




Stone tool shaping without direct cultural transmission

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ABSTRACT

While environment and biology play important roles, the complexity and variability of human life today depends in many ways on special cultural processes. Terminologies differ, but the key insight is that these processes are required to enable and to produce copies of behavior or artifacts that otherwise lie fully or partly beyond individual reach. Such “know-how copying” has proven rare in the animal kingdom, and is nearly or fully absent in contemporary apes, suggesting an evolution in hominins. It has been claimed that the earliest widely accepted instances of shaped stone artifacts – handaxes, which appear with the Acheulean (c. 1.9–1.6 Mya) – must have required know-how copying. The argument holds that the knowledge of how to shape (shaping know-how) handaxes is beyond individual reach in principle. If true, handaxes would be a valid marker for the presence of know-how copying. We tested this specific claim in two complementary studies using the “puppet method,” a new methodology that experimentally disentangles knapping know-how and shaping know-how. Knapping-naïve “puppeteers” were tasked with replicating target shapes by directing the flake removals of an expert “puppet” knapper, who was not shown the target shapes. As a validation of the puppet method, we first tested if knapping-naïve puppeteers could shape glass blanks into novel, non-archaeological shapes (Arbitrary Shape Study). Two types of analyses, a sorting task and geometric morphometric analyses, confirmed that they could. We then tested whether knapping-naïve puppeteers could replicate an Acheulean handaxe target shape in stone by directing the puppet knapper (Handaxe Study). Three expert lithic archaeologists independently classified the outcomes and confirmed that naïve participants successfully created handaxe shapes. Across both studies, our findings indicate that not all shaping know-how requires direct access to cultural models, and this also holds true for handaxe shaping *per se*. This conclusion aligns with recent calls for a reorientation in the search for the origins of know-how copying in the hominin lineage.

1. Introduction

Among all living species, human culture is likely unique in being

open-ended across behavioral domains (see Borg et al., 2024; Tennie et al., 2018), in which, over generations, it can cumulate and combine to supra-individual levels in an ongoing evolutionary process (compare

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Boyd and Richerson, 1996; Tennie et al., 2009; Tomasello, 1999). While the interdependent complexities of environment and biology play important and sometimes necessary roles, many human behaviors and artifacts depend, wholly or partly and directly or indirectly (Moore and Tennie, 2025), on special cultural transmission processes. Such cultural products – from skyscrapers to speaking Somali to salsa dancing – can be considered “culture-dependent” (Reindl et al., 2017) in that they cannot be invented *de novo* by a lone individual, culturally unconnected from these traits. Rather, culture-dependent traits depend upon 1) prior cultural evolution to help produce the traits (including their precursor(s)), 2) cultural access to these evolved traits, and, importantly, 3) the ability to copy these evolved traits or their precursor(s) (Boyd and Richerson, 1996; Clay and Tennie, 2018; Tennie et al., 2009; Tomasello, 1999). When these conditions coincide, not only does culture evolve, but the copiers themselves are ontogenetically changed – as noted already by Vygotsky (1978; compare Bender et al., 2024, Reindl et al., 2018) – in a process of biocultural co-evolution.

In comparative culture research, culture is broadly defined (Mesoudi, 2011): culture is a product rooted in processes of social learning. Types of culture vary, and are determined by the types of information that are affected by social learning. There can be cultures around know-what (e.g., what to eat, what raw material to use for a tool), know-where (e.g., where food or raw materials are), etc. Any type of social learning can also happen in the negative form: e.g., social learning of know-what *not* to eat (e.g., this mushroom). Finally, models may or may not be actively fostering social learning. If they are, the label “teaching” is added (compare Caro and Hauser, 1992), e.g., teaching of know-what to eat (compare Hoppitt et al., 2008). Yet, it is the production of copies of know-how – copying how others act, speak, build things – that enables and maintains much of human culture today (Boyd and Richerson, 1996; Tennie et al., 2009; Tomasello, 1999). “Know-how copying” applies when a specific occurrence of know-how is copied, in such a way that the observer’s know-how is and has to be causally linked to the model’s know-how, specifically (Buskell and Tennie, 2025). Know-how copying can occur via multiple social learning mechanisms, including, for example, teaching of know-how. But importantly, instances of such copying-dependent know-how can also be dependent on know-how copying in indirect ways – e.g., where there is a dependence on language, as language in turn depends on know-how copying (Moore and Tennie, 2025). Some of contemporary humans’ social learning abilities themselves may be products of bio-cultural co-evolution (compare Heyes, 2018) – including know-how copying (Andersson and Tennie, 2023; Enquist et al., 2023; Tennie, 2019).

Know-how copying is exceedingly rare in the animal kingdom, however. It occurs most frequently in one behavioral domain – the vocal domain. But even there, it remains rare – humpback whale song being one of best-supported cases, because they are unstable and show signs of rapid cultural change (Garland et al., 2017). Directly and indirectly, the relative lack of know-how copying among animals imposes major limits on the cultural evolution of animal know-how, as well as on the bio-cultural co-evolution and open-endedness of animal cultures. Animal know-how derives mainly from individual – as opposed to social – learning, although the social learning of other types of information can and often does catalyze and regulate the frequency of know-how development (compare Tennie et al., 2009; Tennie et al., 2020a). Cultural evolution in animals – in the rare cases where it exists – relates mainly to types of information other than know-how (e.g., pigeons socially learning where to fly to (Sasaki and Biro, 2017); orangutans socially learning their substantial know-what-to-eat repertoire (Howard-Spink et al., 2025)). These patterns raise the key question of when the open-ended, domain-general cultural evolution of know-how began in our lineage.

The problem requires triangulation and the comparative approach. Turning to apes, even in the tool domain (our focus here), very few candidates for copying-dependent know-how remain, since most ape know-how has proven reinventable by naïve individuals without

cultural access to know-how models (Gunasekaram et al., 2024; Tennie, et al., 2009, 2020a). Thus, at least in most cases, apes do not actually have to copy their tool know-how, which fits with the robust finding that, at most, they rarely copy tool know-how (Bandini et al., 2021b; Tennie et al., 2020b). This pattern is consistent with findings in non-tool behavioral domains, where apes also lack a need for know-how copying (e.g., little to no know-how copying in the ape vocal domain (Janik and Knörnschild, 2021) as well as the ape gestural domain (Byrne et al., 2017)). And so, ape tool cultures exist under a broad definition of culture, yet the underlying social learning types are different, acting more like know-how catalysts (Sterelny and Hiscock, 2024; Tennie, et al., 2009, 2020a). In this way, they merely regulate the frequency of ape tool behavioral know-how reinvention (e.g., by socially providing information on the whereabouts and types of raw materials) but they do not directly make copies of know-how (Bandini et al., 2021b; Tennie, et al., 2009, 2020a). It then follows that the key capacity of copying *copying-dependent* know-how (henceforth: know-how copying) most likely arose in the hominin lineage *after* our last common ancestor with chimpanzees, our closest living relatives, i.e., after 6.5–9.3 Mya (Moorjani et al., 2016).

Stone tools, along with cut-marked bones, represent our main window into millions of years of hominin behavior, and may therefore offer clues into human culture’s origins. A key concept here in archaeology is the emergence of “imposed form” in stone artifacts (Mellars, 1989) – that is, the ability to shape stone by knapping (henceforth: shaping). Shaping requires 1) *knapping know-how* (Bamforth and Finlay, 2008; Moore, 2019; Pargeter et al., 2020) or *savoir faire* (Pelegrin, 1991, 1993): the perceptual-motor skills to predictably produce individual flakes and 2) knapping knowledge (Bamforth and Finlay, 2008; Moore, 2019; Pargeter et al., 2020) or *connaissance* (Pelegrin, 1991, 1993): the ability to strategically organize removals to produce the intended shape – what we call here: *shaping know-how*. When a specific artifact shape was copied, shaping also entails shape know-how copying (also known as end-state emulation; see e.g., Reindl et al., 2017).

Importantly, evidence for knapping know-how, shaping know-how and/or shape know-how does not in itself speak to their sources. Each may be partially or fully dependent on know-how copying – directly and/or indirectly – or may be derived in other, complex ways. Only when know-how copying is truly necessary for a particular behavior can know-how copying be inferred from the presence of that specific type of know-how. Conversely, when know-how copying is not necessary, know-how copying cannot be inferred from the mere occurrence of that know-how (Buskell and Tennie, 2025). To determine if direct know-how copying is necessary in any particular case (“target” know-how), motivated subjects who lack past or present models of the target know-how (i.e., naïve subjects) are tested (Tennie and Hedwig, 2009). If such subjects produce the target know-how on their own, then logically it does not require direct know-how copying – it does not require know-how models. Its mere presence (e.g., in the archaeological record) would subsequently become unable to clearly pinpoint such underlying know-how copying. These tests have been performed on the earliest knapping know-how (Snyder et al., 2022; Westergaard and Suomi, 1995; see also Masi et al., 2022; Motes-Rodrigo et al., 2022) and on early shape know-how (Moore and Perston, 2016; Toth, 1985), but not yet on the earliest *shaping* know-how.

