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1 A preliminary study of rotation velocity regulation in pottery wheel-throwing:  
2 fieldwork with Indian potters using the low-inertia kick-wheel

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**Abstract**

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33 The present study examined rotation velocity regulation in pottery wheel-throwing.  
34 Long assumed to be a key parameter in the control of the centrifugal force, we interpret its role  
35 rather as a means to control the linear velocity at the point of hand-clay contact. To test this  
36 hypothesis, we set up a field experiment with Indian potters working with a low-inertia kick-  
37 wheel. Six expert potters were asked to produce eight types of pots (four shapes × two masses),  
38 each type in five specimens (in total each potter threw 40 vessels). We measured the rotation  
39 velocity during the pre-forming and forming fashioning phases, as well as the maximal vessel  
40 radii at the end of both phases. Results demonstrated that potters reduced the rotation velocity  
41 from the pre-forming phase to the forming phase, but also for the large clay masses compared  
42 to the small clay masses, and -uniquely during the forming phase- for the shapes characterized  
43 by the largest diameter. Overall, the observed decreases in rotation velocity corresponded to  
44 increases in mean vessel diameter, suggesting that the potters were applying a limit on the linear  
45 velocity. Our results thus provide empirical evidence supporting the role of linear velocity as a  
46 key functional parameter in wheel-throwing. Directly relating to the potter-vessel interaction,  
47 it indicates both when and by how much the rotation velocity deceleration caused by the  
48 exertion of manual pressure forces should be compensated, as well as how to avoid the risk of  
49 velocity-induced collapse. While only preliminary, our results also suggest that large-sized  
50 ancient wheel-thrown vessels were most likely produced using low-velocity and high-inertia  
51 wheels. Future work, examining rotation velocity regulation over different types of wheels, is  
52 needed to allow definite conclusions to be drawn.

53  
54  
55 **Key words:** pottery wheel-throwing, [potter's wheel](#), rotation velocity, linear velocity, motor  
56 skill, expertise, field experiment, low-inertia kick-wheel

61 **1. Introduction**

62

63 In pottery, fashioning is the process of deforming a lump of clay into a desired container  
64 shape. While the resulting vessel will eventually be solidified by firing, during fashioning the  
65 clay remains elastoplastic, meaning that deformations caused by small forces are elastic and  
66 hence reversible, whereas deformations caused by larger forces are plastic and hence  
67 permanent. Fashioning thus requires the application of sufficient force levels to give rise to  
68 plastic deformation of the clay to attain the desired shape. At the same time, however, the  
69 evolving mechanical structure (i.e., the pottery vessel) must continuously remain sufficiently  
70 strong to avoid collapse (Gandon et al., 2011a). Potters must therefore deftly control the  
71 deforming manual pressure forces exerted on the clay surface.

72

73 Fashioning techniques exploiting a wheel-based rotation device can be distinguished  
74 depending on the contribution of the wheel's rotational motion to the fashioning sequence. The  
75 three general variants of such fashioning techniques, identified in the archaeological record or  
76 directly observed in ethnographic studies, are wheel-finishing, wheel-shaping, and wheel-  
77 throwing (Ther & Toms, 2016; Roux, 2019). Of these three, only wheel throwing exploits the  
78 the wheel's rotational motion over the complete fashioning sequence, which, thereby, poses  
79 requirements on rotation velocity in terms of regularity and magnitude. The advent of wheel-  
80 throwing, with the clay's surface continuously moving relative to the potter's hands, definitely  
81 marked a breakpoint in the evolution of ceramic fashioning techniques (Leroi-Gourhan, 1943;  
82 Van der Leeuw, 1993; Pierret, 2001; Roux & Courty, 1998). While, on the one hand, it allowed  
83 for considerable gains in production rate and product regularity (Roux, 2012, 2019), it, on the  
84 other hand, required the development of specific sensorimotor capabilities for mastering the  
85 skill and thereby longer apprenticeship (Roux & Corbetta, 1989).

86

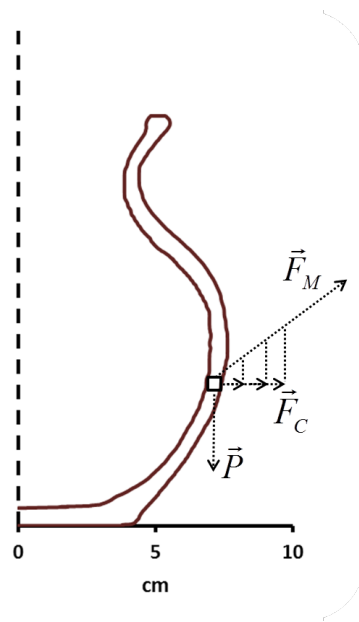
87 Across cultures and time, wheel-throwing has been practiced with different kinds of  
88 wheels (often referred to as fast-wheels) that vary in the ways they are activated (Rice, 1987).  
89 While variations in rotation velocity in the wheel-throwing process have been noted and the  
90 need for regularity has been underscored (RJB: DO YOU HAVE A REF?), to date the  
91 regulation of the rotation velocity over the entire wheel-throwing process has not been  
92 described for any kind of wheel. This is quite surprising, given that such rotation velocity  
93 regulation constitutes the technical trait distinguishing wheel-throwing using the (fast-) wheel

94 from wheel-finishing and wheel-shaping using the turntable and the slow-wheel. The present  
95 study provides a first step to filling this gap, so as to allow archaeologists to better understand  
96 how ancient rotation devices may have been used. Identifying how potters operated the (fast-  
97 )wheel will also shed some light on the complex relation existing between the properties of the  
98 rotation devices (size, inertia, maximal rotation velocity), the vessels characteristics (size, shape  
99 and weight), and the fashioning techniques used by the potter (wheel-finishing, wheel-shaping,  
100 and wheel-throwing) (Roux & Miroschedji, 2009; Roux & Jeffra, 2015; Ther et al., 2017).

101

102 Among archaeologists, the rotation velocity in wheel-throwing has commonly been  
103 regarded as a parameter controlling the resultant centrifugal force, which, in turn, has widely  
104 been considered as an active agent in the clay deformation process (Foster, 1959; Jeffra, 2011;  
105 Méry et al., 2010; Orton et al., 1993; Rice, 1987). While novice potters may regularly  
106 experience collapse of their vessel during fashioning, due to insufficiently-controlled force  
107 balances, this should not be taken to imply that expert potters face the same problems. Indeed,  
108 a recent finite-element mechanical modelling exercise (Gandon et al., 2019) demonstrated that  
109 in expert potter wheel-throwing the centrifugal forces generated by vessel rotation  
110 systematically remained far below the force threshold for plastic deformation. For experts, the  
111 centrifugal force is not, therefore, an active agent in the sense of plastically deforming the clay  
112 by itself. However, like the (downward-acting) gravitational forces, the (outward-acting)  
113 centrifugal forces do affect the pressure forces the potter must apply to fashion the desired  
114 vessel: In order to control the net deforming force applied to the clay, the potter needs to  
115 modulate the (muscular) manual pressures forces exerted in the vertical and radial directions as  
116 a function of the magnitude of these non-muscular forces (Fig. 1). Still, as follows from Gandon  
117 et al.'s (2019) demonstration, in wheel-throwing the operative centrifugal forces resulting from  
118 wheel rotation remain small relative to the pressure forces exerted by a competent potter.  
119 Therefore, for expert potters at least, regulation of rotation velocity during wheel-throwing  
120 should be considered from another angle.

