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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 ω_x and ω_y the frequencies, and ϕ_x and ϕ_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.

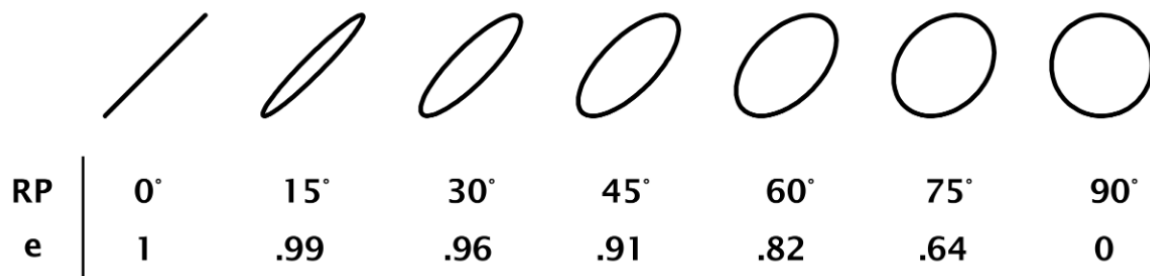
101 This model then enables the generation of biological elliptic motions whose trajectory
102 can be continuously morphed from a line (RP = 0°) to a circle (RP = 90°) by simply acting on
103 RP (see Figure 1). It will be used in the four following experiments in order to generate visual
104 and auditory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

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° . 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

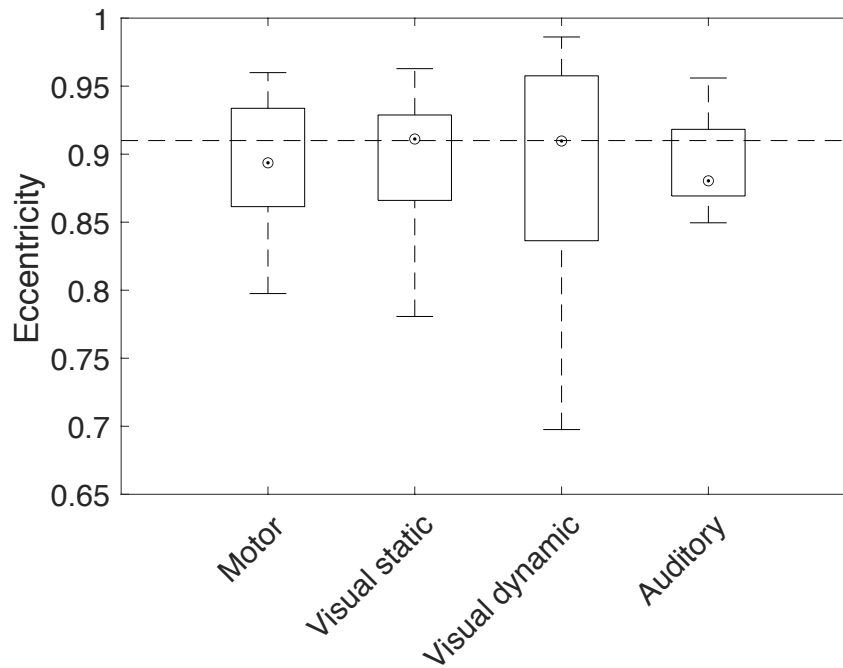
246 the adjustment protocol was inspired on one proposed by the on proposed Carlyon and
247 colleagues (Carlyon et al., 2010). The eccentricity of the ellipse could be modified either with
248 a large or a small modification of the actual eccentricity by using top-down and left-right-
249 arrows respectively, 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 25th and 75th 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° , 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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