In the archaeological record, the first occurrence of both shape know-how and shaping know-how is widely attributed to Acheulean handaxes. These artifacts appear during the Acheulean, beginning around 1.9–1.6 Mya in eastern Africa (Beyene et al., 2013; Diez-Martín et al., 2015; Lepre et al., 2011; Mussi et al., 2023; Semaw et al., 2020). Handaxes are relatively large, bifacially reduced stone artifacts that are, on average, almond-like in shape (de la Torre, 2016; Wynn, 1995). To produce Acheulean handaxes, hominins had to know what types of stone could be knapped and select cobbles or produce large flake blanks from these materials suitable for handaxe production (Sharon, 2010; Stout et al., 2025). To intentionally shape the blank, the hominins would then

have had to apply shaping know-how to impose the handaxe shape onto the blank via a sequence of flake removals. Each flake removal, in turn, would entail the application of knapping know-how: knowledge of how to identify suitable platforms combined with the perceptual-motor skills to remove an intended flake with a hammerstone by sufficiently and simultaneously controlling multiple factors, including force, angle of blow (Li et al., 2023) and platform depth.

The handaxe shape is often described as being “intentionally imposed”, i.e., shaped (e.g., García-Medrano et al., 2019; Hosfield et al., 2018; Pelegrin and Roche, 2017; Roche and Texier, 1990; Sharon et al., 2011; Shipton and Clarkson, 2015; Shipton et al., 2019; Shipton and White, 2020; Wynn, 1995; Wynn and Gowlett, 2018): “For the first time a preconceived form was imposed on the stone being flaked [...] rather than allowing a form to emerge via the process of manufacture” (McNabb, 2020, p. 2). Moreover, handaxe shape know-how is often understood as having been copied: “because the handaxe shape appears not to have been determined by its function, its raw material or a flaking procedure, then this idea must have been transferred from one individual to another,” making the handaxe shape “a true cultural category” (Wynn, 1995, pp. 12, 19). Handaxes were geographically widespread and were produced for well over a million years. Over the course of the Acheulean in some regions, trends towards greater standardization, regularity and refinement of some handaxe shapes have been reported (Beyene et al., 2013; Herzlinger et al., 2021; Iovita et al., 2017; Saragusti et al., 1998; Shipton and White, 2020). Overall, however, the stability and persistence of handaxe shapes in the archaeological record is taken by many as evidence that handaxe shaping know-how must have been directly transmitted via a variety of proposed social learning mechanisms, including imitation, overimitation and special types of teaching – all variants of what we call, here, know-how copying (Chazan, 2012; Gärdenfors and Högberg, 2017; Goren-Inbar, 2011; Högberg et al., 2015; Hosfield et al., 2018; Key, 2023; Lycett and von Cramon-Taubadel, 2008; McNabb, 2020; Mithen, 1999; Morgan et al., 2015; Shipton et al., 2009; Shipton, 2010; Shipton and Nielsen, 2015; Shipton and Nielsen, 2018; Shipton, 2019; Shipton, 2020; Wynn, 1995). Shipton (2019), for example, argues, “The maintenance of finished tool forms, and the various manufacturing methods underpinning their creation in different rock types, requires high-fidelity imitation” (p. 335). Shaping handaxes is considered to be very difficult for contemporary knappers to learn without copying from models (Shipton and Nielsen, 2018) and is said to be too complex for an individual to reinvent, as it involves complex, hierarchically organized manufacturing sequences (McNabb, 2020; Shipton and Nielsen, 2015). Importantly, it has been claimed that handaxe shaping know-how must have been copied already at the beginning of the Acheulean (e.g., Gärdenfors and Högberg, 2017; Högberg et al., 2015; Key, 2023; Morgan et al., 2015). In sum, the literature on the Acheulean clearly contains the idea that the presence of handaxes can be used to infer the direct copying of both shaping know-how and shape know-how among the hominins that produced them.

Challenging these assumptions, others have argued that neither shape know-how nor shaping know-how copying are required to explain the persistence of handaxe shapes during the Acheulean, particularly in the case of early handaxes. From a cultural evolutionary perspective, the nature and pace of change during the Acheulean is not well compatible with direct cultural transmission of know-how, which implies accelerated evolution and diversification (Richerson and Boyd, 2005). Alternative explanations for the stability and persistence of handaxe shapes exist. The behaviors underlying the production of handaxes may have come to be partially under genetic control, potentially via the Baldwin Effect (Corbey et al., 2016; Corbey, 2020). More generally, handaxe production may have been within individual reach of their hominin makers in principle (Tennie, et al., 2016, 2017) (see also Supplemental Section 7). Some have suggested the handaxe shape *per se* may have been an unintentional byproduct of applying a constrained set of knapping procedures to raw materials with certain morphological

characteristics (Davidson, 2002, 2016) – as supported empirically by Moore and Perston (2016). Indeed, a recent study of Early Acheulean handaxes from Gona suggests their shapes were not intentionally imposed, but may rather have arisen as a byproduct of material constraints in interaction with other behavioral goals, namely the intention to produce and maintain cutting edges on large ergonomic tools (Stout et al., 2025).

Our focus here, however, is on the direct culture-dependency of *shaping* know-how in particular. To inform this debate, we tested whether handaxe shaping know-how *per se* requires direct cultural access to shaping know-how models. Modern human test subjects, naïve to knapping know-how and shaping know-how (via knapping) were tasked with replicating a handaxe target shape, in the absence of handaxe shaping models (past or present). If even one such subject successfully shapes a handaxe, the occurrence of handaxe shapes *per se* becomes invalid as a secure indicator of underlying know-how copying from shaping models.

To operationalize our study, we empirically validated (Arbitrary Shape Study) a method originally proposed as a thought experiment by Moore (2019) – termed here the “puppet method.” In the original formulation, an expert “puppet” knapper must follow the directions of a knapping-naïve individual, who instructs the expert where to remove pieces from a cobble in the aim of producing a handaxe (Moore, 2019). The expert becomes solely responsible for the removal of individual flakes, under the direction of the knapping-naïve “puppeteer,” who must either develop their own shaping know-how or fail in their shaping attempts. The Arbitrary Shape Study tested the validity of the method’s main aims: to disrupt the expert knapper’s shaping know-how while keeping her knapping know-how repertoire intact, enabling the shaping abilities of knapping-naïve individuals to be tested. To achieve this goal, we used novel, arbitrary (in the sense they are non-archaeological) target shapes. The puppet method was applied again in the Handaxe Study, where knapping-naïve subjects were tasked with replicating a handaxe target shape in stone by directing the puppet’s flaking sequence. The Handaxe Study thus tested whether naïve subjects can develop handaxe shaping know-how in the absence of shaping models.

If the puppet method proves valid (Arbitrary Shape Study), and if handaxe shaping know-how occurs in the absence of shaping models (Handaxe Study), this would show that the handaxe shaping know-how *per se* cannot pinpoint direct copying from shaping models. If, on the other hand, the puppet method proves invalid or naïve humans fail to shape stone into a handaxe shape via the puppet, this would leave the hypothesis intact that handaxe shaping *per se* might depend on direct know-how copying.

2. Arbitrary Shape Study methods

2.1. The puppet method

We operationalized the puppet method by using naïve subjects (in both studies: modern humans, naïve at start of testing to both knapping know-how and shaping know-how) that were provided with a target shape (henceforth: target) and motivation – here, the aim of reproducing the target in a volume of knappable material (a blank). Subjects (henceforth: puppeteers) directed the expert puppet knapper what to do, one flake removal at a time. Puppeteers were tested independently in single tests during which the puppet (ETM) and experimenter (NF) were present.

