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1 **Hearing elliptic movements reveals the imprint of**
2 **action on prototypical geometries**

3

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14

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.

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
34 sensory channel (Theurel et al., 2012; Kalénine et al. 2011) and via a motor restitution
35 (Feldman, 2000; Kalénine et al., 2013). Alternatively, the possibility to recall prototypes
36 through visual and haptic modalities or motor output may suggest common processing of these
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 motor cues? Answering this question
40 would provide a new path to understanding the influence of the motor system on human
41 learning, memory, and cognition. This would indeed suggest that human movement dynamics
42 and more generally the sensory-motor contingencies influence the structuration of geometric
43 shape categories during development.

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

54 distort the visuomotor coupling of biological motions (Thoret et al, 2016a, 2016b). Taken
55 together, these studies suggest that simple geometric shapes can be evoked through the auditory
56 channel and that the auditory modality may play a significant role in the perception and
57 production of geometric shapes.

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

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

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

80

81 **A model of biological elliptic motor dynamics**

82 Biomechanical mechanisms involved in graphical production as handwriting have been
 83 extensively investigated. It has been shown that dynamic and geometric properties of elliptic
 84 motions can be modeled by explicit equations. The dynamic approach of movement production
 85 supports the idea that planar hand movements can be modeled by two harmonic oscillators ($x(t)$,
 86 $y(t)$) whose frequencies, amplitudes and phases evolve over time (Hollerbach, 1981) with the
 87 following system:

$$88 \quad \begin{cases} x(t) = A_x(t) \cos(\omega_x(t) + \phi_x(t)) \\ y(t) = A_y(t) \cos(\omega_y(t) + \phi_y(t)) \end{cases}$$

89 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
 90 of the two oscillators. In the case of periodic elliptic motions, this model can be simplified by
 91 equaling the amplitudes and frequencies of the oscillators ($A(t) = A_x = A_y = A$ and $\omega(t) = \omega_x =$
 92 $\omega_y = \omega$):

$$93 \quad \begin{cases} x(t) = A \cos(\omega t) \\ y(t) = A \cos(\omega t + RP) \end{cases} \quad (1)$$

94 where A is the amplitude, $\omega = \frac{2\pi}{T}$ the frequency with T the period of the motion, and $RP = \phi_x$
 95 $- \phi_y$ the relative phase between the oscillators $x(t)$ and $y(t)$.

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

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

101 It should be noted that this model complies with the biological rules, namely the 1/3 power law
102 (Lacquaniti et al., 1983).

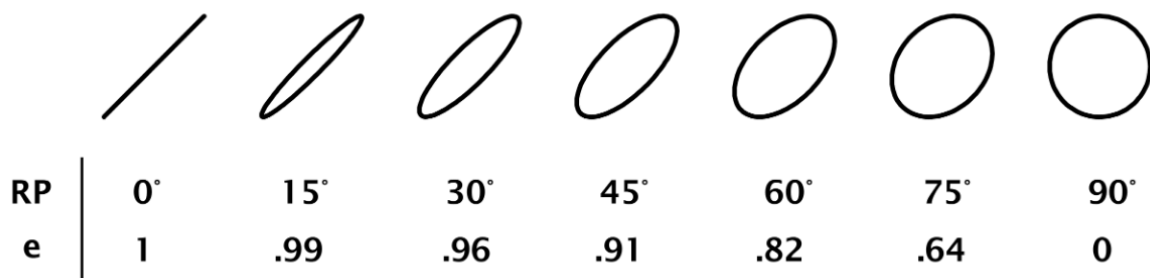
103 This model then enables the generation of biological elliptic motions whose trajectory
104 can be continuously morphed from a line ($RP = 0^\circ$) to a circle ($RP = 90^\circ$) by simply acting on
105 RP (see Figure 1). It will be used in the four following experiments in order to generate visual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

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

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

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

113



114

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

117

118 Experiment 1 – Static Visual Output

119 The first experiment aimed to evaluate the prototype of the ellipse from visual restitution (i.e.,

120 visual output). To that aim, an adjustment protocol was established. Participants were asked to
121 adjust the eccentricity of static ellipses on a screen to evoke the most representative shape of
122 this geometric category.

123

124 **Methods**

125 *Participants.* Twenty right-handed participants (8 women) with an average age of 30.6
126 years (SD = 12.8) voluntarily took part in the experiment. All the participants were naive to the
127 purpose of the experiment. As in all the following experiments, participants gave their informed
128 consent before the study, and the experiment was approved by the Aix-Marseille University
129 ethical committee. For this experiment and the three subsequent ones, participants were selected
130 from various groups, including personal acquaintances, students, engineers, researchers, and
131 professors at the CNRS Campus Joseph Aiguier in Marseille, as well as individuals from the
132 Sport Science Faculty of Aix-Marseille University in Marseille, France.

