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Abstract

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

Key words: pottery wheel-throwing, potter's wheel, rotation velocity, linear velocity, motor skill, expertise, field experiment, low-inertia kick-wheel

1. Introduction

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

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

Across cultures and time, wheel-throwing has been practiced with different kinds of wheels (often referred to as fast-wheels) that vary in the ways they are activated (Rice, 1987). While variations in rotation velocity in the wheel-throwing process have been noted and the need for regularity has been been underscored (RJB: DO YOU HAVE A REF?), to date the regulation of the rotation velocity over the entire wheel-throwing process has not been described for any kind of wheel. This is quite surprising, given that such rotation velocity regulation constitutes the technical trait distinguishing wheel-throwing using the (fast-) wheel from wheel-finishing and wheel-shaping using the turntable and the slow-wheel. The present study provides a first step to fillling this gap, so as to allow archaeologists to better understand how ancient rotation devices may have been used. Identifying how potters operated the (fast-)wheel will also shed some light on the complex relation existing between the properties of the rotation devices (size, inertia, maximal rotation velocity), the vessels characteristics (size, shape and weight), and the fashioning techniques used by the potter (wheel-finishing, wheel-shaping, and wheel-throwing) (Roux & Miroschedji, 2009; Roux & Jeffra, 2015; Ther et al., 2017).

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

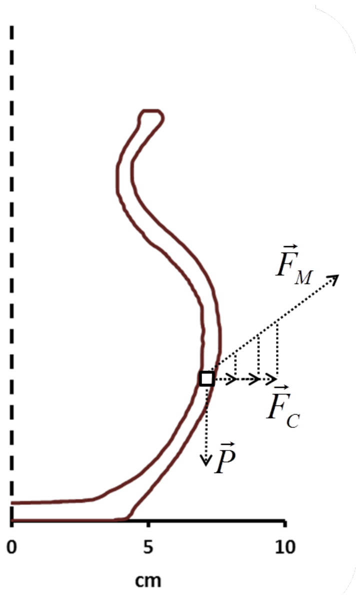


Fig 1. The forces applied over the clay surface during wheel throwing. $\vec{F}_M$: the manual pressure force exerted by the potter, $\vec{P}$: the weight of the clay, $\vec{F}_C$: the weight of the clay. The pressure forces exerted by the potter can be resolved into vertical, radial and tangential components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

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

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

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

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

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

2. Materials and methods

2.1. Experimental setting

Six professional potters gave their written consent to participate in the field experiment. The participants (right-handed men) were all over 25 years old (31.3 ± 4.5 yrs) and had a minimum of ten years of wheel-throwing experience (16.5 ± 6.4 yrs). They all originated from the village of Jahanjirabad (Uttar Pradesh, India) and belong to the Multani-Khumar community. In India, the wheel-pottery handicraft is learned within endogamous castes which throw standardized traditional objects at high production rates (Kramer, 1997; Roux & Corbetta, 1989; Saraswati & Behura, 1964). The experiment took place in a traditional pottery workshop in the participants' village. All fashioning was performed on the same low-inertia kick-wheel (Fig. 2, bottom panel) using soft red clay (1.7 kg/cm² indentation hardness). Participants were asked to reproduce four different model shapes using two different quantities of clay, leading to a total of eight experimental conditions (Table 1). To assess the reproducibility of behavior, five specimens were produced in each of the eight experimental conditions, so that each potter produced a total of 40 pots. The shapes (referred to as cylinder, bowl, sphere and vase) were presented as drawings without providing indication of absolute size to be produced. The quantity of clay provided for each trial corresponded to a mass of either 0.75 kg or 2.25 kg. The participants were instructed to accurately reproduce the proportions of the models, to throw vessels with the thinnest walls possible, and to refrain from embellishment operations at the end of the fashioning. No tools were used but a basin of water to wet the clay. Potters produced the 40 vessels working at their own pace. The experimenter was present during the experimental task to monitor progress and ensure procedural consistency. Participants freely practiced the task one day before the experiment. Data acquisition relied on non-invasive methods detailed in the following sections (Fig. 3).