The puppet was not allowed to see the target. At the start of each attempt (trial), the puppeteer was allowed to inspect the target and the blank while the puppet was turned away. The target was then hidden in an opaque box. Trials then proceeded with the puppeteer directing the puppet to remove one flake at a time via a combination of verbal communication and pointing. Each flake removal proceeded with the puppeteer tracing the outline of the volume for the puppet to remove with a pointer (a pen). The puppet solely determined whether it was

possible to remove the indicated volume in light of her knapping know-how. If the puppet was at least 90 % certain that she could remove the indicated volume with a single flake, she then proceeded to do so. Hard hammer, soft stone hammer (sandstone), soft organic hammer (antler), and indirect percussion (antler punch) were all allowed (Supplemental Fig. S1). The puppet was solely responsible for deciding which knapping technique and which specific percussor to use for each flake removal, in light of the morphology of the piece and of the volume the puppeteer indicated to remove. The puppet was allowed to abrade a platform edge prior to striking the blank. The puppet was not allowed to remove any flakes “on her own” – thus precluding platform preparation by anticipatory flaking after Moore (2010) – but could only remove a flake following an explicit instruction by the puppeteer. For each flake removal, the puppet was allowed to strike a single blow, except in the case of specific mis-hits (see Supplemental Section 1.4). In some cases, the puppet deemed the indicated removal to be impossible and the puppeteer was then required to choose an alternative removal. Puppeteers were prohibited from using language that would provide any hint to the target’s form or communicate more than one intended removal at a time. After each flake removal, the puppeteer reinspected the blank before indicating the next volume for the puppet to remove. The experiment continued in this way until the puppeteer declared that the piece was as close to the target as they believed they could get it and the trial ended. At the time the study was conducted, the expert puppet knapper (ETM) had 6–7 years of knapping experience and had achieved Callahan’s (1979) Learning Phase E of biface reduction. After each attempt, all flakes were collected and stored, in addition to the finished pieces, which were 3D scanned. For further details, see Supplemental Sections 1 and 2.1–2.4.

This experimental design served to disentangle knapping know-how from shaping know-how: the puppet was solely responsible for applying the former in removing individual flakes, but was prevented from applying the latter. Specifically, the puppet controlled all the variables internal to each flake removal, including percussion technique, percussor mass, force of blow, platform depth and angle of blow. This design treats the puppet’s expert knapping know-how as a “black box,” which was artificially provided to the knapping-naïve puppeteers. The puppeteers, in turn, were solely responsible for applying shaping know-how – the ability to strategically organize removals to produce the intended shape – since they determined location, general shape and sequence of flake removals. In this way, the puppet method tested if the puppeteers

could (or could learn to) sequentially organize individual removals towards imposing the targets, i.e., if they could succeed in developing shaping know-how.

2.2. Dates and subjects

The Arbitrary Shape Study was conducted between April 30th and July 4th, 2021. Four puppeteers were tested (EK, JS, LR and MH – referred to below as P1, P2, P3 and P4. Two were female (ages 21 and 23) and two were male (ages 26 and 28). Puppeteers could not be, or have ever been, archaeology students, and they could not have had any experience stone knapping, either by observation or self-experience. All puppeteers declared that they fulfilled these requirements.

2.3. Materials and procedure

Each puppeteer attempted to impose 12 geometric targets, unknown to the puppet (ETM). The targets consist of six plan shapes in two sizes each – the larger Size 1 and smaller Size 2 (Fig. 1). Targets sharing the same plan shape are referred to as a “shape-pair.” Targets were imposed onto painted hemispherical glass blanks (Snyder et al., 2024) measuring 10 cm in diameter and 4.5 cm in height (Fig. 2). The 12 targets were modelled in Blender (version 2.91.0) and 3D printed using a Formlabs Form 2 printer. The sequence in which each puppeteer attempted to impose the targets was randomized via partial counterbalancing (DePuy and Berger, 2014) to reduce the possibility of the puppet inferring the morphology of the targets across later trials. Whether the participants were successful in their shaping attempts was assessed independently via a sorting task and geometric morphometric (GM) analyses.

2.4. Sorting task

The sorting task simulated assigning artifacts to archaeological typologies on the basis of morphology. This task was performed independently on separate days by two individuals (S1 and S2) who had not previously seen the completed puppeteer shaping attempts. S1 is an archaeologist who contributed to the study design (CT), while S2 is not an archaeologist (Emily Ujifusa) and was naïve to the study’s design and aims. The sorter was seated at a table with the 12 targets before them. The 45 shaping attempts that were produced by the puppeteers were presented to them one-at-a-time in randomized orders and they were

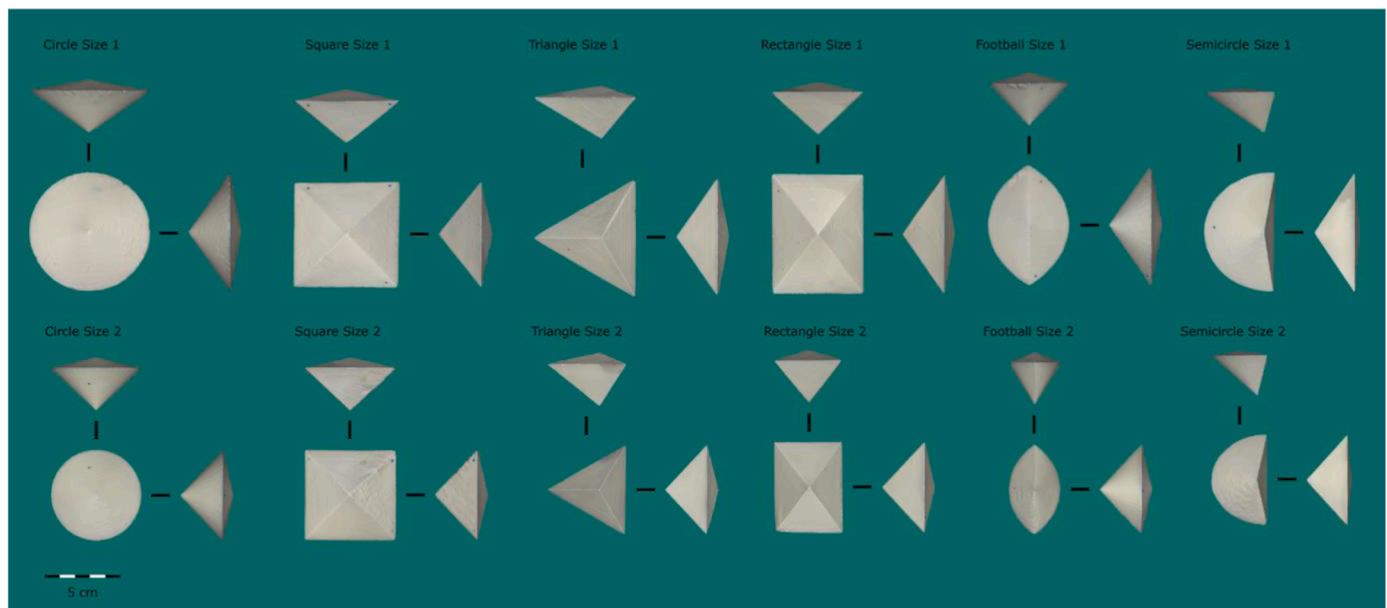


Fig. 1. Targets used in Arbitrary Shape Study. Twelve targets based on six plan shapes, each in two sizes, depicted in standard orientation.



Fig. 2. Near-hemispherical painted glass blank used in the Arbitrary Shape Study. Human hand for scale.

asked to indicate which target each piece was closest to.

2.5. Geometric morphometric analyses

GM is an approach to studying morphology based on the coordinates of landmarks that encode the spatial relationships between corresponding points, providing a representation of overall morphology (Adams et al., 2004). Targets and completed puppeteer shaping attempts were scanned and 3D models were created using an Artec Space Spider (Artec Inc., Luxembourg) with Artec Studio Professional 12. Models were placed in a standard orientation in MeshLab (Version, 2016.12) and landmarked in R (R Core Team, 2020), using RStudio (RStudio Team, 2020) and the package geomorph (version 4.0.10; Adams and Otárola-Castillo, 2013). Geometrically explicit orientation and landmarking protocols were followed to minimize arbitrary shape differences deriving from orientation and to place landmarks based on established geometric correspondence (Perner, 2018). A total of 100 landmarks (26 fixed landmarks and 74 semilandmarks) were placed on each specimen. Intra-observer repeatability error was assessed by re-landmarking a subset of 6 specimens and reperforming the shape-distance analysis two times. For further details, see Supplemental Sections 2.6-2.9.

The landmark data were transformed using full Procrustes superimposition (Mitteroecker and Gunz, 2009) to isolate shape differences. Here, *shape* refers to geometric properties of an object without considering differences in size, while *form* encompasses both shape and size (Mitteroecker et al., 2013). In parallel, partial Procrustes superimposition was performed on the original landmark data using PAST (version 4.03; Hammer et al., 2001). In this operation, size differences are preserved alongside shape differences. A Procrustes distance (shape-distance) matrix and a partial Procrustes distance (form-distance) matrix were created to quantify the morphological similarity between each pair of specimens. For each shaping attempt, the closest target in terms of

shape and form was determined by identifying the smallest (partial) Procrustes distance between the piece and the twelve targets, as well as between the piece and the six target shape-pairs, using Microsoft Excel.