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

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

143 *Task.* The participants were asked to adjust the eccentricity of the static ellipse displayed
144 on the screen so as to set the most representative geometric shape of this category. The notion

145 of the most representative ellipse was explained in French to the participants by the following
146 sentences (here translated in English): *Ellipses correspond to any closed shape between a line*
147 *and a circle. When you imagine an ellipse, you may have one particular elliptic shape in mind.*
148 *You will adjust the ellipse on the screen to display the ellipse you think is the most prototypical.*
149 The adjustment protocol was based on the one proposed by Carlyon et al. (2010). The ellipse
150 eccentricity was adjusted thanks to 6 different keys defined on the keyboard: “<<<” – “<<” –
151 “<” and “>” – “>>” – “>>>”. Depending on the selected key, the ellipse eccentricity was
152 modified with different step sizes. The higher the number of arrows the greater the step size,
153 *i.e.* the modification of the eccentricity. To avoid a possible non-sensorial bias due to the
154 orientation of the arrows (right or left), the action of the keys on the eccentricity differed across
155 participants. Hence, for half of the participants, arrows that pointed to the right increased the
156 eccentricity and for the other half they had the opposite effect. In addition, the step sizes were
157 not the same in both directions. Hence, for a given participant, all the arrows in one direction
158 (right or left) increased for instance the eccentricity by steps of {.01; .02; .03} while the others
159 (left or right) decreased the eccentricity by steps of {-.1; -.001; -.005}. Finally, 11 repetitions
160 for each size starting from 11 different initial eccentricities equally distributed between 0 and
161 1 were executed. The experiment was then composed of 33 trials, *i.e.* 3 {Sizes} x 11
162 {repetitions}, presented according to two pseudo-random series counterbalanced across the
163 participants. The participants were prompted to explore the whole range of possibilities with
164 the large arrows and to refine their adjustment with the smaller ones. For each participant, 33
165 final eccentricities were collected and the median was computed.

166

167 **Experiment 2 – Motor Output**

168 The goal of this experiment was to evaluate whether a prototypical eccentricity of an
169 ellipse can be elicited by a motor output. A motor production task was set up during which the

170 participants were asked to draw the ellipse which best represents this geometric shape category.

171 **Methods**

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

175 *Apparatus.* The participants sat in front of a Wacom Intuos5 graphic tablet enabling to
176 record graphic movements with a spatial precision of $5 \cdot 10^{-3}$ mm and a sample rate of 129 Hz.
177 The data were recorded and collected using an interface programmed with the Max/MSP
178 software. The experiment was conducted in a lighted room.

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

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

194 The geometric characteristics of the drawn ellipses were analyzed according to the

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

201

202 **Experiment 3 – Dynamic Visual Output**

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

206 **Methods**

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

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

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

220 collected and the median was computed.

221 *Apparatus.* The apparatus was the same as in Experiment 1.

222

223 **Experiment 4 – Auditory Output**

224 Here, participants were submitted to auditory stimuli generated with the dynamic
225 characteristics of the motor performances recorded in experiment 2 and were asked to modify
226 this dynamic to evoke a friction sound that conveys the most representative elliptic movement
227 exclusively from the auditory modality. By using monophonic sounds, only dynamic
228 information was transmitted to the participants, as opposed to the visual cases in which both
229 spatial and dynamic cues were contained in the stimuli. Hence, this experiment intended to
230 show whether geometric prototypes could emerge from the auditory stimulations, which would
231 signify that spatial information is not strictly needed to evoke a prototype.

232 **Methods**

233 *Participants.* Twenty participants (9 women) with an average age of 32.1 years (SD =
234 9.56) voluntary took part in the experiment. None of them participated to the experiments 1, 2
235 & 3.

236 *Stimuli.* Stimuli were monophonic synthetic friction sounds simulating the motion of a
237 pencil on a rough surface, e.g., a piece of paper. A physically based model which simulates the
238 physical sound source as the result of successive impacts of a plectrum, here a pencil nail, on
239 the asperities of a surface, was used (Conan et al., 2014). The surface roughness is modeled by
240 a noise reflecting the different heights of the surface asperities. Movements on this surface is
241 then simulated processing this noise according to the velocity profile of the movement: the
242 faster the movement the more impacts there are. From a signal processing point of view, such
243 an operation is equivalent to a low-pass filter on the noise with a central frequency directly
244 linked to the movement velocity. The filtered noise is finally convolved with an impulse

245 response simulating the resonance of an object such as a table. To control the synthesis model,
246 we used the 60 motions (3 recordings x 20 participants) recorded in the motor experiment
247 (Experiment 2).