121



122

123 **Fig 1. The forces applied over the clay surface during wheel throwing.**  $\vec{F}_M$ : the manual  
 124 pressure force exerted by the potter,  $\vec{P}$ : the weight of the clay,  $\vec{F}_C$ : the weight of the clay. The  
 125 pressure forces exerted by the potter can be resolved into vertical, radial and tangential  
 126 components (the tangential component, not represented in this 2D figure, is oriented orthogonal  
 127 to the page). When the potter fashions the clay outwards, the centrifugal force is added to the  
 128 radial component of the pressure forces. When we consider the clay together with the wheel,  
 129 we use the expression ‘wheel-throwing system’ (Pierret, 2001).

130

131 In fashioning a vessel by wheel-throwing, two main phases can be distinguished. The  
 132 process begins with a *pre-forming phase* in which the potter centers the mass of clay on the  
 133 wheel and sets the stage for the subsequent forming process by opening (i.e., hollowing) the  
 134 centered lump of clay. During the *forming phase*, thinning the clay (known as “pulling”) brings  
 135 out the initial form as the vessel rises from its base, while the ultimate form is attained during  
 136 the final shaping. These two fashioning phases involve different pressure forces in terms of  
 137 magnitude and orientation. In the pre-forming phase large pressure forces are required to  
 138 constrain the mass of clay into a centered lump. As Roux and Corbetta (1989) have  
 139 experimentally shown, this step of centering is rarely mastered by apprentices before the age of  
 140 14 years because of a lack of strength. During hollowing, the pressure forces required to dig  
 141 into the lump of clay will also be high when a large mass of clay is to be deformed. From pulling

142 to final shaping (i.e., during the forming phase), the thickness of the vessel walls decreases  
143 progressively, reducing the magnitude of the pressure forces the potter can safely apply.

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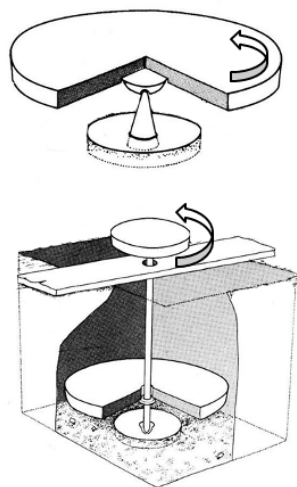
145 As the clay is continuously moving relative to the hands, the exertion of any manual  
146 pressure forces normal to the clay surface creates friction, adding to the inherent, but usually  
147 small, friction operating at the wheel's fulcrum. Being a resistive force, friction represents a  
148 kinetic energy loss, leading the wheel to decelerate. When potters use an electrical wheel, this  
149 energy loss is constantly compensated by the electrical energy injected into the system via the  
150 motor. This is not the case, however, for the traditional wheels used in ancient pottery  
151 communities and which can be still seen in use today (Fig. 2). For non-electrical wheels, the  
152 rotational kinetic energy of the wheel-throwing system is maintained by human effort. A stick-  
153 wheel requires the potter to interrupt the fashioning process to accelerate the wheel with the  
154 help of a hand-held stick. Because of this process-disrupting characteristic, a stick-wheel  
155 typically has a large moment of inertia allowing minimization of the deceleration caused by the  
156 friction forces. A foot-operated kick-wheel, on the other hand, allows the potter to insert energy  
157 by modulating the frequency and/or intensity of kicking, allowing the fashioning activity to  
158 continue with only short interruptions.

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165 **Fig 2. Two kinds of non-electrical wheels in use in northern India.** Top panel: the high-  
166 inertia stick-wheel used by the Prajapati Hindu potters. Bottom panel: the low-inertia kick-  
167 wheel used by the Multani Muslim potters. We have measured equivalent maximal rotation  
168 velocities during fashioning in these two wheels: 222 and 230 rpm for the stick-wheel and kick-  
169 wheel respectively. The left-side drawing is adapted from Orton et al. (1993). (color for the  
170 online version)

171

172 Neither the rotational kinetic energy of the wheel-throwing system nor its rotation  
173 velocity are directly perceived by the potter. What the potter perceives, via haptic and visual  
174 sensations, are the thickness of the vessel walls and the linear velocity at which these walls pass  
175 through the hands. Linear velocity ( $v$ ) is defined as  $v = \omega r$ , where  $\omega$  is the rotation velocity of  
176 the wheel-throwing system and  $r$  the distance between the wheel's rotation axis and the walls  
177 of clay. During fashioning, energy loss due to friction can be perceived in the ensuing  
178 deceleration of the linear velocity; the potter can then respond by accelerating the wheel-  
179 throwing system. To gently deform the clay and maintain axial symmetry, the linear velocity  
180 should be regular and sufficiently high to allow the pressure forces to be continuously applied  
181 over the complete circumference of the vessel. This requirement sets a minimal linear velocity  
182 necessary for the fashioning process. According to Hulthen (1974), such minimal velocity  
183 would be on the order of 0.7 m/s, but one should note that it varies with vessel diameter. One  
184 may also expect an upper limit on the linear velocity, beyond which the potter can no longer  
185 control the fashioning process because of incompressible delays in human sensorimotor  
186 capabilities. At high velocities, the centrifugal force may also come into play, increasing the  
187 risk of vessel collapse. Hence, the linear velocity at the point of clay-hand contact may well be  
188 a key functional parameter in wheel-throwing. It is the parameter that would indicate how much  
189 and when to compensate the deceleration caused by the friction forces, and how to avoid risk  
190 of collapse. Indeed, in a previous study we have shown that potters maintain the linear velocity  
191 within a certain range, measuring values comprised between 0.3 and 1.2 m/s for an average of  
192 0.7 m/s (Gandon et al., 2011b), thus partly corroborating Hulthen's hypothesis (op. cit.). What  
193 still needs to be demonstrated is how the linear velocity is controlled by the potter. If it is a key  
194 functional parameter in wheel-throwing as we suggest, it should be controlled to adapt to the  
195 operative task constraints that vary as a function of fashioning phase and vessel characteristics  
196 (mass and shape).



197

198 To test this hypothesis, we set up a field experiment with expert potters in northern India  
199 (Uttar Pradesh). We recorded the rotation velocity of a low-inertia kick-wheel which requires  
200 frequent driving (acceleration), and thus provides a privileged means to study a potter's 'on-  
201 line' regulation of the rotation velocity. Participants were asked to produce pots of four different  
202 shapes, each shape being thrown with two different masses. The experimental requirement to  
203 produce vessels of different mass and shape implies that the vessels produced will differ in  
204 diameter. Directly recording the linear velocity of the clay wall during fashioning was not  
205 possible without interfering with the hand-clay interface . Instead, we developed a method to  
206 measure the rotation velocity throughout the fashioning process. Given the direct (radius-  
207 mediated) relation between the linear velocity and the rotation velocity, we expected that the  
208 changes in the rotation velocity would be coherent with the control of the linear velocity. This  
209 lead to the operational hypothesis that the control of the linear velocity should be observable  
210 through a decrease in rotation velocity as the diameter of the vessel increases: from the pre-  
211 forming to the forming phase, for the large mass compared to small mass, and in the forming  
212 phase for the largest diameter shapes. We emphasize that compensating for the kinetic energy  
213 loss is energy-consuming and thus tiring for potters using a non-electrical wheel. Traditional  
214 craftsmen usually produce a large quantity of pots per day (hundreds of middle size pots for  
215 example) and, in line with the energy efficiency characteristics of motor skill experts **RJB:**  
216 **REF?**), we assume that they have developed a low (muscular) energy consuming behavior. We  
217 postulate therefore that expert potters throw vessels with the wheel at a rotation velocity  
218 allowing the linear velocity to remain within an optimal range, keeping it as far as possible  
219 below the values where the centrifugal forces would threaten the structural integrity of the pot.  
220 Prior to presenting our main, rotation velocity related results, we will present the  
221 standardization of the vessel assemblages (i.e., variability of vessels' absolute dimensions)  
222 which accounts for the reproducibility of the participants' fashioning behavior.