2.6. Statistical analysis

A puppeteer's shaping attempt was considered successful if it was most similar to its intended target among the 12 potential targets; if it was more similar to any of the 11 unprovided targets, the shaping attempt was considered unsuccessful. Since the targets represent six shape pairs that differ in size (Fig. 1), success was also assessed at the coarser level of the six shape-pairs. Here, an attempt was considered successful if it was most similar to either target in its intended target's shape-pair.

The null hypothesis was evaluated that no more shaping attempts were successful than would be expected by chance. We assumed a 1/12 probability that an attempt would be most similar to each of the 12 targets at random. To assess the statistical significance of the results, exact binomial tests based on this probability were conducted on the puppeteers' average success rate according to each analysis. This test was only applied to the results of one iteration of the sorting task, that with the lower average success rate. Exact binomial tests were conducted in base R (R Core Team, 2020) using RStudio (RStudio Team, 2020). The interrater reliability between the two iterations of the sorting task was assessed by calculating Cohen's Kappa statistic (Landis and Koch, 1977) with the package irr (version 0.84.1; Gamer et al., 2012). The results of the interrater reliability test are reported in Supplemental Section 3.3.

The landmark data, Excel workbook and entire R code (R Core Team, 2020) used for all the analyses in the Arbitrary Shape Study and to produce the data visualizations contained in this paper are available at <https://doi.org/10.5281/zenodo.17914237> under the license CC-BY.

3. Arbitrary Shape Study results

3.1. Overview

Out of 48 total attempts, three attempts were stopped prematurely due to violations of the experimental protocols and were excluded (Supplemental Section 3.1). On three different attempts, major knapping accidents occurred (Supplemental Sections 1.4 and 3.1), after which the puppeteers were allowed a second attempt with a new blank, all of which were completed. In all, 45 completed puppeteer shaping attempts were included in the analysis (Supplemental Table S1), a subset of which are depicted in Fig. 3. 3D models of the targets used and shaping attempts produced in this study are available at Pedestal 3D, an online repository of the University of New England (<https://une.pedestal3d.com/r/Sx3mU2qn9m>).

3.2. Results: sorting task

S1 sorted 27 out of 45 shaping attempts (60 %) to their intended target. These attempts are considered successful. In total, 42 out of 45 shaping attempts (93 %) were sorted to their intended target shape-pair by S1. S2 sorted 26 out of 45 shaping attempts (58 %) to their intended target. In total, 37 out of 45 shaping attempts (82 %) were sorted to their intended target shape-pair by S2. For further details, see Supplemental Section 3.2-3.3.

An exact binomial test was conducted on the average puppeteer's success rate according to S2 (the iteration with the lower average success rate), conservatively rounding 6.5 successes down to 6 ($k = 6$, $n = 12$, $p = 1/12$, $p < 0.01$). This statistically highly significant effect demonstrates the puppeteers successfully imposed more targets than would be expected by chance according to the results of the sorting task.

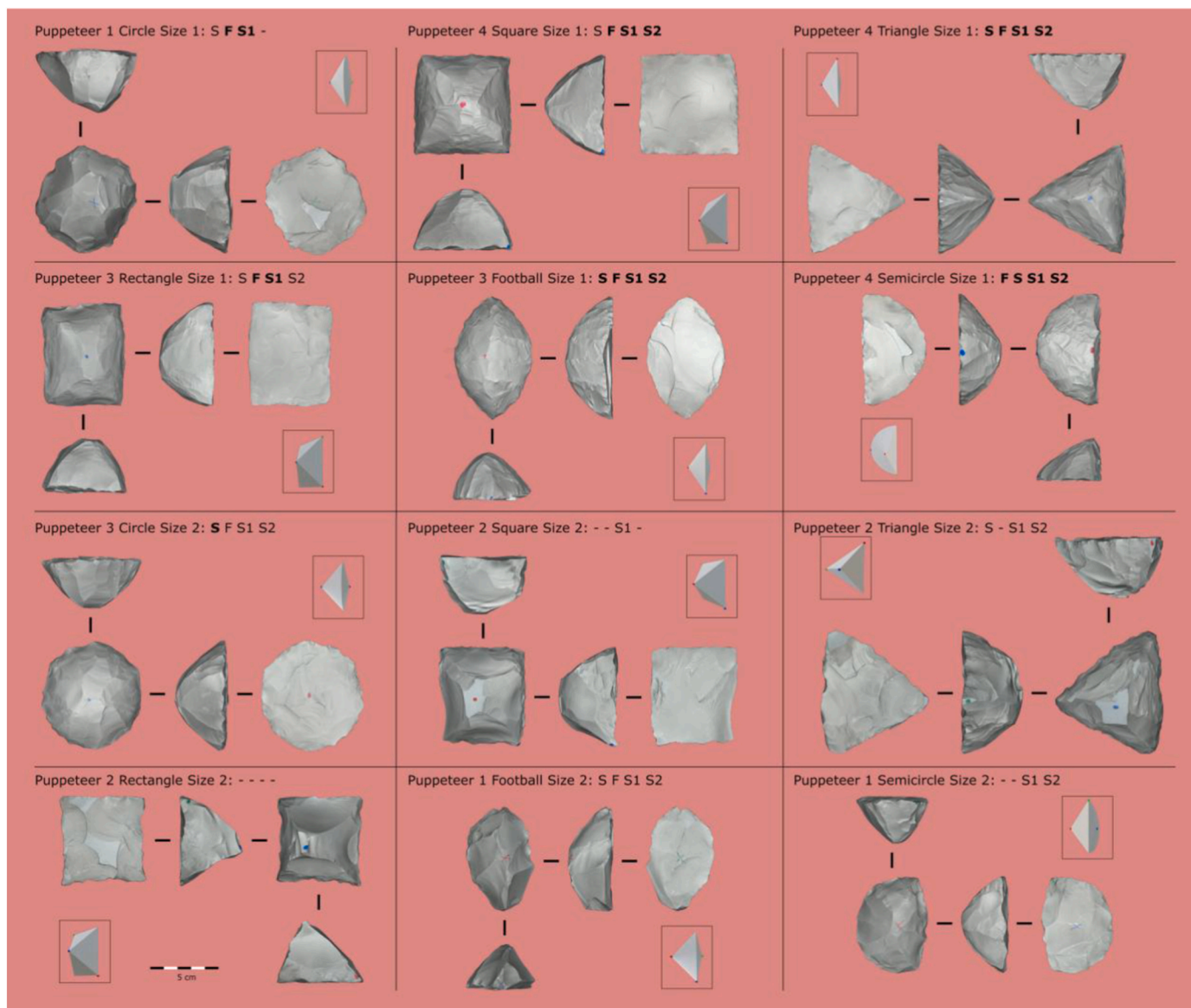


Fig. 3. Twelve completed puppeteer shaping attempts out of 45 total produced in the Arbitrary Shape Study. One example is depicted for each target. Above each specimen, “S”, “F”, “S1” and “S2” indicate that the specimen was successful according to the analyses of GM Shape, GM Form, Sorter 1 and Sorter 2, respectively, with bold indicating success at the level of the 12 targets, non-bold indicating success only at the level of the six target shape-pairs, and unsuccessful attempts indicated by a dash. In the rectangular boxes are 3D models of the targets showing corresponding points on the targets and finished pieces indicated by the puppeteers upon the completion of each shaping attempt (Supplemental Section 2.4).

3.3. Results: GM analyses

In the shape-distance analysis, 20 out of 45 shaping attempts (44 %) were closest in shape to their intended target and are considered successful. In total, 35 out of 45 shaping attempts (78 %) were successful at the level of the six target shape-pairs. On average, the puppeteers successfully imposed 5 of 12 targets. An exact binomial test on this average performance indicates that this result is statistically significant ($k = 5, n = 12, p = 1/12, p < 0.01$).

In the form-distance analysis, 21 out of 45 shaping attempts (47 %) were closest in form to their intended target and are considered successful. In total, 30 out of 45 shaping attempts (67 %) were successful at the level of the six target shape-pairs. On average, the puppeteers successfully imposed 5.25 of 12 targets. An exact binomial test on this average performance indicates that this result is statistically significant ($k = 5, n = 12, p = 1/12, p < 0.01$). For further details, see Supplemental Section 3.4-3.5. The results of all analyses are summarized in Fig. 4.