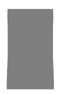
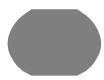
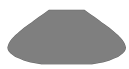
Shape	Cylinder		Bowl		Sphere		Vase	
2D drawing								
Mass of clay (kg)	0.75	2.25	0.75	2.25	0.75	2.25	0.75	2.25

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

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

2.2. Data acquisition and analysis

2.2.1. Vessel assemblages

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

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

2.2.2. Rotation velocity

Wheel rotation velocity was measured by means of a magnet fixed to the lower side of the kick-wheel's rotating plateau and a magnetic sensor (NI USB-6008, National Instruments) attached to the wooden support structure. The magnetic field sampling was performed at 100 Hz, with a measure of rotation velocity thus being available after each full turn of the wheel. Acquisition of rotation velocity was synchronized with video recordings of the potter's fashioning behavior (Panasonic NV-GS320) allowing the start and end points of the two phases of the wheel-throwing to be identified (Fig. 3). We focused on fashioning durations and rotation velocities during the pre-forming phase (Phase 1) and the forming phase (Phase 2).

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

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

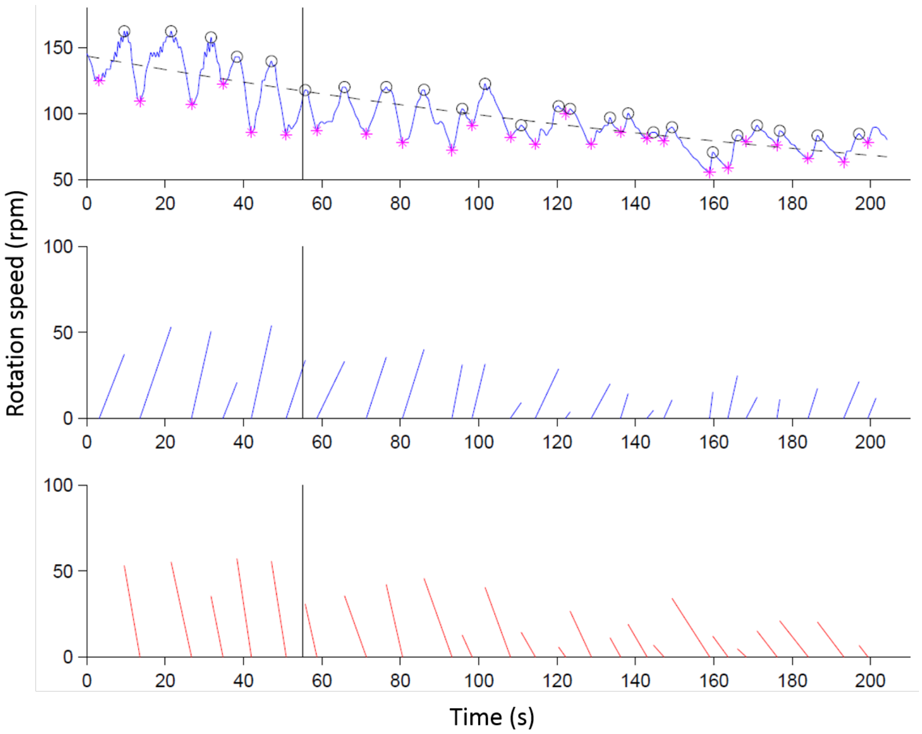


Fig 4. Example of rotation velocity recording over the course of fashioning. This example is from a potter fashioning a 2.25 kg cylinder. The top panel presents rotation velocity as a function of time, revealing both the global decrease in rotation velocity as well as the alternation between local increases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

3. Results and discussion

3.1. Vessel assemblages

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

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

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*

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

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)

Phase 2	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)

Table 3. Maximal radius of the vessels at the end of the pre-forming and forming phases. Means and standard deviations (between parentheses) were calculated across the six participants. Phase 1: pre-forming phase; Phase 2: forming phase.