248 *Task.* The participants were asked to modify the sound to evoke an elliptic motion for
249 which the trajectory was the most representative of an ellipse. They were implicitly adjusting
250 the delay between the recorded oscillators which implicitly modify the ellipse's roundness. For
251 each of the 60 movements to adjust, 4 periods of the initial recording were used to generate the
252 stimuli. The participants were informed when they reached limits, i.e. 0 or 1 eccentricity, and
253 the adjustment protocol was inspired by one proposed by Carlyon and colleagues (Carlyon et
254 al., 2010). The eccentricity of the ellipse could be modified either with a large or a small
255 modification of the actual eccentricity by using top-down and left-right-arrows respectively, by
256 steps of .10/.3 and .05/.2 respectively. In order to avoid an experimental bias, for each opposite
257 key, e.g., left/right, the roundness was modified with a different step so that participants could
258 not count the number of taps to adjust the friction sound. The participants were prompted to
259 explore the whole range of possibilities with the large arrows and to refine their adjustment
260 with the smaller ones.

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

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

267 **Results**

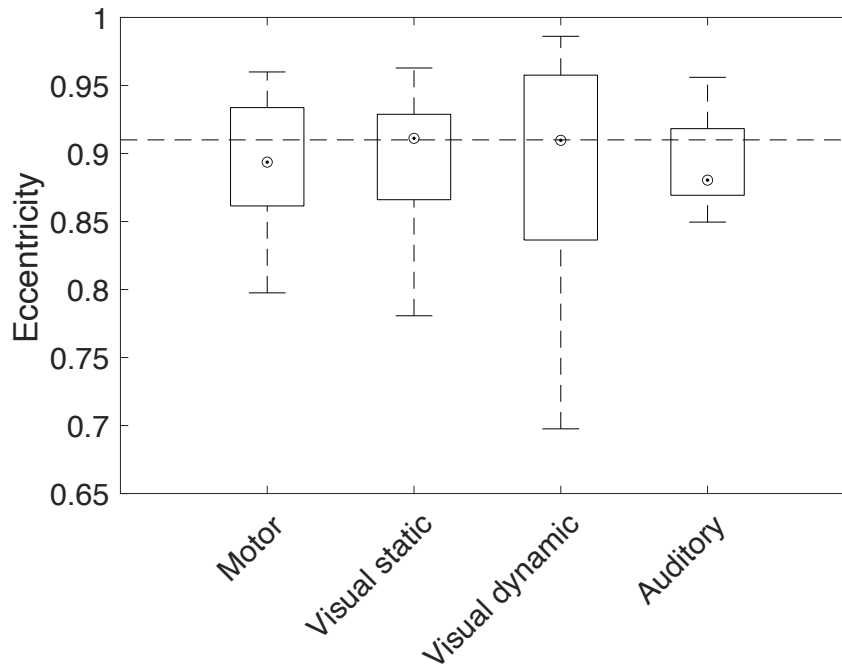
268 *Coherence between prototypes.* We first investigated whether the four different
269 experiments led to four different prototypes. For each experiment, we ensured the normality of

270 the different distributions by using a Lilliefors test (all non-significant, Bonferroni corrected
271 $\alpha=.05/4=.0125$). It must be noted that for the auditory experiment the Lilliefors test was only
272 marginally significant because of Bonferroni corrections ($p=.0176$). Therefore, in the following
273 we used both parametric and non-parametric approaches. Two statistical tests were applied: (1)
274 a non-parametric Kruskal-Wallis test with experiment as a factor ($df=3$; $\chi^2= 1.14$; $p=.76$); (2)
275 parametric Bonferroni corrected pairwise t-tests between the different experiments. Results
276 were all non-significant ($df=19$, motor vs. visual static: $p=.33$, $BF_{10}=.35$; motor vs. visual
277 dynamic: $p=.84$, $BF_{10}=.23$; motor vs. auditory: $p=.92$, $BF_{10}=.23$; visual static vs. visual
278 dynamic: $p=.55$, $BF_{10}=.27$; visual static vs. auditory: $p=.25$, $BF_{10}=.42$; visual dynamic vs.
279 auditory: $p=.82$, $BF_{10}=.24$) (Figure 2a). These tests thus supported an absence of significant
280 difference between the motor, the visual - static and dynamic - and the auditory prototypes.