4. Arbitrary Shape Study discussion

As the first operationalization of a new method, the Arbitrary Shape Study was designed to test the validity of the puppet method. It also evaluated whether the generalized ability to impose form by knapping (shaping know-how *per se*) requires direct access to shaping models. Four knapping-naïve “puppeteers” were tasked with imposing a series of 12 arbitrary geometric targets on hemispherical glass blanks by directing a “puppet” expert knapper. The results of a sorting task and GM analyses indicate that the puppeteers successfully imposed these arbitrary target shapes at rates well above what would be expected by chance. These findings demonstrate, robustly and reliably, that shaping know-how-naïve humans can impose some shapes onto stone-like materials by knapping (here, via the puppet knapper) in the absence of a direct shaping model. This study deliberately privileged high internal validity (by using non-archaeological targets and standardized glass blanks), which always comes with limitations (Supplemental Section

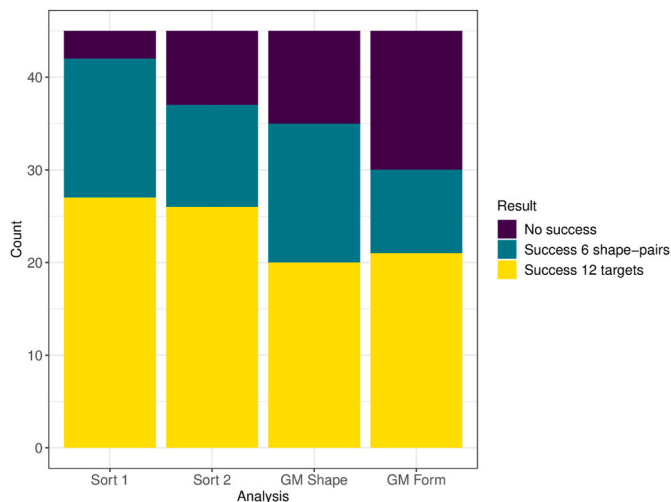


Fig. 4. Count of successful and unsuccessful shaping attempts in the Arbitrary Shape Study according to each analysis. Green indicates attempts that were successful at the level of the six target shape-pairs but not the 12 individual targets. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.9). It was important in this first test, however, to use novel target shapes that were unknown to the puppet. Any successful shaping – as happened here – must logically then be due to the puppeteers' shaping know-how, and not the puppet's (see also Supplemental Section 3.8). We therefore consider this study to be a validation of the puppet method: the experiment successfully used knapping-naïve puppeteers and an expert puppet knapper to disentangle knapping know-how and shaping know-how. The puppet method is thus no longer a theoretical possibility (Moore, 2019), but a real and useable method in the toolkit of experimental archaeology.

5. Handaxe Study methods

5.1. Dates and subjects

The Handaxe Study was conducted between June 2nd and 23rd, 2022. Two puppeteers were tested: ES (male, 24) and MB (female, 27), referred to below as P5 and P6. Both fulfilled the same requirements as puppeteers in the Arbitrary Shape Study (i.e., not archaeology students and no experience stone knapping by either observation or self-experience).

5.2. Materials and procedure

The puppet method was applied exactly as described in Section 2.1, with the following exceptions. Knapping know-how was limited to hard hammer percussion (Supplemental Table S18), since most handaxes were created with this technique. Acheulean handaxes were produced either by reducing tabular nodules and cobbles, or from large flake blanks removed from large cores (Sharon, 2008, 2010). Therefore, we provided basalt flake blanks and tabular pieces of flint as raw materials (Supplemental Fig. S21). Flint was collected from the ENCI quarry in Maastricht, Netherlands. ETM selected tabular pieces, including naturally fractured pieces. Angular basalt boulders produced by dynamite blasting were selected by ETM at the Theodor Stephan KG clay mine in Burbach, Germany. ETM later produced large flake blanks from several boulders using hard hammer percussion.

The average width, length and thickness measurements of 2925 handaxes spanning the Acheulean across three continents (Sharon, 2007 and references therein) were used to create a roughly almond-shaped “idealized” handaxe shape in Blender, which was then printed on a

Formlabs Form 2 printer (Fig. 5A). The target's surface was deliberately made smooth (i.e., flakeless), since the inclusion of flake scars could have both been a distraction and a confounding source of information on handaxe shaping for the puppeteers.

In the Handaxe Study, the puppet knew that the target shape was a handaxe, as she was asked to select and produce blanks suitable for handaxe manufacture, although she was not shown the specific target shape. She also had prior experience producing handaxes, and had achieved Callahan's (1979) Learning Phase E of biface reduction when the study was conducted. Although the aim of the puppet method is precisely to disrupt the expert puppet knapper's ability to deploy their shaping know-how, these factors do introduce a potential source of bias, in that the puppet could have unconsciously adjusted individual flake removals in ways that favored the production of a handaxe shape. It would be difficult to completely eliminate such potential bias in this experiment using a human puppet knapper, since proficient knappers today are generally familiar with handaxe shapes and how to make them (see Sections 7 and 8.2 for further discussion).

5.3. Warm-up session

Prior to each puppeteer's first shaping attempt with each raw material, they were provided with a piece of the same material (flint or basalt), whose morphology was unsuitable for handaxe production, and allowed to indicate removals to the puppet with no particular goal in mind, until 10 removals had been completed. This limited “warm-up session” provided the puppeteers with some opportunity to experience how both raw materials fractured and what kinds of removals were possible prior to attempting to impose the handaxe target.

5.4. Test phase: puppet condition

Each puppeteer completed at least one attempt in flint and basalt. One puppeteer (P5) was tested a second time with flint, as a flint nodule was still available.

5.5. Expert comparisons: non-puppet condition

After testing was concluded, two expert knappers (ETM and Rudolf Walter) were independently given the handaxe target along with basalt flake blanks and flint nodules, and were asked to reproduce the handaxe target in each material (Supplemental Fig. S24). Expert 1 completed two attempts on basalt after the blank fractured in half early during reduction.

5.6. Classification method

Three archaeologists specialized in lithic technology (David Boysen, Berrin Cep, and Radu Iovita), who were unaware of either study's designs and questions, were recruited to act as independent coders. They were presented with the puppeteers' four practice pieces (from the warm-up session), the puppeteers' completed handaxe attempts, and the expert comparison pieces (Supplemental Fig. S22–24) – for each coder in a randomized order. The coders were read a series of questions by the experimenter (NF or CT; see Supplemental Section 4.2), including how they would classify a given piece typologically (Question 1) and if they would be surprised to see a given piece described as a handaxe, cleaver or pick in the scientific literature (Question 2). The coders were then shown the target shape. Whenever a coder described a piece as a handaxe (in response to either Question 1 or 2), they were also asked to rank how closely the piece matched the target on a scale of 1–9, with 1 indicating no similarity and 9 a perfect match (Question 3).