223 **2. Materials and methods**

224





225 **2.1. Experimental setting**

226

227 Six professional potters gave their written consent to participate in the field experiment.  
228 The participants (right-handed men) were all over 25 years old ( $31.3 \pm 4.5$  yrs) and had a

229 minimum of ten years of wheel-throwing experience ( $16.5 \pm 6.4$  yrs). They all originated from  
 230 the village of Jahanjirabad (Uttar Pradesh, India) and belong to the Multani-Khumar  
 231 community. In India, the wheel-pottery handicraft is learned within endogamous castes which  
 232 throw standardized traditional objects at high production rates (Kramer, 1997; Roux &  
 233 Corbetta, 1989; Saraswati & Behura, 1964). The experiment took place in a traditional pottery  
 234 workshop in the participants' village. All fashioning was performed on the same low-inertia  
 235 kick-wheel (Fig. 2, bottom panel) using soft red clay ( $1.7 \text{ kg/cm}^2$  indentation hardness).  
 236 Participants were asked to reproduce four different model shapes using two different quantities  
 237 of clay, leading to a total of eight experimental conditions (Table 1). To assess the  
 238 reproducibility of behavior, five specimens were produced in each of the eight experimental  
 239 conditions, so that each potter produced a total of 40 pots. The shapes (referred to as cylinder,  
 240 bowl, sphere and vase) were presented as drawings without providing indication of absolute  
 241 size to be produced. The quantity of clay provided for each trial corresponded to a mass of  
 242 either 0.75 kg or 2.25 kg. The participants were instructed to accurately reproduce the  
 243 proportions of the models, to throw vessels with the thinnest walls possible, and to refrain from  
 244 embellishment operations at the end of the fashioning. No tools were used but a basin of water  
 245 to wet the clay. Potters produced the 40 vessels working at their own pace. The experimenter  
 246 was present during the experimental task to monitor progress and ensure procedural  
 247 consistency. Participants freely practiced the task one day before the experiment. Data  
 248 acquisition relied on non-invasive methods detailed in the following sections (Fig. 3).

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Shape	Cylinder		Bowl		Sphere		Vase	
2D drawing								
Mass of clay (kg)	0.75	2.25	0.75	2.25	0.75	2.25	0.75	2.25

255

256 **Table 1. The eight experimental conditions.** Potters were asked to produce four different  
257 shapes (cylinder, bowl, sphere and vase) with two different clay masses (0.75 and 2.25 kg).

258

259



260

261

262 **Fig 3. The non-invasive experimental setting.** The potter performed the task while wheel  
263 rotation velocity and vessel profiles were recorded with a computer and a video camera  
264 respectively. A thin insulated cable connected the rotation velocity measurement device (fixed  
265 to the wheel) to the computer acquisition system. (color for the online version)

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## ***2.2. Data acquisition and analysis***

271

272

### ***2.2.1. Vessel assemblages***

273

274 Using a Panasonic NV-GS320 camcorder, all behavioral sessions were filmed under  
275 standardized conditions: the camera was fixed on a tripod with lens orientation centered on the  
276 vertical rotation axis of the wheel. The camera was positioned at 4 to 6 m from the wheel. The  
277 lower edge of the video image was aligned with the working surface of the wheel and the image  
278 was centered on the vertical rotation axis of the wheel. The plane of the camera was  
279 perpendicular to the plane of the wheel working surface (Fig. 3). The zoom was adapted to fully  
280 cover a 36-cm high by 42-cm wide calibration object (inverted T-shape) that could be placed  
281 on the wheel's working surface. Two images of each vessel were extracted from the films, one  
282 after the pre-forming phase (Phase 1: centering and hollowing, during which the large surfaces  
283 of both hands are in contact with the clay) and the other at the end of the forming phase (Phase  
284 2: thinning and final shaping, during which only one or two fingers of each hand are in partial  
285 contact with the clay). The beginning of Phase 1 was defined by the onset of the first manual  
286 centering action, generally corresponding to the moment of maximal rotation velocity. Phase 1  
287 ended (and Phase 2 began) when the potter initiated the first pulling action. Phase 2 ended when  
288 the last final shaping action was completed. These 2D images adequately captured the  
289 consistently axisymmetric shape of the vessels. From the images, we extracted the 2D  
290 coordinates of the right-side cross-sectional profiles by tracing them out on a Cintiq 21UX  
291 Wacom® tablet with integrated screen. The profile coordinates were converted from pixels to  
292 centimeters using a calibration factor obtained from the dimensions of the calibration object.  
293 Next, the profiles were re-sampled to generate an equal number of points (256 in total) at regular  
294 height intervals along the y-axis and finally the coordinates were smoothed with a low pass  
295 filter. Because the thrown vessels were typically symmetric, profiles were subsequently  
296 converted to full pot outlines by recentering at  $x=0$  and multiplying the x coordinates by -1  
297 to create the corresponding left edge. Using the between-trial variabilities over the five specimens  
298 thrown by each participant (for each of the eight experimental conditions), the standardization  
299 of production was assessed via the coefficients of variation ( $CV = 100\% * \text{standard deviation} /$   
300  $\text{mean}$ ) computed on the absolute dimensions of the final vessel (height, base, aperture, maximal  
301 diameter, and height at the maximal diameter). We also measured the maximal vessel radii at  
302 the end of the pre-forming phase and at the end of the forming phase.

### 303 **2.2.2. Rotation velocity**

304

305 Wheel rotation velocity was measured by means of a magnet fixed to the lower side of  
306 the kick-wheel's rotating plateau and a magnetic sensor (NI USB-6008, National Instruments)

**Commenté [BR1]:** Reported as such in the Results section and Table 2. Is fine to express as percentage.

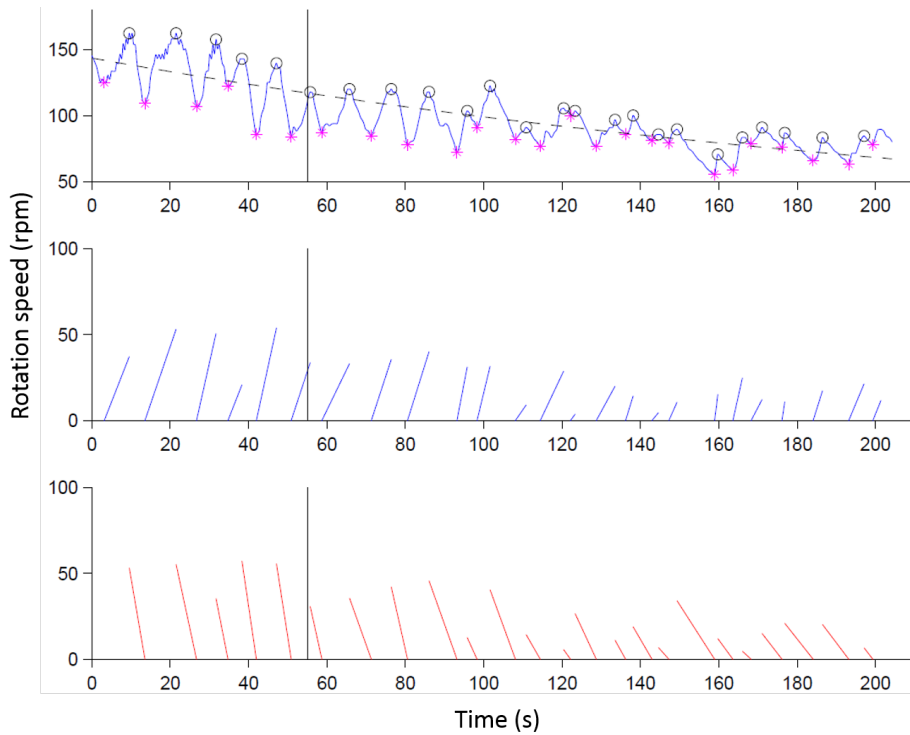
307 attached to the wooden support structure. The magnetic field sampling was performed at 100  
308 Hz, with a measure of rotation velocity thus being available after each full turn of the wheel.  
309 Acquisition of rotation velocity was synchronized with video recordings of the potter's  
310 fashioning behavior (Panasonic NV-GS320) allowing the start and end points of the two phases  
311 of the wheel-throwing to be identified (Fig. 3). We focused on fashioning durations and rotation  
312 velocities during the pre-forming phase (Phase 1) and the forming phase (Phase 2).