281 *Eccentricity of the prototypes.* Secondly, we investigated the eccentricity of the
282 prototypes for each experiment. The mean eccentricity values were: 1) motor: $Mdn=.89$,
283 $iqr=.067$, $M=.89$, $SD=.046$; 2) visual static: $Mdn=.91$, $iqr=.062$, $M=.90$, $SD=.044$; 3) visual
284 dynamic: $Mdn=.91$, $iqr=.121$, $M=.88$, $SD=.086$; 4) auditory: $Mdn=.88$, $iqr=.049$, $M=.88$,
285 $SD=.061$ (Figure 2a). We determined a statistically based confidence interval for each
286 prototype, one in each experiment. We linearly sampled the eccentricity range between 0 and
287 1 with 1000 equally spaced eccentricity values. We then ran 1000 one sample t-tests between
288 the data distribution of each experiment and the 1000 eccentricity values. The results of each
289 of the 1000 tests characterizes whether the distribution is different from the candidate
290 eccentricity. For each of the 1000 t-tests, the inverse of the bayes factor $BF_{10,inverse}=1/BF_{10}$ was
291 stored. $BF_{10,inverse}$ can be interpreted exactly as BF_{10} , but for *no difference* with the null
292 hypothesis, the higher the $BF_{10,inverse}$ the less different the distribution with the candidate
293 eccentricity. We here assume that $BF_{10,inverse}>3$ characterizes a fair threshold for no difference
294 with the null hypothesis, i.e. the eccentricity value can be considered in the prototype range

295 (Jeffreys, 1961; Goodman, 1999; Held & Ott, 2016). As results distributions were globally
296 localized, the $1/BF_{10}$ curve is an inverse U-shape. For each experiment, we therefore used
297 $BF_{10, inverse=3}$ as a threshold to determine the lower and upper bound of the confidence interval.
298 We also computed the eccentricity ecc_{max} leading to the highest $BF_{10, inverse}$. This provides a third
299 estimation of the elliptic prototype eccentricity for each experiment. This analysis provides the
300 following results: motor: $ecc_{max}=.883$, $CI_{BF_{10, inverse}}=[.869,.897]$ - visual static: $ecc_{max}=.899$,
301 $CI_{BF_{10, inverse}}=[.892,.909]$ - visual dynamic: $ecc_{max}=.888$, $CI_{BF_{10, inverse}}=[.871,.905]$ - auditory:
302 $ecc_{max}=.880$, $CI_{BF_{10, inverse}}=[.870,.893]$. To investigate specifically whether they differ from the
303 known preferential ellipse of eccentricity .91, t-tests between the distributions and the .91 value
304 were conducted. Results revealed no significant differences ($df=19$, Bonferroni corrections
305 $\alpha=.05/4=.0125$, motor: $p=.1$, $BF_{10}=.82$ – visual static: $p=.34$, $BF_{10}=.354$ – visual dynamic:
306 $p=.25$, $BF_{10}=.42$ - auditory: $p=.05$, $BF_{10}=1.37$). Altogether, these analyses revealed that the
307 experiments provide comparable prototypes, with an average eccentricity of .887. These
308 prototypes are slightly below the preferential intermediate ellipse of eccentricity .91 observed
309 in the literature (see General Discussion).

310



311

312 *Figure 2.* Averaged eccentricities obtained from the four experiments. The boxplot represents
 313 the median (dot), the 25th and 75th percentiles (the bottom and top edges of the box). The
 314 whiskers (vertical dashed line) extend to the most extreme data points below 1.5 the
 315 interquartile range. The dashed line indicates the value .91 corresponding to the elliptic
 316 movement attractor.

317

318 **General Discussion**

319 In this study, we aimed at investigating whether a common prototype of elliptic shapes elicited
 320 across modalities, especially from auditory stimuli, could be identified. We compared the
 321 restituted geometry through different outputs (visual, motor and auditory) across a series of four
 322 experiments. A common elliptic prototype characterized by an eccentricity of .887 was
 323 uncovered, hence demonstrating the common encoding of this prototype.

324 This complements knowledge from previous studies on the existence of prototypical
 325 geometric shapes (Rosch, 1973, 1975; Feldman, 2000; Kalénine et al., 2013). This is also in
 326 line with those from Wamain et al. (2011), who highlighted that the ellipse drawn

