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Behavior, learning, and lithics:

Understanding the process of learning, and handaxe production through behavior

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An abstract of
a thesis submitted to the Faculty of Emory College of Arts and Sciences
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Abstract

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Archaeologists argue that stone toolmaking, or knapping, is linked to the evolution of language, teaching, and social learning. Handaxe making is an energy-intensive, and complex skill that archaeologists have associated with a cognitive shift in the hominin lineage. Due to the nature of the archaeological record, information about behavioral traits that accompanied the practice of handaxe making is scarce. While handaxe analysis can reliably predict some aspects of ancient toolmaking, analysis of behavioral data is crucial to capturing processes such as core manipulation, and equifinality. While modern experiments have helped to shed light on the factors that influence variation in handaxe production, few studies have focused on how individual behavioral variability affects variation in handaxe production.

I analyzed video recordings from the most comprehensive and longest-running handaxe-making training experiment conducted yet. In this experiment, novice knappers were given 90-hours of expert training in Late Acheulean style handaxe making. I established a methodology to code behavioral data by tracking variables related to the kinematics and processes of handaxe making. In this thesis, I explore the relationship between different knapping behaviors, and lithic products. The data show that performance can be traced through handaxes, debris, and behaviors, and point to factors that lead to differential acquisition of skills across novice knappers. Furthermore, similarity of lithic outcomes resulting from a highly variable knapping behaviors highlight the ambiguity in the behavioral interpretation of technological features on artifacts. The study and its methodological contributions highlight the importance of qualitative approaches to understanding studies of real-world skill acquisition, add a new dimension to our understandings of prehistoric technologies, and expand the range of inferences that can be drawn from lithic artifacts in the archaeological record.

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Introduction

Paleolithic stone toolmaking is a cognitively complex skill (Ambrose, 2010; Stout and Chaminade, 2012), and was accompanied by a host of cognitive and behavioral shifts in the hominin lineage. However, modelling of ancient behavior based on artifacts has proven challenging. Experimental archeological studies draw analogies between ancient hominin, and modern human toolmaking and skill-acquisition capacities. This study focuses on the behaviors of novice toolmakers as they learn to make a particular kind of complex stone tool known as a handaxe over a 90-hour training period. By creating a method to studying knapping behaviors in a quantitative, and qualitative fashion, I strive to add to the methodological approaches towards behavioral analysis in archeology. I focus on two main questions. Firstly, I focus on the question of whether individuals provided with the same conceptual knowledge, and relevant training acquire and apply skills in a similar manner, and whether this skill acquisition can be traced in their behaviors, and in the stone tools produced. My second question is how particular toolmaking behaviors relate to different characteristics of the handaxe produced. Finally, I provide support for studying individual behaviors to understand the process of skill-acquisition in toolmaking, which traditional experiments in archeology have largely ignored.

I. Experimental approach

Archeological sites only preserve the lithic artifacts, but not the behaviors associated with them. Experimental archeology strives to bridge the gap between the artifacts, and the behavior by conducting toolmaking experiments under controlled conditions (Outram, 2008), with experiments being used to answer a wide range of questions ranging from tool function, use-life, fracture mechanics, biomechanics, to skill, and cognition. Tightly controlled experimental studies (with high external validity) have found variations in handaxe shape arise due to combinations of different factors such as raw material variability, and reduction intensity (i.e. how heavily flaked a handaxe is) (McPherron and Dibble, 1999; Shipton and Clarkson, 2015). External characteristics of the core being knapped, such as size, shape, presence of cortex, and regularity of material (Ashton and McNabb, 1994; Eren et al., 2011), as well as internal characteristics of the rock, such as isotropy, brittleness, hardness, and granularity (Callahan, 1979; Whittaker, 1994; Andrefsky and Andrefsky Jr, 1998) have all been considered in prior experimental studies as factors that affect the final handaxe produced. These experiments illustrate that handaxe making is a complicated skill requiring control over multiple variables.

While some aspects of ancient toolmaking, such as effect of rock quality and properties, can be accurately inferred used highly controlled experiments with a high degree of external validity, other aspects of the process can be more speculative, such as posture, or placement and manipulation of the nodule (Lin et al., 2018). Certain processes, for example, are equifinal to others, meaning they leave the same discernible traces on rocks as other processes. In order to answer the question of equifinality in lithic production, we need to analyze tool-production behaviors. Replicative experimental studies recreate the effect of variables in order to understand real-world processes that underlie behavior and stone-tool making by connecting the archeological record to models generated by experiments with tightly controlled variables (Eren et al., 2016), and focus on having high internal validity in the experiments. The experiment discussed in this thesis treads a middle ground between external and internal validities, incorporating realistic learning conditions while also maintaining a host of highly controlled variables. Experimental studies that involved giving subjects short training periods found that novice handaxe makers differ from experts in the kinds of handaxes they make (Putt et al., 2014), and in the behaviors they adopt (Geribàs et al., 2010). Thus, handaxe making cannot be easily mastered by novices over short training periods. This highlights the importance of teaching, and training over long periods of time, which a salient factor that many experimental studies seldom incorporate.

