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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 cues? Answering this question is  
40 fundamental to understanding the influence of the motor system on human learning, memory,  
41 and cognition. It is essential both for the language sciences (Sablé-Meyer 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  
46 monophonic friction sounds corresponding to those produced by the pencil of someone drawing  
47 on a paper, were able to recognize specific kinematics characterizing biological motion, in  
48 particular the 1/3 power law linking the tangential velocity of the hand movement to the  
49 curvature of the drawn shape (Lacquaniti et al., 1983). In addition, they were even able to  
50 discriminate geometric shapes, such as a circle, an ellipse, and a line, simply by listening to  
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

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  
64 respectively. From a dynamic point of view and concerning the  $1/3$  power law, the accelerations  
65 of an elliptic movement increase as the distance between the focal points of the ellipse increases  
66 (i.e., when the ellipse tends towards a line). Ellipses can be distinguished by ear from circles  
67 and lines and do not involve discontinuity movements. Hence, this geometric shape has been  
68 chosen for the present study.

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

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

## 79 **A model of biological elliptic motor dynamics**

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

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

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

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

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

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

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

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

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

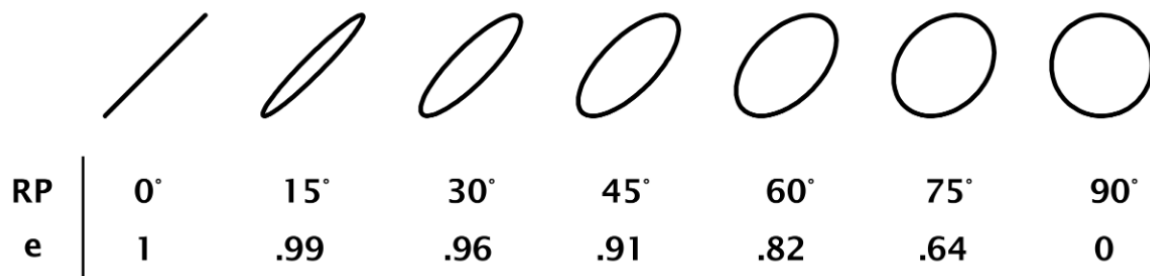
101 This model then enables the generation of biological elliptic motions whose trajectory  
102 can be continuously morphed from a line (RP = 0°) to a circle (RP = 90°) by simply acting on  
103 RP (see Figure 1). It will be used in the four following experiments in order to generate visual  
104 and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

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

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

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

111



112

113 *Figure 1.* Continuum of different ellipse shapes from a line (left) to a circle (right) with the  
114 corresponding 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.

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  $A_1 = 3\text{cm}$ ,  $A_2 = 5\text{cm}$ ,  $A_3 = 10\text{cm}$  were  
130 chosen. The ellipses were rotated counterclockwise by  $45^\circ$  to conform to the preferential  
131 drawing inclination of an ellipse for right-handed persons (Danna et al., 2011).

132 *Apparatus.* The participants sat in front a computer screen (DELL 1907fp) with a  
133 resolution of 1280 x 1024 pixels and a frame rate of 60 Hz. The ellipses were displayed at the  
134 center of the screen and the interface was programmed with Max/MSP software  
135 (<http://cycling74.com/>). Participants modified the ellipse eccentricities by using a MIDI AKAY  
136 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: “<<<<” – “<<” –  
145 “<” and “>” – “>>” – “>>>”. Depending on the selected key, the ellipse eccentricity was



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**

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

169 *Apparatus.* The participants sat in front of a Wacom Intuos5 graphic tablet enabling to  
170 record graphic movements with a spatial precision of  $5 \cdot 10^{-3}$ mm and a sample rate of 129 Hz.

171 The data were recorded and collected using an interface programmed with the Max/MSP  
172 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 3<sup>rd</sup>-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.

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

195

## 196 **Experiment 3 – Dynamic Visual Output**

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

### 200 **Methods**

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

204 *Stimuli.* The visual stimuli were white spotlights displayed on a black background  
205 moving on elliptic paths of different sizes and with different periods according to the dynamic  
206 model defined in equation (1). As in Experiment 1, the elliptic paths were rotated  
207 counterclockwise by  $45^\circ$ . Three periods of the spotlight motion ( $T_1 = 1.2s$ ,  $T_2 = 1.5s$ ,  $T_3 = 1.8s$ )  
208 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**

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

221 movement exclusively from the auditory modality. By using monophonic sounds, only dynamic  
222 information was transmitted to the participants, as opposed to the visual cases in which both  
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

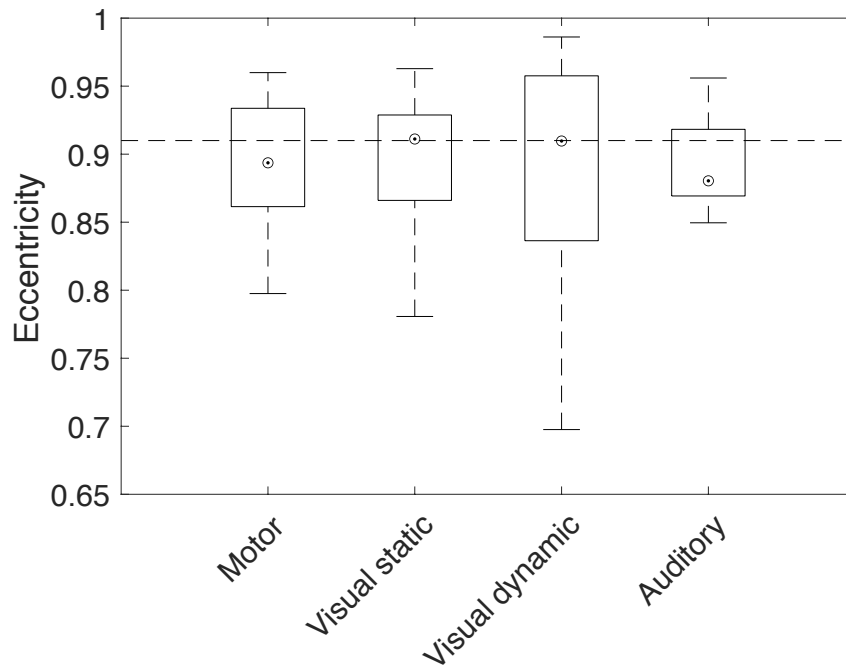
246 the adjustment protocol was inspired on one proposed by the on proposed Carlyon and  
247 colleagues (Carlyon et al., 2010). The eccentricity of the ellipse could be modified either with  
248 a large or a small modification of the actual eccentricity by using top-down and left-right-  
249 arrows 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.

254 *Apparatus.* Sounds were presented through Sennheiser HD650 headphones and the  
255 sample rate of the soundcard was 44100 Hz with 16-bit resolution. The friction sounds were  
256 real-time synthesized with MATLAB software. The experiment was carried out in a quiet room.  
257 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**

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



268

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

274

## 275 **General Discussion**

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

281

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

284 line with those from Wamain et al. (2011), who highlighted that the ellipse drawn  
285 spontaneously has a relative phase close to  $45^\circ$ , 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; Sallagoity 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

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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