3.2. Regulation of the rotation velocity: global analysis

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

Rotation velocity (see Fig. 5-B) was considerably lower during Phase 2 (on average 86.4 rpm) than during Phase 1 (on average 120.2 rpm) ($F(1, 5) = 271.16$, $p < .001$). This striking difference confirmed our hypothesis that the larger vessel diameters present in the forming phase induce a lower rotation velocity than the smaller vessel diameters present in the pre-forming phase, in line with the control of linear velocity. Mass systematically affected the rotation velocity ($F(1, 5) = 73.34$, $p < .001$) during both phases, with the larger masses being thrown at slightly lower rotation velocities (on average 100.1 and 106.5 rpm for 2.25 and 0.75 kg vessels respectively). This difference, although small, could also be explained by the control of the linear velocity: with larger masses inducing larger vessel diameters (in both the pre-forming and forming phases, see Table 3), a reduced rotation velocity is required for the larger masses to maintain the linear velocity within a comfortable range. Another reason explaining the lower rotation velocity for the larger masses could be that for a given amount of energy injected by one kick, an object with a greater moment of inertia would gain a smaller increase in rotation velocity. This would suggest that potters may be limited in the intensity of the kick they can perform comfortably. Finally, post-hoc analysis of the Shape x Mass x Phase interaction ($F(3, 15) = 3.36$, $p < .05$) indicated that Shape affected rotation velocity only during the second phase, with the 2.25 kg bowl having a smaller rotation velocity than the other 2.25 kg shapes (Fig. 5-B). This was once again coherent with the control of linear velocity which should be limited by a decrease in the rotation velocity for the largest diameter shapes.

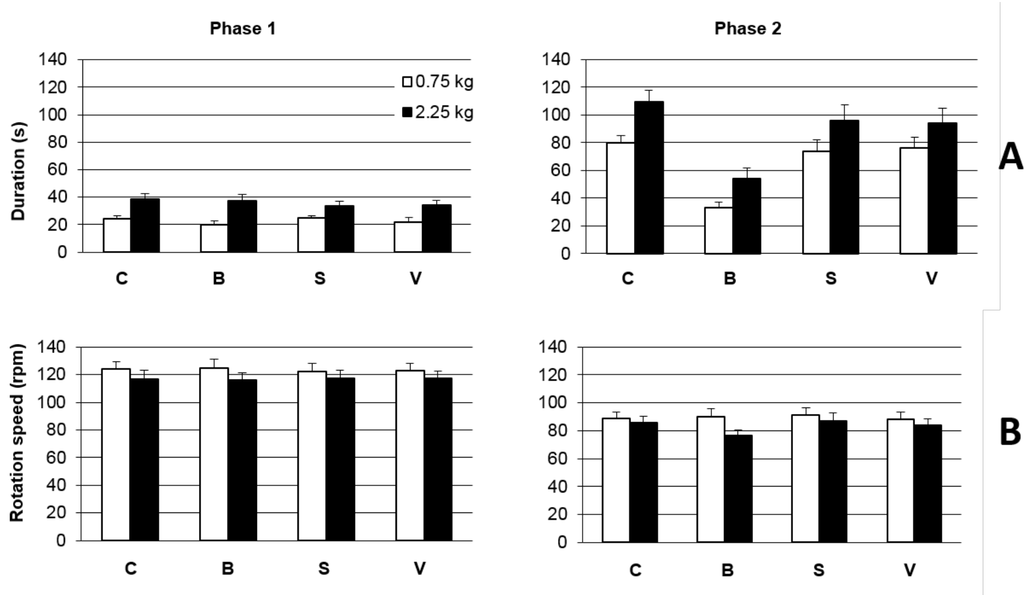


Fig 5. Average fashioning duration and average rotation velocity as a function of Phase, Mass, and Shape. Duration in seconds (A); Average rotation velocity in rotations per minute (B). The error bars represent the between-participants standard error. Phase 1: pre-forming phase; Phase 2: forming phase.

