al. (2013), common proportions can be observed. The length to width ratio for prototypical 291 rectangles and the semi-major to semi-minor axis ratio for prototypical ellipses are both close 292 to 2.3, which corresponds to .9 in term of eccentricity.

293 Above all, these results suggest a common coding of prototypical shape geometry and 294 more generally further support the role of the sensorimotor loop on our perceptual processes 295 (O'Regan and Noë, 2001; Varela et al., 1992; O'Regan, 2011). Interestingly, 296 neuropsychological studies demonstrated that motor schemes are re-activated during perceptual 297 processes through different sensory modalities (Chao and Martin, 2000; Creem-Regehr and 298 Lee, 2005; Grafton et al., 1997; Grèzes and Decety, 2002; Kohler et al., 2002; Bangert et al., 299 2006; Zatorre et al., 2007), and through motor imagery (for a review see Jeannerod, 1995 or 300 Grosprêtre, Ruffino and Lebon, 2015). Concerning handwriting, it has been shown that seeing 301 a letter activates the cortical processes involved when producing the corresponding script 302 (Longcamp et al., 2003; James and Gauthier, 2006; Longcamp et al., 2006). Similarly, 303 perceiving a geometric shape may share processes involved when we are drawing it. In 304 Experiment 4, an elliptic prototype that did not differ from the visual and motor outputs was 305 elicited from monophonic sounds that only carried dynamic cues. This salient result shows that 306 the elliptic prototype is not only geometric but also can be transmitted through a dynamic 307 dimension. Hence without rejecting the necessity of visual experience in the emergence of 308 prototypical shapes (Theurel et al., 2011; Kalénine et al., 2011), our data suggest that the

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309	prototypical shape is encoded through a common process based on the underlying covariation
310	between biological kinematics and shape geometry which characterizes the corresponding
311	drawing movement (Lacquaniti et al., 1983) and its perception through several sensory channels
312	(Viviani et al., 1992; Viviani and Stucchi, 1989; Viviani et al., 1987; Thoret et al., 2014). This
313	unified percept (Hommel et al., 2001) can then be recalled even through the auditory modality,
314	which does not provide any spatial cues. Further experiments with other geometric shapes are
315	needed to precisely assess the central role of the sensorimotor loop in the emergence of
316	prototypical shape geometries.
317	
318	Authors contributions
319	Conceived and designed the experiments: ET MA LB SY RKM. Performed the experiments:
320	ET. Analyzed the data: ET MA LB SY RKM. Contributed reagents/materials/analysis tools:
321	ET. Wrote the paper: ET MA LB SY RKM
322	
323	Declaration of interests
324	The authors declare no competing interests.
325	
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