313

314 Observation of the evolution of rotation velocity over time during fashioning revealed  
315 both global and local changes (Fig. 4). First, we analyzed the global changes focusing on the  
316 fashioning durations and on the average rotation velocities. Next, we focused on the  
317 characteristics of local increases and decreases in rotation velocity, defined as acceleration and  
318 deceleration bouts, respectively. Acceleration bouts resulted from the potter kicking the wheel  
319 with his (right) foot, thereby increasing rotation velocity. Deceleration bouts resulted from the  
320 dissipation of rotational kinetic energy due to friction forces, thereby decreasing rotation  
321 velocity. Because the friction forces are (to a very large extent) determined by the clay-  
322 deforming pressure forces, we can consider the decrease in rotation velocity observed during  
323 deceleration bouts as indicative of the pressure force exerted by the potter. Bouts were  
324 operationally identified by a peak-finding algorithm that determined the local maxima and  
325 minima in the rotation velocity time series. Velocity differences of less than 4 rpm were  
326 discarded. Acceleration bouts ran from a local minimum to the subsequent maximum, while  
327 deceleration bouts ran from a local maximum to the subsequent minimum. For each vessel  
328 thrown, the number of acceleration and deceleration bouts was determined, together with their  
329 duration, amplitude and average rate of velocity change (i.e., acceleration or deceleration  
330 magnitude).

331 In order to analyze the characteristics of the wheel-throwing process exhibited by expert  
332 kick-wheel potters, we used repeated-measures ANOVAs with factors Shape (4 levels), Mass  
333 (2 levels), and Phase (2 levels), while local analyses also included the factor Bout Type (2  
334 levels, acceleration or deceleration).

335



336

337 **Fig 4. Example of rotation velocity recording over the course of fashioning.** This example  
338 is from a potter fashioning a 2.25 kg cylinder. The top panel presents rotation velocity as a  
339 function of time, revealing both the global decrease in rotation velocity as well as the alternation  
340 between local increases and decreases. The identified minima and maxima in rotation velocity  
341 are indicated by asterisks and circles, respectively. The lower panels present the local increases  
342 (acceleration bouts, middle panel) and decreases (deceleration bouts, bottom panel) in  
343 linearized form. Each line's slope corresponds to the corresponding bout's magnitude of  
344 acceleration or deceleration. For ease of comparison between bouts, deceleration is expressed  
345 in absolute values. The vertical line crossing the graphs indicates the end of Phase 1 and the  
346 beginning of Phase 2. (color for the online version)

347

348

### 349 **3. Results and discussion**

350

#### 351 **3.1. Vessel assemblages**

352

353 To quantify participants' consistency in final vessel shape produced Table 2 presents  
 354 the coefficients of variations of the final vessels' absolute dimensions, for each of the four  
 355 shapes (cylinder, bowl, sphere, and vase) and the two masses (0.75 and 2.25 kg). As expected,  
 356 the traditional context of production and the level of expertise of the participants gave rise to  
 357 highly standardized assemblages. The values of the CVs were close to the 5% reported in  
 358 previous studies with expert potters (Gandon et al., 2014a; Gandon et al., 2014b; Roux, 2003).  
 359 This result indicates that the participants succeeded in the experimental task. They produced  
 360 the experimental assemblage with a high level of standardization reflecting expert performance.

361 Table 3 presents the average maximal radius of the vessels at the end of the Phase 1  
 362 (pre-forming) and 2 (forming), for each of the eight experimental conditions. We observed that  
 363 the maximal radii at the end of phase 1 were limited and dependent on the Mass only (on the  
 364 average 4.1 and 5.8 cm, for the 0.75 and 2.25 kg vessels respectively). At the end of phase 2,  
 365 the maximal radii observed depended on both the Mass and the Shape, varying in a range of 4.7  
 366 to 15.6 cm (for the 0.75 kg cylinders and 2.25 kg bowls respectively). These results demonstrate  
 367 that the Shape parameter does not influence the centering and hollowing but only the thinning  
 368 and final shaping stages.

369

Shape	Mass (kg)	H (%)	B (%)	A (%)	MD (%)	HMD (%)
Cylinder	0.75	6.4	5.1	4.8		
	2.25	5.8	5.8	4.4		
Bowl	0.75	5.4	4.6	2.8		
	2.25	4.5	4.5	2.5		
Sphere	0.75	4.0	5.1	6.1	4.0	6.6
	2.25	6.3	4.7	6.3	1.9	7.5
Vase	0.75	4.7	6.2	6.9	4.3	8.7
	2.25	4.7	6.4	7.8	3.1	7.9

370

371 **Table 2. Coefficients of variation of the vessels' absolute dimensions.** The values correspond  
 372 to the average across the six participants. H: Height, B: Base, A: Aperture, MD: Maximal  
 373 Diameter, HMD: Height at Maximal Diameter.

374

Maximal radius (cm)								
Shape	Cylinder		Bowl		Sphere		Vase	
Mass (kg)	0.75	2.25	0.75	2.25	0.75	2.25	0.75	2.25
Phase 1	4.1 (0.3)	5.7 (0.3)	4.2 (0.3)	5.9 (0.2)	4.1(0.2)	6,0 (0.2)	4.2 (0.2)	6,0 (0.3)

<b>Phase 2</b>	4.8 (0.1)	6.7 (0.2)	10.7 (0.6)	15.6 (0.5)	7.2 (0.4)	10.7 (0.4)	7.6 (0.4)	11.4 (0.4)
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375

376 **Table 3. Maximal radius of the vessels at the end of the pre-forming and forming phases.**

377 Means and standard deviations (between parentheses) were calculated across the six  
378 participants. Phase 1: pre-forming phase; Phase 2: forming phase.