327 spontaneously has a relative phase slightly below 45° , i.e. an eccentricity slightly below .91, and
328 with those from pure motor experiments aiming at revealing the preferentially drawn ellipse
329 (Dounskaia et al., 2000; Sallagoity et al., 2004; Danna et al., 2011) corresponding to stable
330 states, so-called motor attractors (Kelso, 1986) (cf. Figure 2). Our results showed that the
331 perceptual prototype – either visual or auditory – is coherent with the motor one, with an
332 eccentricity value slightly below the intermediate ellipse of .91. This eccentricity difference
333 may arise from the intention of the participants which were different because of a different task.
334 Here we asked them to draw the most prototypical ellipse, which wasn't present at all in the
335 spontaneously drawn ellipses asked in Wamain et al. (2011). This slight difference suggests
336 that we cannot obviously exclude that other cue also might have shaped the geometry of the
337 prototype than motor constraint such as visual experience. Interestingly, when superimposing
338 the prototypical ellipse obtained in the present study with the prototypical rectangle highlighted
339 by Kalénine et al. (2013), common proportions can be observed. The length to width ratio for
340 prototypical rectangles and the semi-major to semi-minor axis ratio for prototypical ellipses are
341 both close to 2.3, which corresponds to .9 in term of eccentricity.

342 Above all, these results suggest a common coding of prototypical shape geometry and
343 more generally further support the role of the sensorimotor loop on our perceptual processes
344 (O'Regan and Noë, 2001; Varela et al., 1992; O'Regan, 2011). Interestingly,
345 neuropsychological studies demonstrated that motor schemes are re-activated during perceptual
346 processes through different sensory modalities (Chao and Martin, 2000; Creem-Regehr and
347 Lee, 2005; Grafton et al., 1997; Grèzes and Decety, 2002; Kohler et al., 2002; Bangert et al.,
348 2006; Zatorre et al., 2007), and through motor imagery (for a review see Jeannerod, 1995 or
349 Grosprêtre, Ruffino and Lebon, 2015). Concerning handwriting, it has been shown that seeing
350 a letter activates the cortical processes involved when producing the corresponding script
351 (Longcamp et al., 2003; James and Gauthier, 2006; Longcamp et al., 2006). Similarly,

352 perceiving a geometric shape may share processes involved when we are drawing it. In
353 Experiment 4, an elliptic prototype that did not differ from the visual and motor outputs was
354 elicited from monophonic sounds that only carried dynamic cues. This salient result shows that
355 the elliptic prototype is not only geometric but also can be transmitted through a dynamic
356 dimension. Hence without rejecting the necessity of visual experience in the emergence of
357 prototypical shapes (Theurel et al., 2011; Kalénine et al., 2011), our data suggest that the
358 prototypical shape is encoded through a common process based on the underlying covariation
359 between biological kinematics and shape geometry which characterizes the corresponding
360 drawing movement (Lacquaniti et al., 1983) and its perception through several sensory channels
361 (Viviani et al., 1992; Viviani and Stucchi, 1989; Viviani et al., 1987; Thoret et al., 2014). This
362 unified percept (Hommel et al., 2001) can then be recalled even through the auditory modality,
363 which does not provide any spatial cues. Further experiments using the same auditory based
364 paradigm, in particular with other geometric shapes, are needed to precisely assess the central
365 role of the sensorimotor loop in the emergence of prototypical shape geometries.

366

367 **Limitations & Perspectives**

368 This study has mainly two methodological limitations. Firstly the investigation was made at
369 group level and subjects were different in each experiment. This allowed us to strikingly
370 highlight the existence of a common prototype between a set of different participants in each
371 modality. This was the main hypothesis of this study and the reason why the elliptic prototype
372 was primarily investigated at group level. It would be of interest to investigate this issue at
373 subject level to exclude that such a prototype may vary across modalities for a given set of
374 participants. However, such a subject level investigation would require a different experimental
375 procedure as one experiment might influence the result of the others. In this case it would not
376 be possible to completely disentangle a potential priming between them. Secondly, the

377 experiment was performed in controlled laboratory experimental conditions with a population
378 of N=80 (4x20). The generalizability of the result could be improved by running such a series
379 of experiments on a larger number of participants with online testing platforms. Lastly, and this
380 is probably the most important conceptual limitation of this study, we have here investigated
381 the prototype of only one shape, the ellipse, which is a very specific shape without any
382 discontinuities, and which moreover can be drawn continuously. To generalize our results, it
383 would be relevant to run the experiment with a more complete set of shapes such as rectangles
384 or triangles, that have been subject to a certain number of studies in the past. This would
385 nevertheless require refinements in the sound modeling procedure due to the discontinuities in
386 the drawing movement of such shapes.

387

388 **Authors contributions**

389 Conceived and designed the experiments: ET MA LB SY RKM. Performed the experiments:
390 ET. Analyzed the data: ET MA LB SY RKM. Contributed reagents/materials/analysis tools:
391 ET. Wrote the paper: ET MA LB SY RKM

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393

394 **Declaration of interests**

395 The authors declare no competing interests.

396

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