3.3. Regulation of the rotation velocity: local analysis

Figure 4 shows the evolution of the rotation velocity during the throwing of a cylindrical pot. Based on equivalent time series for all pots, Figure 6-A presents the average number of acceleration and deceleration bouts as a function of Phase, Mass, and Shape. Significant main effects on the number of acceleration and deceleration bouts were found for Mass ($F(1, 5) = 16.31$, $p < .01$), Phase ($F(1, 5) = 23.45$, $p < .01$), and Shape ($F(3, 15) = 19.98$, $p < .01$). These main effects were accompanied by significant interactions between Shape x Phase ($F(1, 5) = 26.02$, $p < .001$) and Type x Mass x Phase ($F(1, 5) = 8.99$, $p < .05$). Post-hoc analysis of the Shape x Phase interaction revealed that Shape did not affect the number of bouts during Phase 1. During Phase 2, however, an effect of Shape came to the fore, with a larger number of both acceleration and deceleration bouts for the cylinder than for the sphere and vase (p's $< .05$). Fashioning a bowl required the smallest number of bouts (p's $< .05$). These results mirrored those observed for duration (Fig. 5-A) and revealed the same effects: centering and hollowing were performed in less time than thinning and final shaping, fashioning was longer for larger clay masses, and fashioning familiar shapes was faster than fashioning less familiar shapes.

As can be seen from Figure 6-B, the amplitude of the change in rotation velocity was systematically smaller for the acceleration bouts than for the deceleration bouts (on average 22.3 vs. 27.0 rpm, respectively; main effect for Type $F(1, 5) = 63.86$, $p < .001$), a finding consistent with the observed global decrease in rotation velocity over the course of fashioning. Significant main effects on the amplitude of change in rotation velocity were found for Phase ($F(1, 5) = 103.90$, $p < .001$), and Shape ($F(3, 15) = 3.57$, $p < .05$), accompanied by significant interactions between Type x Mass ($F(1, 5) = 8.99$, $p < .05$), Type x Shape ($F(3, 15) = 16.41$, $p < .001$), Shape x Phase ($F(1, 5) = 6.60$, $p < .0.01$) and Mass x Phase ($F(1, 5) = 35.17$, $p < .01$). Post-hoc analyses of this pattern of results revealed that Shape did not affect the amplitude of change in rotation velocity during Phase 1. During Phase 2, fashioning a bowl was characterized by acceleration and deceleration bouts of larger amplitudes than fashioning the other shapes (p's $< .05$), showing that the potter allowed himself a larger range of rotation velocity for this bowl shape. Fashioning the larger masses gave rise to acceleration and deceleration bouts of larger amplitude during Phase 1, while such an effect of mass was no longer observed during Phase 2. This indicates that more clay deformation was effected for larger clay masses during centering and hollowing (Phase 1), but not during thinning and final shaping (Phase 2).