379

380

381 **3.2. Regulation of the rotation velocity: global analysis**

382

383 Figure 5 presents the average fashioning duration and the average rotation velocity as a  
384 function of Phase, Mass, and Shape. As can be seen from Fig. 5-A, Phase 1 was systematically  
385 shorter than Phase 2 (on average 29.3 and 77.1 s, respectively;  $F(1, 5) = 67.47, p < .001$ )  
386 indicating that centering and hollowing require much less time than thinning and final shaping.  
387 During both phases fashioning the 2.25 kg mass took longer than fashioning the 0.75 kg mass  
388 (on average 62.1 and 44.2 s, respectively;  $F(1, 5) = 41.08, p < .001$ ), which can be explained  
389 by the larger quantity of clay to deform. Post-hoc (Newman-Keuls) analysis of the Shape x  
390 Phase interaction ( $F(3, 15) = 40.07, p < .001$ ) indicated that Shape did not affect the duration  
391 of Phase 1. In Phase 2, the cylinder took longer to throw than the sphere and vase which in turn  
392 took longer than the bowl ( $p$ 's  $< .05$ ). Average durations were 94.5, 84.8, 85.2, and 43.8 s for  
393 the cylinder, sphere, vase and bowl respectively. We interpret this result as reflecting the  
394 different levels of familiarity participants had with the distinct shapes: the bowl is a common  
395 shape for Indian potters whereas the cylinder is less familiar.

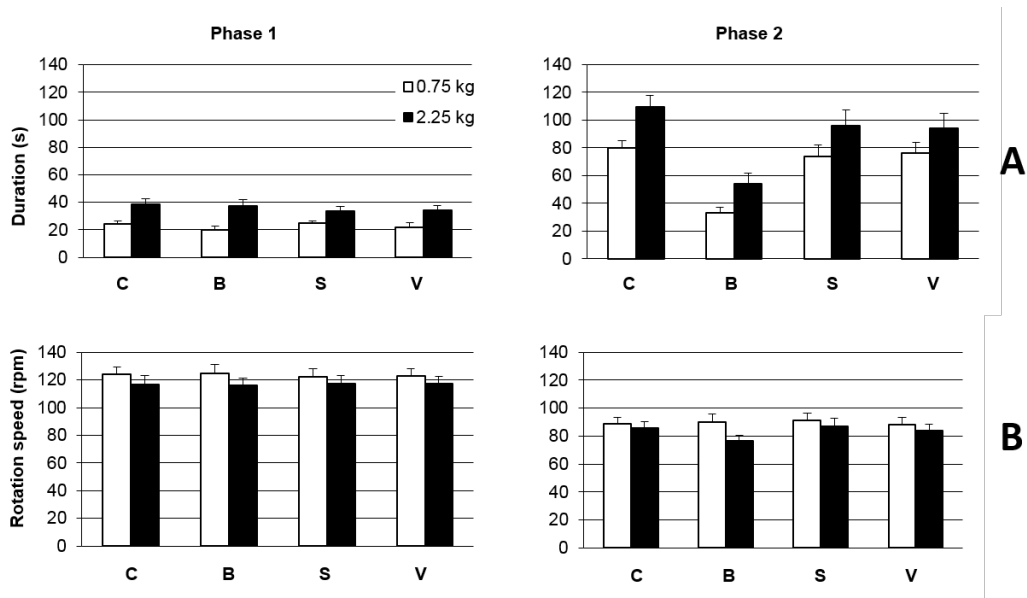
396

397 Rotation velocity (see Fig. 5-B ) was considerably lower during Phase 2 (on average  
398 86.4 rpm) than during Phase 1 (on average 120.2 rpm) ( $F(1, 5) = 271.16, p < .001$ ). This striking  
399 difference confirmed our hypothesis that the larger vessel diameters present in the forming  
400 phase induce a lower rotation velocity than the smaller vessel diameters present in the pre-  
401 forming phase, in line with the control of linear velocity. Mass systematically affected the  
402 rotation velocity ( $F(1, 5) = 73.34, p < .001$ ) during both phases, with the larger masses being  
403 thrown at slightly lower rotation velocities (on average 100.1 and 106.5 rpm for 2.25 and 0.75  
404 kg vessels respectively). This difference, although small, could also be explained by the control  
405 of the linear velocity: with larger masses inducing larger vessel diameters (in both the pre-  
406 forming and forming phases, see Table 3), a reduced rotation velocity is required for the larger



407 masses to maintain the linear velocity within a comfortable range. Another reason explaining  
 408 the lower rotation velocity for the larger masses could be that for a given amount of energy  
 409 injected by one kick, an object with a greater moment of inertia would gain a smaller increase  
 410 in rotation velocity. This would suggest that potters may be limited in the intensity of the kick  
 411 they can perform comfortably. Finally, post-hoc analysis of the Shape x Mass x Phase  
 412 interaction ( $F(3, 15) = 3.36, p < .05$ ) indicated that Shape affected rotation velocity only during  
 413 the second phase, with the 2.25 kg bowl having a smaller rotation velocity than the other 2.25  
 414 kg shapes (Fig. 5-B). This was once again coherent with the control of linear velocity which  
 415 should be limited by a decrease in the rotation velocity for the largest diameter shapes.

416



417

418 **Fig 5. Average fashioning duration and average rotation velocity as a function of Phase,**  
 419 **Mass, and Shape.** Duration in seconds (A); Average rotation velocity in rotations per minute  
 420 (B). The error bars represent the between-participants standard error. Phase 1: pre-forming phase;  
 421 Phase 2: forming phase.

422

423

### 424 3.3. Regulation of the rotation velocity: local analysis

425

426 Figure 4 shows the evolution of the rotation velocity during the throwing of a cylindrical  
 427 pot. Based on equivalent time series for all pots, Figure 6-A presents the average number of

428 acceleration and deceleration bouts as a function of Phase, Mass, and Shape. Significant main  
429 effects on the number of acceleration and deceleration bouts were found for Mass ( $F(1, 5) =$   
430  $16.31, p < .01$ ), Phase ( $F(1, 5) = 23.45, p < .01$ ), and Shape ( $F(3, 15) = 19.98, p < .01$ ). These  
431 main effects were accompanied by significant interactions between Shape x Phase ( $F(1, 5) =$   
432  $26.02, p < .001$ ) and Type x Mass x Phase ( $F(1, 5) = 8.99, p < .05$ ). Post-hoc analysis of the  
433 Shape x Phase interaction revealed that Shape did not affect the number of bouts during Phase  
434 1. During Phase 2, however, an effect of Shape came to the fore, with a larger number of both  
435 acceleration and deceleration bouts for the cylinder than for the sphere and vase ( $p$ 's  $< .05$ ).  
436 Fashioning a bowl required the smallest number of bouts ( $p$ 's  $< .05$ ). These results mirrored  
437 those observed for duration (Fig. 5-A) and revealed the same effects: centering and hollowing  
438 were performed in less time than thinning and final shaping, fashioning was longer for larger  
439 clay masses, and fashioning familiar shapes was faster than fashioning less familiar shapes.

440

441 As can be seen from Figure 6-B, the amplitude of the change in rotation velocity was  
442 systematically smaller for the acceleration bouts than for the deceleration bouts (on average  
443  $22.3$  vs.  $27.0$  rpm, respectively; main effect for Type  $F(1, 5) = 63.86, p < .001$ ), a finding  
444 consistent with the observed global decrease in rotation velocity over the course of fashioning.  
445 Significant main effects on the amplitude of change in rotation velocity were found for Phase  
446 ( $F(1, 5) = 103.90, p < .001$ ), and Shape ( $F(3, 15) = 3.57, p < .05$ ), accompanied by significant  
447 interactions between Type x Mass ( $F(1, 5) = 8.99, p < .05$ ), Type x Shape ( $F(3, 15) = 16.41, p$   
448  $< .001$ ), Shape x Phase ( $F(1, 5) = 6.60, p < .01$ ) and Mass x Phase ( $F(1, 5) = 35.17, p < .01$ ).  
449 Post-hoc analyses of this pattern of results revealed that Shape did not affect the amplitude of  
450 change in rotation velocity during Phase 1. During Phase 2, fashioning a bowl was characterized  
451 by acceleration and deceleration bouts of larger amplitudes than fashioning the other shapes  
452 ( $p$ 's  $< .05$ ), showing that the potter allowed himself a larger range of rotation velocity for this  
453 bowl shape. Fashioning the larger masses gave rise to acceleration and deceleration bouts of  
454 larger amplitude during Phase 1, while such an effect of mass was no longer observed during  
455 Phase 2. This indicates that more clay deformation was effected for larger clay masses during  
456 centering and hollowing (Phase 1), but not during thinning and final shaping (Phase 2).