6. Handaxe Study results

The expert coders were not distracted by the practice pieces, which

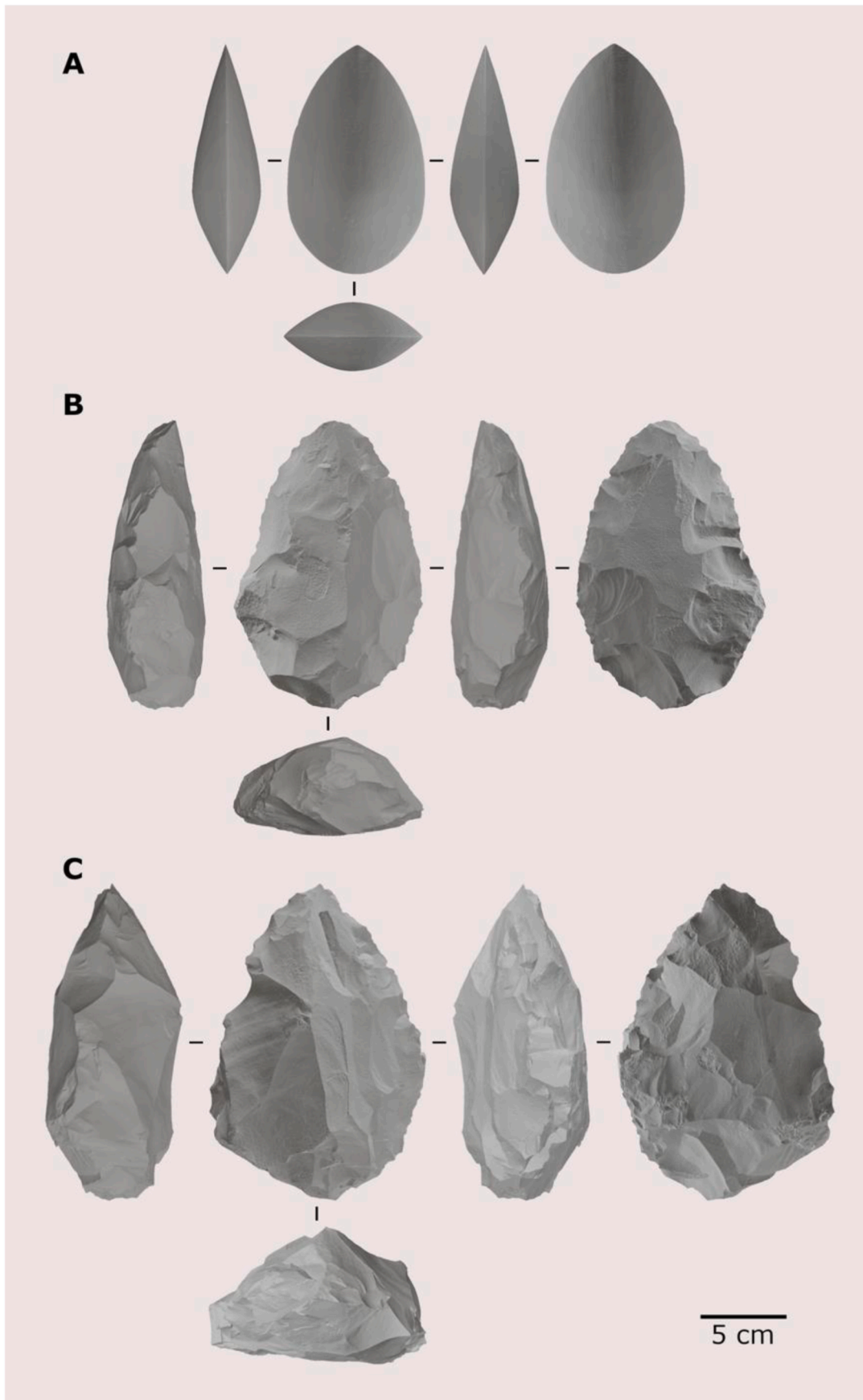


Fig. 5. Handaxe target and puppeteer handaxe shaping attempts classified by one or more expert coders as handaxe shapes in the Handaxe Study. A) Handaxe target. B) P6, flint attempt. C) P5, flint attempt 2. All images created from 3D scans.

were never judged as handaxe shaped, nor as bifacially worked pieces (Table 1). As expected, they often coded the expert knappers' handaxe attempts as handaxe shapes – in 11 of 15 cases their codings included the handaxe category (in response to Questions 1 and/or 2), with most other codings including bifacial categories. These results validate the three coders as reliable experts, and our classification method as suitable to detect handaxe shapes. The average target matching score for expert attempts coded as handaxes was 7.5.

P5's handaxe shaping attempt in basalt and their first attempt in flint were both classified as Levallois cores. All three expert coders included the category of handaxe for P6's flint attempt (average target matching score: 2.7), and one coder likewise included P5's second flint attempt in the handaxe category (albeit with the lowest target matching score; Fig. 5 and Table 1). Thus, expert coders judged attempts from both puppeteers as successfully resulting in handaxe shapes – and in one case (P6's flint attempt) this judgement was provided universally across three expert coders. Moreover, related bifacial and LCT categories were used by the expert coders to describe other handaxe shaping attempts of the two puppeteers. The clear outcome is that shaping-naïve puppeteers can, in principle, shape handaxes in the absence of shaping models.

Basalt proved the more challenging material for both the puppeteers and the expert knappers due to the presence of internal flaws (Supplemental Section 5.1), potentially explaining why the best outcomes were achieved with flint.

7. Handaxe Study discussion

We applied the validated puppet method to test if two naïve modern human puppeteers could successfully impose a handaxe shape in the absence of a shaping model, by instructing a puppet knapper. Three independent lithic experts proved reliable coders of handaxes and related shapes. These coders judged two of the puppeteer handaxe shaping attempts as handaxe shaped – in one case, all three coders agreed. Additional puppeteer handaxe shaping attempts were sometimes coded as categories adjacent to handaxes (e.g., LCT). Overall, naïve puppeteers succeeded in creating handaxe shapes by directing the puppet knapper, without access to shaping models.

Unlike in the Arbitrary Shape Study, in the Handaxe Study the puppet was aware what the target shape was, although she was not shown the handaxe target and therefore did not know its specific size and morphology. As an experienced knapper, she also had prior experience producing handaxe shapes on her own. The puppet method is not designed to remove such previous knowledge from the puppet, who brings both prior shaping and knapping know-how to the experiment. Instead, the method is designed to inhibit the puppet from applying her shaping know-how: the puppet is clearly instructed to only remove the volumes that are indicated by the puppeteer, in a sequence determined by the puppeteer. If the method is applied correctly, evidence for successful shaping must therefore be due to puppeteer's efforts, and not those of the puppet. Said in a different way: even where puppet already has shaping know-how regarding the target shape (as was the case here in the Handaxe Study), successful shaping will owe mainly, or even solely, to the shaping efforts of the puppeteers in determining the location, general outline and sequence of flake removals.

It might still be argued that a small amount of shaping effect may “creep in” owing to the puppet's knapping choices (e.g., a slightly larger flake here, a slightly misplaced impact point there, etc.). Any such bias could only have had an impact at the level of individual flake removals, within which the puppet controlled knapping variables. Our two studies together provide empirical evidence that these effects, if at all present, are too small to invalidate the results. That is, “shaping-creep” by the puppet is unlikely to have contributed majorly to the successful handaxe shapes in the Handaxe Study. Firstly, if such bias were a major contributor, we would have seen near expert levels and frequencies of shaping success in the Handaxe Study. Second, the puppet's execution of the puppeteers' instructions was watched critically by the experimenter,

Table 1

Coder responses for each piece in the Handaxe Study. Question 1: How would you classify the piece typologically? Question 2: Could the piece be described as a handaxe, cleaver or pick in the literature? Question 3 (only for pieces coded as handaxes in response to Questions 1 and/or 2): how closely does the piece match the target on a scale of 1 (no similarity) to 9 (perfect match). Dashes indicate no LCT categories were listed (Question 2) or question did not apply (Question 3).

Piece	Question	Coder 1	Coder 2	Coder 3
Practice Pieces				
P5 Flint	1	Unifacial scraper	Flake (but not sure)	Core on flake
	2	–	Cleaver	–
	3	–	–	–
P5 Basalt	1	Core	Core	Core
	2	–	–	–
	3	–	–	–
P6 Flint	1	Unifacial chopper, Scraper, Core	Core, Backed scraper	Multi-platform core
	2	–	–	–
	3	–	–	–
P6 Basalt	1	Core	Flake	Core, Large flake
	2	–	–	–
	3	–	–	–
Expert Handaxe Attempts				
Expert 1 Flint	1	Handaxe	Bifacial tool	Handaxe
	2	Handaxe	Handaxe	Handaxe
	3	9	9	8
Expert 1 Basalt 1	1	Blattspitze, Biface, Handaxe	Bifacial tool	Handaxe
	2	Handaxe	Handaxe	Handaxe
	3	8	7	8
Expert 1 Basalt 2	1	Limace, Bifacial scraper	Bifacial tool	Handaxe, Core
	2	–	–	–
	3	–	–	6
Expert 2 Flint	1	Edge scraper	Bifacial tool, Point	Biface (made on Kombewa flake)
	2	–	–	Handaxe
	3	–	–	7
Expert 2 Basalt	1	Handaxe	Bifacial tool	Handaxe
	2	Handaxe	Handaxe	Handaxe
	3	8	6	7
Puppeteer Handaxe Attempts				
P5 Flint 1	1	Core (approaching Levallois)	Core, Levallois core	Discoid core
	2	–	–	–
	3	–	–	–
P5 Flint 2	1	LCT	Bifacial tool	Core, Biface
	2	Cleaver	Handaxe	–
	3	–	1	–
P5 Basalt	1	Core	Core with some preparation, Levallois-like	Flat preformed core, Levallois
	2	–	–	–
	3	–	–	–
P6 Flint	1	Handaxe, Handaxe preform	Bifacial tool, Preform	Handaxe, Core
	2	–	Handaxe	Handaxe
	3	3	1	4
P6 Basalt	1	Biface, LCT, Core	Core	Core
	2	Cleaver	–	–
	3	–	–	–

who did not notice any intentional deviations from these instructions. In this way, the general location and shape of each flake removal, as well as the specific sequence of flake removals, were kept under the puppeteers' control. It is likely that any puppet "shaping-creep" was successfully curbed in this way, starkly limiting its down-the-line effects. Third, "shaping-creep" via the puppet cannot explain the puppeteers' success in the Arbitrary Shape Study, since the geometric targets were unknown to the puppet, who had also never produced these precise shapes. Successful shaping by the puppeteers (including in the course of their earliest attempts, see Supplemental Section 3.8) therefore did not depend on the puppet's prior shaping know-how. Triangulating these lines of evidence, we argue that it would not be parsimonious to assume that puppet "shaping-creep" invalidated our results in either study. It would be difficult, though not impossible, to measure the potential impact of such "shaping-creep" resulting from the puppet's prior shaping know-how where it exists. An alternative strategy is method development – improvements to the puppet method that reduce further the risk of such influences (or even remove them completely; see Section 8.2 for such suggestions). For our current purposes, however, as long as any puppet "shaping creep" is a minor contributor – as was likely the case here – even the current method and results are valid.