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

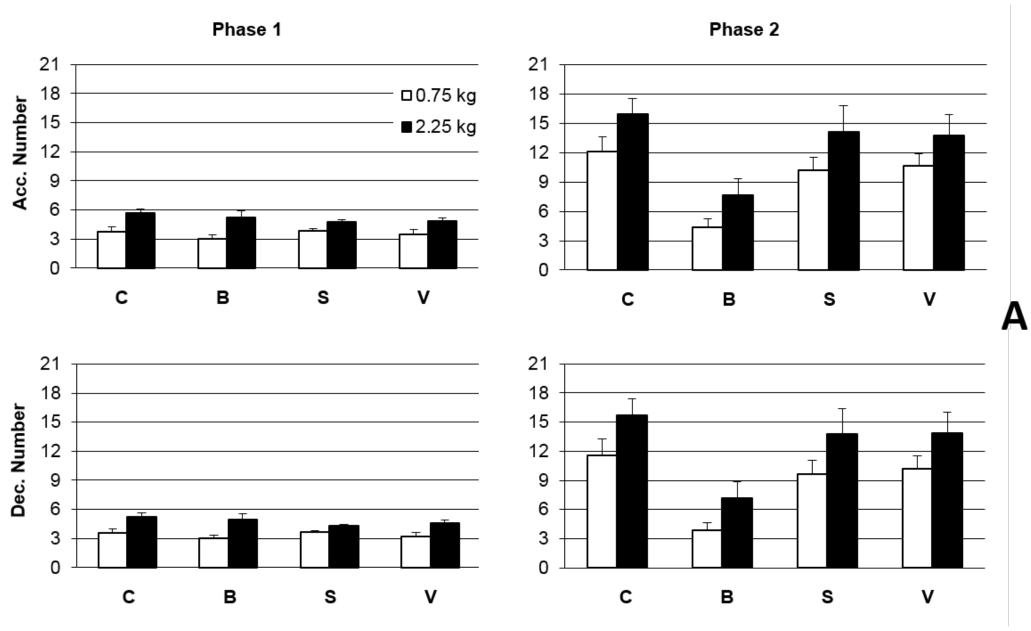
Phase ($F(3, 15) = 2.75$, $p < .05$). Post-hoc analysis of the overarching Type x Shape x Phase interaction revealed that deceleration bouts increased in duration from Phase 1 to Phase 2, while acceleration bouts decreased from Phase 1 to Phase 2.

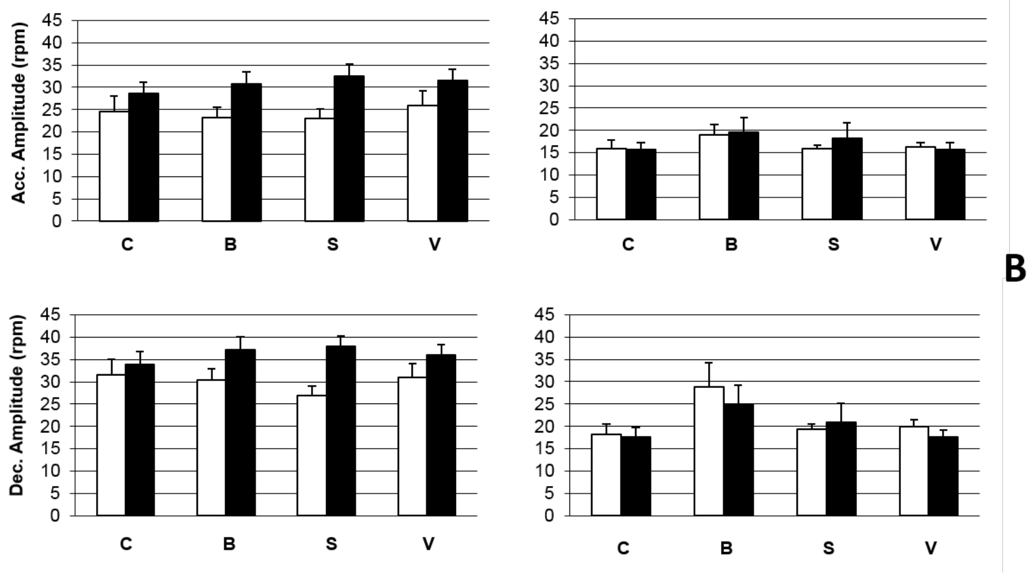
The absolute values of rotation velocity acceleration and deceleration (denoted A/D), occurring during acceleration and deceleration bouts, are presented in Figure 6-D. They directly represent the forces at the origin of the changes in rotation velocity, that is, the pressure forces for the decelerations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