457

458 Figure 6-C presents the duration of acceleration and deceleration bouts as a function of  
459 Phase, Mass, and Shape. A main effect for Type ( $F(1, 5) = 14.86, p < .01$ ) was accompanied by  
460 significant interactions between Type x Phase ( $F(1, 5) = 96.47, p < .001$ ) and Type x Shape x

461 Phase ( $F(3, 15) = 2.75, p < .05$ ). Post-hoc analysis of the overarching Type x Shape x Phase  
462 interaction revealed that deceleration bouts increased in duration from Phase 1 to Phase 2, while  
463 acceleration bouts decreased from Phase 1 to Phase 2.

464

465 The absolute values of rotation velocity acceleration and deceleration (denoted A/D),  
466 occurring during acceleration and deceleration bouts, are presented in Figure 6-D. They directly  
467 represent the forces at the origin of the changes in rotation velocity, that is, the pressure forces  
468 for the decelerations and the kicking forces for the accelerations. A significant main effect on  
469 A/D was found for Phase ( $F(1, 5) = 50.29, p < .001$ ), while significant interactions were found  
470 for Type x Mass ( $F(1, 5) = 25.36, p < .01$ ), Type x Phase ( $F(1, 5) = 92.59, p < .001$ ), and Mass  
471 x Phase ( $F(1, 5) = 43.90, p < .01$ ). Post-hoc analyses of this pattern of results revealed larger  
472 A/Ds during both acceleration and deceleration bouts for the larger masses in Phase 1  
473 (comparable to the effect observed for the amplitudes), while similar levels of A/D were  
474 observed for the two masses in Phase 2. This reveals that the mass parameter mainly affects the  
475 pressure and kicking forces during Phase 1. Although no effect of Shape reached statistical  
476 significance, we note that for the bowl the A/D during the deceleration bouts was somewhat  
477 higher than that of the three other shapes, indicating the application of larger pressure forces.

478

479 Taken together these results show that the transition between the (pre-forming) Phase 1  
480 and the (forming) Phase 2, where potters move from centering and hollowing to thinning and  
481 final shaping, is reflected in the variations in wheel rotation velocity. Interestingly, although  
482 the amplitude of rotation velocity change decreased over the fashioning process (Fig. 6-B)  
483 during both the deceleration and acceleration bouts, these decreases resulted from different  
484 origins. In Phase 2, when the rotation velocity is being reduced (Fig. 5-B), the acceleration and  
485 duration profiles (Figs. 6-D, 6-C) indicate that, during deceleration bouts, the potter exerted  
486 smaller pressure forces than in Phase 1 (Fig. 6-D), but over noticeably longer durations (Fig. 6-  
487 C). In contrast, for the acceleration bouts, the duration of the bouts noticeably decreased in  
488 Phase 2 (Fig. 6-C) and this was accompanied by a smaller reduction in acceleration than that of  
489 deceleration bouts (Fig.6-D). This increased sensitivity with which the potter exerted the  
490 pressure forces in Phase 2 is no doubt an adaptation to the increasing fragility of the thinning  
491 walls. During the forming phase the slightest sudden gesture could destroy the pot, especially  
492 during the final shaping step.

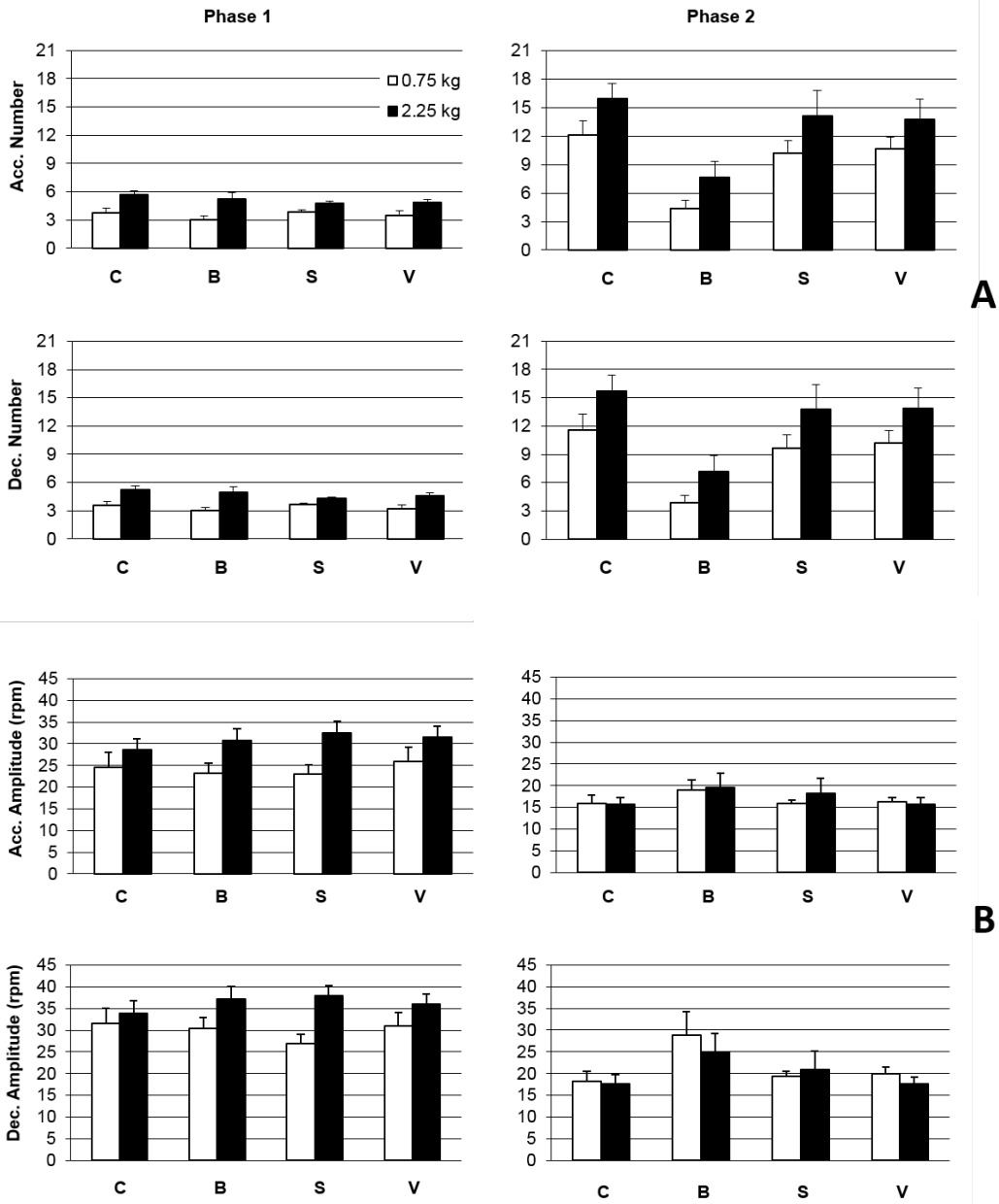
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494