8. General discussion

8.1. Implications for the origins of know-how copying

We first successfully validated (Arbitrary Shape Study) and then implemented (Handaxe Study) a novel experimental methodology – the puppet method – to test whether the general ability to impose arbitrary shapes by knapping and the specific ability to impose a handaxe shape by knapping depend on direct cultural access to shaping models. In this way, we tested whether direct know-how copying is necessary for either the know-how to recreate novel, arbitrary shapes or to recreate handaxe shapes. In both cases, we found that direct access to shaping models was not necessary. This means that copying shaping know-how directly from models is not necessary *per se* for shaping know-how to occur – including for handaxe shapes, *contra* claims to the contrary (Chazan, 2012, Gärdenfors and Högberg, 2017, Goren-Inbar, 2011, Högberg et al., 2015, Hosfield et al., 2018, Key, 2023, Lycett and von Cramon-Taubadel, 2008, McNabb, 2020, Mithen, 1999, Morgan et al., 2015, Shipton et al., 2009, Shipton, 2010, Shipton and Nielsen, 2015, Shipton and Nielsen, 2018, Shipton, 2019, Shipton, 2020, Wynn, 1995; see Section 1). In turn, this means that the most widely accepted first instance of shaping in the archaeological record – the handaxe shape *per se* – is no longer a secure indicator of underlying direct know-how copying from models.

Although the social learning of some types of information, such as know-what and know-where, is empirically widespread in the animal kingdom, the copying of copying-dependent know-how (i.e., know-how copying) is rare, even in apes (e.g., Bandini et al., 2021a; Tennie et al., 2009; Tennie et al., 2020a). In stark contrast, modern humans copy know-how often, with apparent ease and via variable means (e.g., special types of social learning, such as imitation, language, etc.). Know-how copying need not rely on the learner alone: where models actively participate in the process of social learning, this is generally referred to as *teaching*. More specifically, the label *teaching of know-how* applies only when the teacher facilitates the copying of know-how – either by enabling it in the first place, or facilitating it in some way. While teaching in general is ubiquitous among humans (Kline, 2015), teaching of know-how represents a narrower and less frequent subset. Although the exact number of ways in which teachers have facilitated learning in prior studies involving teaching-to-knap is unknown, it is certain that teaching had effects on the learners (e.g., Morgan et al., 2015; Pargeter et al., 2019; Pargeter et al., 2020; Pargeter et al., 2023). Importantly, evidence for teaching of know-how among non-human apes remains sparse (Moore and Tennie, 2015). Moreover, some social

learning mechanisms via which humans today transmit-know how may themselves be copying-dependent products of cultural evolution (Heyes, 2018). Among contemporary humans, teaching of any type is often facilitated by language, for example, which requires know-how copying to begin with, considering that words and gestural signs are cognitively opaque, and thus require cultural transmission (Tennie et al., 2009). Indeed, human know-how copying has become so versatile as to allow us to copy shape know-how that evolved biologically in other species (e.g., plane wing via bird wing shapes, velcro via plant seeds, etc.). Generally, know-how copying, while not the only necessary factor, is both a key and a necessary factor that enabled human culture to have reached supraindividual levels and become open-ended across domains (Borg et al., 2024; Boyd and Richerson, 1996; Henrich, 2016; Tennie et al., 2009, 2018; Tomasello, 1999).

A key question in human evolution is when and how know-how copying arose in our past. It has been suggested that the ability to shape Acheulean handaxes must have required direct know-how copying (Chazan, 2012; Gärdenfors and Högberg, 2017; Goren-Inbar, 2011; Högberg et al., 2015; Hosfield et al., 2018; Key, 2023; Lycett and von Cramon-Taubadel, 2008; McNabb, 2020; Mithen, 1999; Morgan et al., 2015; Shipton et al., 2009; Shipton, 2010; Shipton and Nielsen, 2015; Shipton and Nielsen, 2018; Shipton, 2019; Shipton, 2020; Wynn, 1995). If so, any evidence for handaxe shapes would automatically be a valid indicator for the presence of know-how copying. Shaping by knapping requires knapping know-how (the perceptual-motor skills to predictably remove flakes), and shaping know-how (the ability to think abstractly and plan strategically towards imposing an intended shape) (Bamforth and Finlay, 2008; Moore, 2019; Pargeter et al., 2020; Pellegrin, 1991, 1993; Stout, et al., 2011, 2015).

Our studies focused on the latter. In both studies, "puppeteers" naïve to stone shaping know-how and knapping know-how were tasked with recreating target shapes – non-archaeological shapes in the Arbitrary Shape Study and a handaxe shape in the Handaxe Study – by directing the flake removals of an expert "puppet" knapper, who was not shown the targets. The puppet was able to deploy her learned knapping know-how in the removal of individual flakes, the location and outline of which were indicated by the puppeteers. In practice, this meant that the puppet determined the choice of percussor, the force of the blow, the angle of the blow and platform depth in order to remove each flake indicated by the puppeteers. In these studies, these factors are subsumed under knapping know-how, which was treated as a "black box." The question of whether certain types of knapping know-how are culture-dependent is a separate topic that is not addressed here (though see Bril et al., 2010; Nonaka et al., 2010; Pargeter et al., 2023; Snyder et al., 2022; Stout and Semaw, 2006). As has been theorized (Moore, 2019), the puppet method effectively disentangled knapping know-how from shaping know-how – as evidenced by the puppeteers' successful shaping of novel target shapes which the puppet had never produced prior in the Arbitrary Shape Study.

When the puppet method was applied to handaxe shapes (Handaxe Study), naïve puppeteers successfully recreated handaxe shapes even though they had not observed a shaping model. If direct cultural transmission of shaping know-how were truly required for *any* shaping – and even specifically for *handaxe shaping*, as has been repeatedly claimed (Chazan, 2012; Gärdenfors and Högberg, 2017; Goren-Inbar, 2011; Högberg et al., 2015; Hosfield et al., 2018; Key, 2023; Lycett and von Cramon-Taubadel, 2008; McNabb, 2020; Mithen, 1999; Morgan et al., 2015; Shipton et al., 2009; Shipton, 2010; Shipton and Nielsen, 2015; Shipton and Nielsen, 2018; Shipton, 2019; Shipton, 2020; Wynn, 1995) – either task should have proved impossible, since the puppeteers had no access to shaping know-how models during or prior to the experiment. Yet, in the absence of any shaping model, four naïve puppeteers succeeded in recreating novel, arbitrary shapes (Arbitrary Shape Study) and two further naïve participants succeeded in recreating handaxe shapes according to one or more coders (Handaxe Study). Our findings match suspected cases of natural experiments that may have

similarly resulted in handaxe shaping know-how in the absence of shaping models in the past (Corbey et al., 2016; Tennie et al., 2016), with the recent breakdown of the Movius line (Lycett and Norton, 2010; Norton et al., 2006; Romanowska et al., 2017). Overall, the picture is clearly one in which shaping know-how *per se* is an invalid indicator for a necessity of know-how copying from shaping models.

A number of experiments have explored the influence of various types of social learning models on novice knappers in the production of Oldowan and Acheulean technology (e.g., Morgan et al., 2015; Putt et al., 2014; Shipton et al., 2019), including at the neurological level (Putt et al., 2017; Stout, et al., 2011, 2015). Some studies have used models and training (a type of teaching) to investigate the acquisition of skills underlying Late Acheulean handaxe production under such conditions (Pargeter, et al., 2019, 2020). Our use of the puppet method, however, starts from the opposite premise: subjects were tested without any models (and without teaching) of shaping know-how. This approach of experimentally removing certain social learning pathways addresses a gap in experimental cognitive archaeology. To the best of our knowledge, our studies provide the first experimental evidence for stone shaping know-how development without direct access to know-how models.