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

3.4. Effects of mass and shape on rotation velocity

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


Phase 1
Phase 2
Acc. Number
Dec. Number
0.75 kg
2.25 kg
C
B
S
V
A


Acc. Amplitude (rpm)
Dec. Amplitude (rpm)
C
B
S
V
B

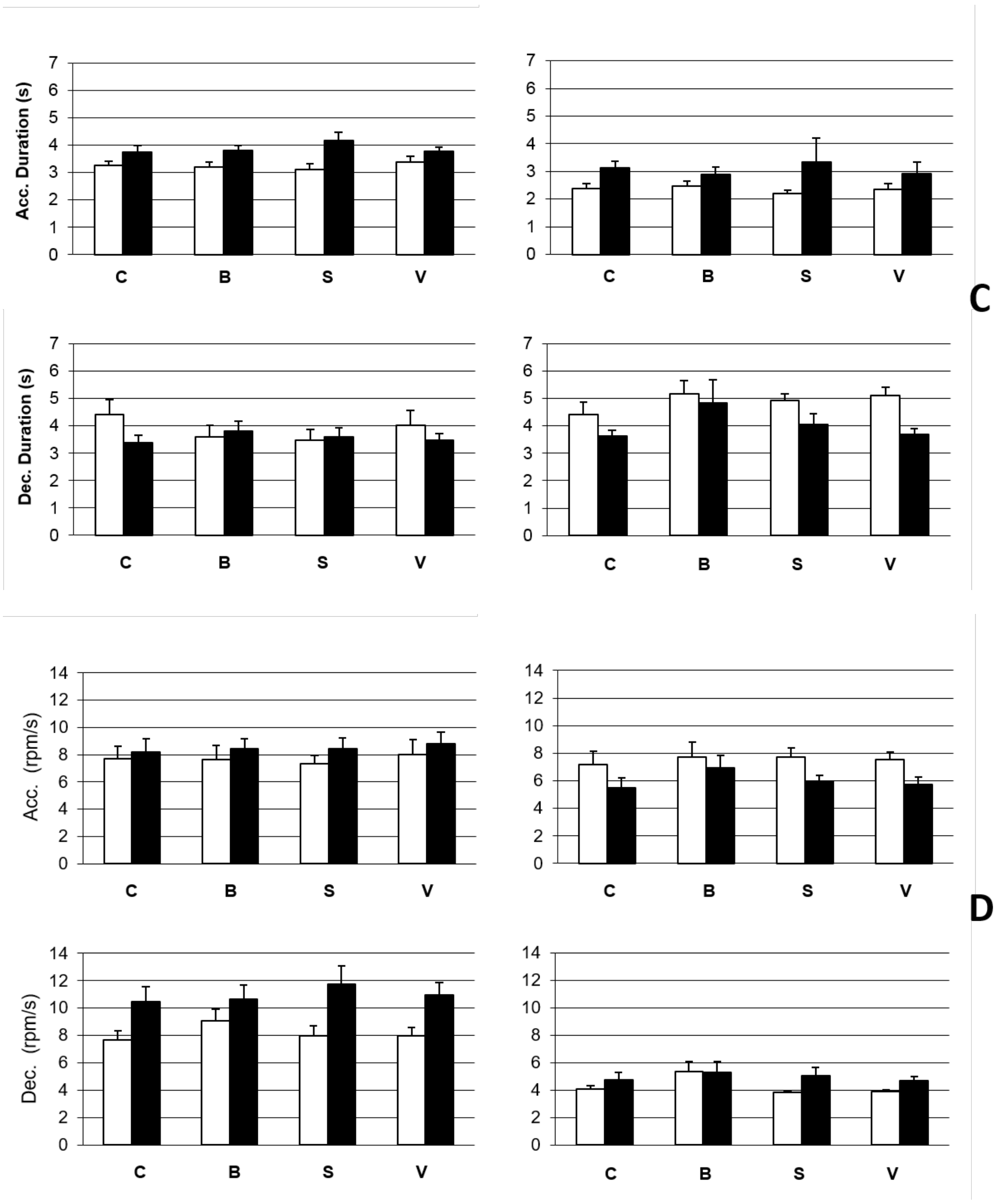


Fig 6. Local characteristics of the rotation velocity as a function of Phase, Mass, and Shape in Phase 1 (pre-forming) and Phase 2 (forming) during acceleration and deceleration bouts. Number of bouts (A), Amplitude of rotation velocity change expressed in rotations per minute (B), Bout duration in seconds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

4. Conclusion

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

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

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

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

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

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

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

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

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

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