**3.4. Effects of mass and shape on rotation velocity**

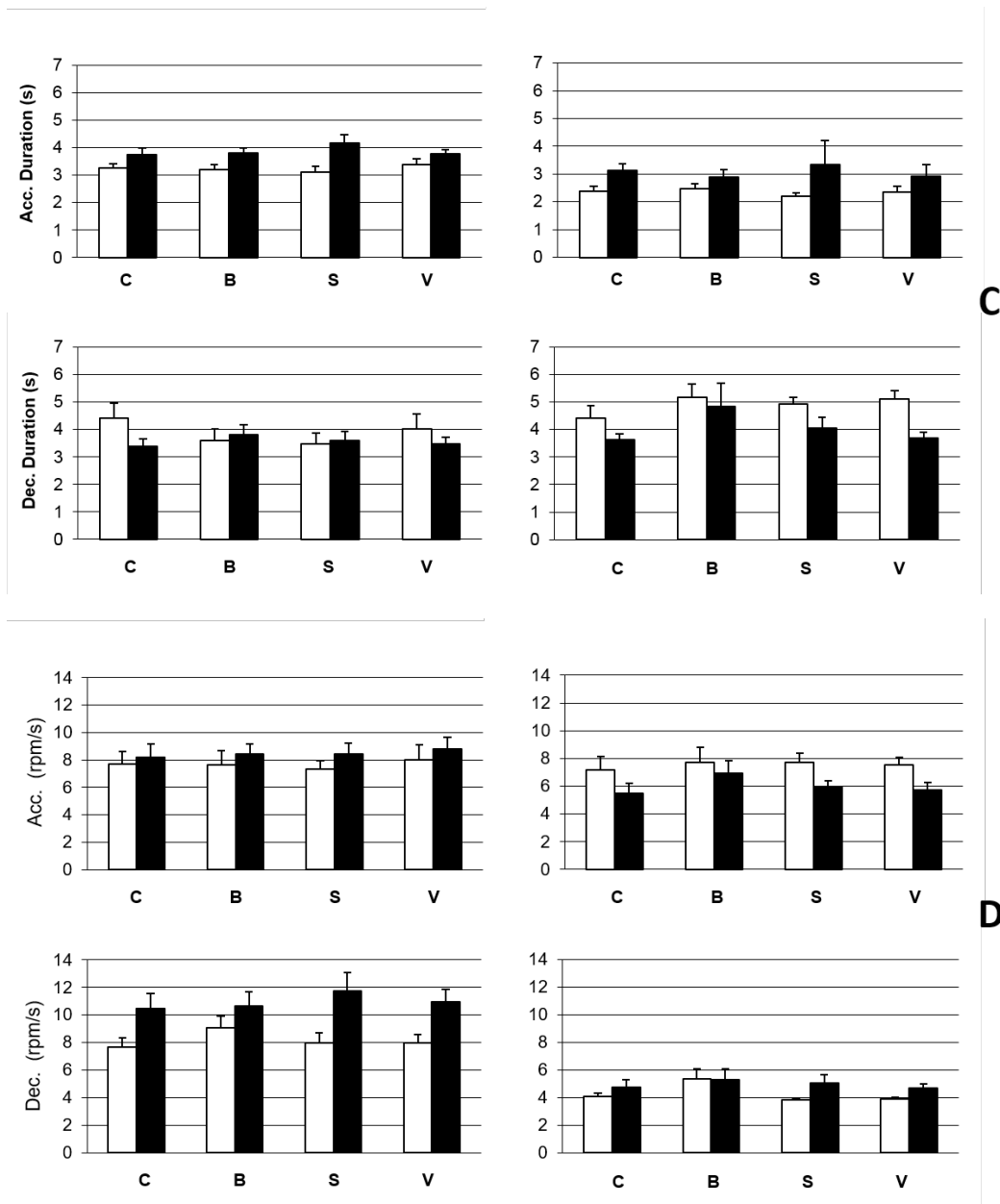
495

496 During the pre-forming phase, fashioning of larger clay masses was achieved with  
497 rotation velocity changes of larger amplitude and acceleration compared to fashioning of  
498 smaller clay masses (Figs. 6-B and 6-D). This confirms that higher manual pressure forces are  
499 required to deform the larger clay masses during the centering and hollowing steps compared  
500 to the thinning and final shaping steps where both small and larger clay masses required  
501 undifferentiated manual pressure forces. Interestingly, these larger changes in rotation velocity  
502 for the larger masses occurred when rotation velocity itself was lower (Fig. 5-B). As stated  
503 earlier, larger masses represent a larger moment of inertia of the wheel-throwing system and to  
504 set the rotation velocity at the same level for both masses would have required to supply more  
505 energy in the kicking for the large masses. Potters did increase the forces applied with each kick  
506 for larger masses as observable in the acceleration increase (Fig. 6-D) but still, they did not  
507 supply sufficient energy to rotate larger masses at the same rotation velocity as smaller masses,  
508 suggesting a limitation in the kick strength. In the forming phase while the mass has no effect  
509 on the amplitude of rotation velocity change of the acceleration bouts (Fig. 6-B), we see that  
510 larger masses undergo lower acceleration (Fig. 6-D) yet over a longer duration (Fig. 6-C). This  
511 increase of sensitivity in the kicking applied during the forming phase for larger vessels  
512 suggests that potters avoid sudden variations in linear velocity for the larger vessels: they  
513 applied longer kicks with less forces which would help to maintain a more constant linear  
514 velocity over the complete circumference of the vessel. Finally, the Shape parameter influenced  
515 the pressure and kicking forces during the forming phase: the most familiar shape (the bowl)  
516 was fashioned with fewer fashioning gestures than the other shapes (Fig. 6-A) but involved  
517 gestures with higher pressure forces (Fig. 6-D), explaining why bowl vessels were produced in  
518 less time (Fig. 5-A).



519

520



521

522

523 **Fig 6. Local characteristics of the rotation velocity as a function of Phase, Mass, and Shape**  
 524 **in Phase 1 (pre-forming) and Phase 2 (forming) during acceleration and deceleration**  
 525 **bouts.** Number of bouts (A), Amplitude of rotation velocity change expressed in rotations per  
 526 minute (B), Bout duration in seconds (C), and Acceleration/Deceleration in rotations per minute  
 527 (rpm) per second (D), for the acceleration (Acc.) and deceleration (Dec.) bouts. The error bars  
 528 represent the between-participants standard error.

529

530

531 **4. Conclusion**

532

533 In line with earlier claims, we believe that the study of technique is essential to the  
534 interpretation of ancient artefacts and tools (Lemonnier, 1986; Bleed, 2008; Dietler & Herbich,  
535 1998; Hegmon, 1998). Here, we addressed the issue of rotation velocity regulation in wheel-  
536 throwing. Long assumed to be a key parameter in the control of the centrifugal force, we  
537 interpreted its role rather as a means to control the linear velocity at the point of hand-clay  
538 contact.

539

540 We demonstrated that during fashioning potters reduced the rotation velocity from the  
541 pre-forming phase to the forming phase, but also for the large clay masses compared to the  
542 small clay masses, and during the forming phase for the shapes characterized by the largest  
543 diameter. This decrease in rotation velocity thus matched the increase of the mean vessel  
544 diameter, thereby corroborating the hypothesis that the potters were applying a limit on the  
545 linear velocity with which the clay passes the pressure-exterting hands. The fact that the  
546 standardization of the experimental productions was close to 5% revealed a high level of  
547 performance. Participants moreover always succeeded in performing the experimental task (not  
548 a single vessel collapsed), indicating that they consistently kept the linear velocity below an  
549 upper limit beyond which the fashioning process would have become uncontrollable. Overall,  
550 these preliminary results provide empirical evidence supporting the role of linear velocity as a  
551 key functional parameter in wheel-throwing. Future work using synchronized measurements of  
552 both rotation velocity and instantaneous vessel diameter at the point of hand-clay contact would  
553 allow precise modeling of the control of the linear velocity in wheel-throwing.