These outcomes caution that our assumptions surrounding the cultural processes underlying early stone tools must be critically examined and cautiously deployed. Archaeological data has a key role to play in unravelling the origins of human culture, as it provides our main window into the evolution of hominin behavior over millions of years. Unhappily, this window is as clouded as it is vast, offering only indirect and incomplete glimpses of certain behaviors over time. Further complicating the problem, a massive gulf separates the cultural and social learning capacities of modern humans from those of other great apes, meaning that human culture arose via stages and processes for which we have no closely related modern comparisons. There is perhaps a natural tendency to anthropomorphize our hominin cousins well into our evolutionary past, imbuing them with social learning and cultural capacities that recall our own. Yet, as the results of this study (and great ape data) illustrate, such assumptions can be unfounded (see also Supplemental Sections 6-7). While know-how copying from shaping models is certainly beneficial for developing shaping know-how, and may be necessary for some (later) stone artifact shapes (see e.g., Pargeter et al., 2019; Pargeter et al., 2020; Stout et al., 2014), it proved unnecessary for all shapes, including handaxe shapes *per se*.

It is important to note, however, that the puppeteers in both studies were all WEIRD (Henrich et al., 2010) human adults, necessarily bringing to the test years of accumulated cultural learning – including via know-how copying. While we controlled for prior direct access to knapping know-how and knapping shaping-know-how, specifically, it thus remains possible that the puppeteers' ability to shape some or all of the target shapes that we tested was partly or wholly due to prior copying of other know-how (the "indirect pathway" *sensu* Snyder et al. (2022)). In line with this idea, recent experimental research suggests that prior experience in non-knapping craft skills can produce structural plasticity in the brain that somewhat facilitates the acquisition of knapping skills (Hecht et al., 2023). While a need for indirect know-how copying is a possibility – and a highly realistic possibility in contemporary humans, who are excellent know-how copiers – it requires careful testing and triangulation, especially when the presence of know-how copying is not a given. Possibilities do not and cannot translate into certainties independent of additional data. For example, although indirect pathways of know-how copying have only recently begun to be investigated in great apes, the overall pattern points away from this factor having large effects – particularly since apes are generally not prone to copy know-how (Tennie et al., 2020a). Despite this, some apes have been observed to successfully, and reliably, shape objects (e.g., shaping branches and twigs before using them as tools (Boesch and Boesch, 1990; Crickette et al., 2004)). This is shaping know-how, too – here, of organic tools – but it is unlikely dependent on know-how

copying, even in indirect ways. Such shaping know-how is proof of principle that we must be careful to attribute any past need for indirect know-how copying from the mere presence of know-how.

We did not find, nor did we expect, the recreation of *Late(r)* Acheulean handaxe shapes by our participants (see also Supplemental Section 6). Over the course of the Acheulean, some handaxes display increasing symmetry and regularity (e.g., Beyene et al., 2013; Herzlinger et al., 2021; Iovita et al., 2017; Saragusti et al., 1998; Shipton and White, 2020). Indeed, refined Late Acheulean handaxes eventually entailed more elaborate production methods, including additional subroutines and subtools (Gärdenfors and Högberg, 2017; Stout, 2011; Stout, et al., 2014, 2021), and there is generally a high difficulty of modern knappers to learn how to produce such late handaxe shapes, even in the direct presence of shaping models (Pargeter, et al., 2019, 2020; Shipton and Nielsen, 2018). In light of these trends, late handaxe shaping know-how and related know-hows represent a more promising case for postulating a need for know-how copying – creating a timeline for the beginnings of human-like culture that seems to be converging inside the last million years (Paige and Perreault, 2024; Tennie, 2023) (see also Supplemental Section 7).

One final result worth highlighting is that two of puppeteer attempts at replicating the handaxe target shape resulted in objects that were coded as both LCTs and cleavers, while another attempt was coded as a discoidal core and four further attempts as Levallois cores or cores approaching Levallois (Table 1). In other words, the objective of copying a single target form resulted in flaked pieces that were attributed to a number of bifacial artifact types. Traditionally, Acheulean LCT types – such as handaxes, cleavers and picks – have been argued to reflect distinct mental templates of tool types and associated production schemes (e.g., Pelegrin, 1993). Others, however, have argued that rather than reflecting true emic categories, many of the labels that archaeologists apply to bifacial artifacts in the early Acheulean – including handaxe, pick, cleaver and discoidal core – may instead arbitrarily subdivide a continuum of morphological variability that generally results from bifacial reduction (Duke et al., 2021; Kuhn, 2020; McNabb et al., 2004; Moore and Perston, 2016; Presnyakova et al., 2018; Stout et al., 2025). The experimental data presented here offer new empirical support for this view, since a number of bifacial tool types were attributed to pieces resulting from a single bifacial (handaxe) target.

8.2. The puppet method: concluding considerations and outlook

Our study successfully moved the puppet method from a theoretical possibility (Moore, 2019) into the realm of reality. The method could even be used in non-knapping contexts and even outside of experimental archaeology. Possible future avenues in archaeology could be to provide naïve puppeteers with functional goals instead of target shapes: e.g., puppeteers directing expert puppet(s) to make a tool to open hides, combine objects, etc. Such studies could shed light on various ideas – and make them more testable – such as notions of affordances (Wynn, 2021; see also Bisson, 2001). The puppet method could also test if young children (Sternke and Sørensen, 2009) the world over are able to shape handaxes (etc.) via a puppet knapper. If so, then handaxe shaping know-how would be less likely to require indirect know-how copying (a common rationale in child studies; e.g., Reindl et al., 2017) – such studies could become part of triangulating the beginnings of copying dependent know-how.

Yet, as this was the first instance of a new method in use, we should remain appropriately cautious. Even though we validated the method in principle in the Arbitrary Shape Study, the possibility remains that in the Handaxe Study the puppet's actions were partly unconsciously biased by virtue of already knowing how to make handaxes. While this very unlikely affected the Arbitrary Shape Study (Supplemental Section 3.8), perhaps our subjects' performance was somewhat boosted, even unconsciously, by the expert knapper in the Handaxe Study. In the future, the puppet method could be improved and such potential biases

("shaping-creep") could be further controlled via a system that further inhibits the inferential powers of the puppet. As a first step, the puppet and puppeteer could be placed in different rooms. From there, the puppeteer could request removals simply by drawing the outlines on the blank directly, or via video clips that would be vetted and cut by the experimenter prior to being shown to the puppet. Alternatively, the puppet and puppeteer could communicate indirectly via a mediator trained in applying the method but naïve to the precise target shape and relevant shaping know-how. Another means to control for puppet biases would be to use multiple expert puppet knappers and use each puppet only once. Alternatively, puppets without handaxe shaping know-how could be "produced" by giving individuals sufficient time to learn knapping and shaping know-how individually, but while keeping them naïve to the specific target's shaping know-how. Similarly, cross-cultural studies could be performed in which puppets are recruited from non-WEIRD (Henrich et al., 2010) societies – especially if they were unfamiliar with Acheulean handaxes. Knappers from societies with traditions of bifacial technology may be less suitable – for example, the Langda adze makers who produce bifacial blanks (Pétrequin and Pétrequin, 1993; Stout, 2002) – whereas others who may lack bifacial shaping know-how, such as the Daasanach pastoralists described in Reeves et al. (2024), would provide a more relevant comparison. Questionnaires assessing target naivety would have to be performed post-test, however, to avoid revealing the target shape prior to testing (see Snyder et al., 2022). Finally, perhaps in the future, potential puppet bias could be completely removed by using a virtual puppet knapper (e.g., Orellana Figueroa et al., 2021) or knapping robot that lacks unconscious bias altogether, should these technologies become available and be successfully validated. Such (virtual) non-human knappers could apply knapping know-how in individual flake removals, while being unable to learn shaping know-how at all. With these promising avenues and more, the puppet method can be an important tool in the interdisciplinary project of triangulating the origins of know-how copying in the hominin lineage.

CRedit authorship contribution statement

Nolan Ferar: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Elena T. Moos:** Writing – review & editing, Validation, Investigation. **Fotios Alexandros Karakostis:** Writing – review & editing, Methodology. **William D. Snyder:** Writing – review & editing, Resources. **Maria Bolzmann:** Writing – review & editing, Investigation. **Michael Haas:** Writing – review & editing, Investigation. **Emanuela Kainz:** Writing – review & editing, Investigation. **Leonie Rau:** Writing – review & editing, Investigation. **Emil Sailer:** Writing – review & editing, Investigation. **Jannik Schönle:** Writing – review & editing, Investigation, Conceptualization. **Mark W. Moore:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Claudio Tennie:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition.

Data

The data and code that support the findings of this study are contained in the manuscript, its supplemental materials, and the data repository Zenodo, at <https://doi.org/10.5281/zenodo.17914237>. 3D models of the coded pieces and target form used in the Handaxe Study are available at the same link. In addition, 3D models of the target forms and completed puppeteer shaping attempts produced in the Arbitrary Shape Study may be viewed and downloaded at Pedestal 3D, an online repository of the University of New England, at <https://une.pedestal3d.com/r/Sx3mU2qn9m>.

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Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jas.2026.106485>.

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