554

555

556 There is no reason to expect that the regulation of the linear velocity would leave any  
557 observable trace on the vessel thrown and the purpose of our study was not to help identify the  
558 wheel-throwing technique used in fashioning ancient vessels by such traces. Ceramic  
559 fashioning techniques – including wheel-throwing – can be identified in other ways, such as  
560 analysis of the surface features and microfabrics (Courty & Roux, 1995; Roux & Courty, 1998;

561 Ther & Toms, 2016). Focusing on the potter's experience, the main contribution of our results  
562 to archaeology consists in furnishing a fuller understanding of the wheel-throwing practice in  
563 which the control of linear velocity surely plays a central role. Our findings also shed some  
564 light on the complex relation between the properties of the rotation devices (size, inertia,  
565 maximal rotation velocity), the characteristics of the vessels produced (size, shape and weight),  
566 and the fashioning techniques used by the potter (wheel-finishing, wheel-shaping, and wheel-  
567 throwing).

568

569 Although the regulation of rotation velocity in wheel-throwing has been implicitly  
570 acknowledged, our work firstly brings original results concretely demonstrating how potters  
571 adapt the rotation velocity to the wheel-throwing constraints. This empirical evidence  
572 strengthens the technical distinction between wheel-throwing – where potters put the rotational  
573 motion to use throughout the fashioning process – and the other fashioning techniques (wheel-  
574 finishing and wheel-shaping) where the rotational motion is used only in certain phases..

575 Secondly, our experiment provides a reference value for the rotation velocity used in fashioning  
576 with the (fast-)wheel, a value supposedly not reached with the turntable and the slow-wheel.  
577 The striking contrast between the rotation velocities in the pre-forming and forming phases  
578 confirms that centering and hollowing require considerably more clay-deforming manual  
579 pressure forces than the thinning and final shaping operations. This leads to the conclusion that  
580 the rotation device should rotate sufficiently fast enough during the pre-forming phase for  
581 wheel-throwing to be possible, with fast enough meaning approximately 120 rpm according to  
582 our measurements (average of 123.5 and 116.8 rpm, for the 0.75 and 2.25 kg clay masses). This  
583 value of 120 rpm can thus be used as a reference to distinguish the (fast-)wheel from the other  
584 devices (turntable and slow-wheel). If an ancient rotation device has a maximal rotation velocity  
585 of 100 rpm, it has more likely been used for wheel-finishing or wheel-shaping than for wheel-  
586 throwing. Corollarily, if ancient vessels are identified as having been thrown, they have quite  
587 certainly been manufactured with a (fast-)wheel allowing a rotation velocity of 120 rpm to be  
588 reached. Importantly, archaeologists should bear in mind that the rotation velocity used in  
589 wheel-throwing could vary with the clay hardness and mass. Experiments to test the effects of  
590 these parameters remain to be done. Nevertheless, in the meanwhile the value of 120 rpm can  
591 serve as a useful reference.

592 Thirdly, the fact that the large-diameter vessels were fashioned with a lower rotation velocity  
593 than small-diameter vessels corroborates recent observations we made in the Hebron (Palestine)



594 pottery-making community where potters use electrical low-velocity wheels for the larger  
595 vessels (above 20-30 cm high) and electrical high-velocity wheels for small and middle-sized  
596 vessels. As demonstrated by our study, large vessels require a reduced rotation velocity to limit  
597 the linear velocity at hand-clay contact. Moreover, the acceleration bouts results suggested that,  
598 during the forming phase, potters avoided sudden variations in linear velocity for the larger  
599 vessels by applying longer kicks. Therefore, we postulate that (fast-)wheels with low-velocity  
600 and high-inertia may be more appropriate for throwing large vessels. A low velocity will  
601 facilitate the limitation of the linear velocity, and a high inertia will allow the deceleration to  
602 be reduced, providing regularity in the application of the pressure forces over the complete  
603 circumference of the vessel, which is particularly important during the forming phase. We may  
604 thus suggest that ancient large thrown vessels were produced with low-velocity and high-inertia  
605 (fast-)wheels, a hypothesis to be further corroborated by studies including different variants of  
606 potter's wheels. For small-diameter vessels, a reduced rotation velocity is not necessary to limit  
607 the linear velocity. As demonstrated by the present results and also observed in the Hebron  
608 pottery community, small and middle-sized vessels are thrown with a higher rotation velocity  
609 than that used for large vessels. A high rotation velocity can be obtained in an equivalent manner  
610 with both high- and low-inertia (fast-)wheels (see legend of Fig. 2), indicating that ancient small  
611 and middle-sized thrown vessels could have been produced with both types of human effort-  
612 driven wheels.

613 Finally, the assessment of the deceleration bouts revealed that participants finely tuned  
614 their manual pressure forces to the precision requirement of the task, with thinner walls (during  
615 the forming phase) being fashioned more sensitively than thicker walls (during the pre-forming  
616 phase). This adaptation to the operative task constraints is a characteristic of motor skill  
617 expertise (Bernstein, 1967; Bril et al., 2010) and explains why experts can not only produce  
618 high-quality artifacts, but can also reliably reproduce the same artifact, that is, produce  
619 standardized assemblages (Table 2). Novice potters certainly need extensive training before  
620 mastering this fine sensitivity of the manual pressure forces exerted during the forming phase.  
621 Our results also indicated that shape familiarity influenced the fashioning behavior of the  
622 participants who exerted larger forces over longer intervals for the bowl. This suggests that,  
623 even when potters are experts, their ability to adjust the pressure forces to the task constraints  
624 becomes more assured for the vessel shapes produced more frequently.

625  
626

627 We believe that this type of research plays a crucial role in the production of empirical  
628 data on the motor skill of craftsmen and provides results that offer insights into archaeological  
629 problems. For future research, it would be interesting to compare different types of wheels that  
630 afford distinct levels of precision in terms of rotation velocity regulation. In our study, it would  
631 have been interesting to experiment with the two types of wheels used in the Indian cultural  
632 area, the stick-wheel and the kick-wheel corresponding respectively to high- and low-inertia  
633 (Fig. 2). Unfortunately, the high-inertia stick-wheel constantly changes its horizontal  
634 orientation (like a spinning top), precluding a reliable recording of the rotation velocity using  
635 our experimental protocol. This could be overcome by methodological developments. The high-  
636 inertia stick-wheel, contrary to the kick-wheel, retains a fast rotation velocity for a long period  
637 of time once it has been activated by the potter. With this kind of wheel, potters therefore cannot  
638 easily control the rotation velocity as they do with the low-inertia kick-wheel (Roux & Jeffra,  
639 2015). Potters would thus be forced to compensate the lesser degree of velocity regulation by a  
640 still finer tuning of their manual pressures, which would increase the difficulty in the fashioning.  
641 One might then expect a longer apprenticeship and perhaps a limitation both in the complexity  
642 of the shapes produced and in the thinness of the walls achieved. These possibilities represent  
643 new avenues of research in the endeavor to understand wheel-throwing fashioning technique.

644

645

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647

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650

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652

653

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655

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