Several experimental studies use quantifiable data from lithic assemblages and experiments with expert handaxe-makers to draw conclusions about hominin behavior and learning. However, there is minimal data on how individuals learn to control for all the factors. Confounding variables can be introduced into a study due to idiosyncratic behaviors of the human subjects (Lin et al., 2018). Brain responses to observations of skilled actions vary by experience (Calvo-Merino et al., 2006; Stout et al., 2011), implying that the aptitude of individual subjects, determined by their past experiences, could affect the outcomes of the skill-acquisition, and toolmaking processes. Understanding the kinds of behaviors toolmakers deploy when faced with different situations, and how they interact with their surrounding in realistic toolmaking situations, requires direct analysis of the individual knapping sessions. I attempt to establish a method to studying knapping behaviors by not only quantifying the frequency of different actions, but also by conducting a qualitative analysis of handaxe making sessions. Behavioral analysis through direct observation has often been overlooked or considered secondary to the lithics in the field of experimental archeology. In this study, I hope to highlight the advantages of using behavior to understand the knapping process, as well as contribute and add to the methods currently being used to study behavior during handaxe making.

Another drawback of major experimental studies so far has been the lack of data on handaxe makers of various skill-levels. They usually approach skill as a dichotomous category- "expert" handaxe makers, who have a certain number of years of experience making handaxes, and “novices,” who have no experience at all with handaxe making. Cognitive demands during the learning period differ from those at the expert stage (Stout et al., 2015). Most lithic experiments brush over the sliding scale of skill-level in pursuit of modal tendencies. However, the archeological record consists of the cumulative behavior of ancient individuals, and understanding the cause of individual variability is crucial to providing a more robust and nuanced understanding of how humans learn motor skills such as stone toolmaking. In this study I track novices through their long-term training period, by analyzing their performance at different time intervals. The novices included in this study had no prior experience making handaxes.

One of the most challenging aspects of handaxe production involves the creation of a bifacial edge. This is achieved by striking flakes off of two opposite faces of a stone core, a method known as bifacial reduction. Based on analysis of handaxes from archeological sites, and experiments with modern expert handaxe-makers, Shipton and Clarkson establish SDI (scar density index) as an effective predictor of core-reduction (2015). Scars are created on cores due to flake removal. In this study, I test whether Shipton and Clarkson’s prediction holds true for novice behaviors associated with core reduction, such as the number of flake removal events. My ultimate goal is to gain a deeper understanding of the relationships between tool-making action patterns, and stone tools themselves.

II. Handaxes in the evolutionary context

The handaxe is a symmetric, bifacially-thinned stone tool which terminates at a pointed tip on one end, and a flat or rounded butt on the other. The earliest handaxes date back to 1.75 million years (Shipton et al., 2018). Handaxes appear in the archeological record at a time period that also saw a large increase in hominin brain size (Ruff et al., 1997). An overlap in brain regions responsible for language-production, and motor activities posits the theory of coevolution of language and toolmaking (Stout et al., 2008). It has been suggested that hominin reliance on stone tool production led to selection favoring increasingly complex language and teaching (Morgan et al., 2015). The collective impact of our extensive cooperation, high cognitive function, and ability to use language allow us to transmit complex information rapidly (Bingham, 1999). The role of teaching over long periods of time becomes a salient factor that many experimental studies have yet to incorporate.

Handaxes have been found on the African continent, Europe, and Asia. They persisted not only across large geographical distances, but also across a long time period, with the some handaxes being found at sites as young at 0.5mya (Shipton et al., 2018). While many theories about handaxe function exist (Clark, 1975; Howell, 1965; Jeffreys, 1965; Jelinek, 1977; Kohn and Mithen, 1999; O'Brien, 1981, 1984; Spikins, 2012; White and Foulds, 2018), no true consensus has yet been reached about what they were used for.

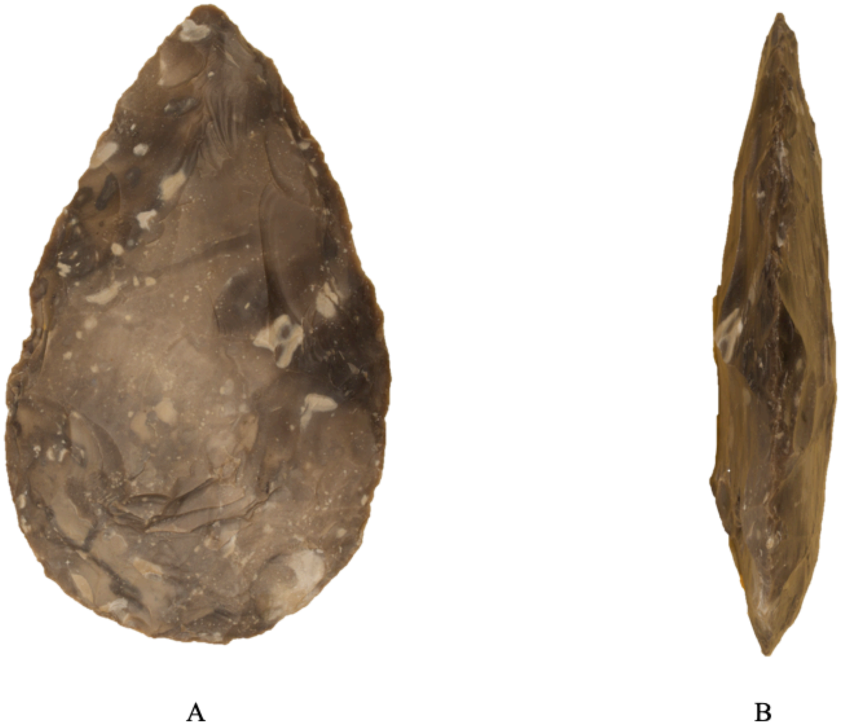

Figure 1: A shows a handaxe in plan view. B shows the same handaxe in profile view

III. Learning to make a handaxe

Stone toolmaking requires both visuomotor coordination and hierarchical action planning (Stout et al., 2008). Handaxe making is a cognitively demanding task that requires the toolmakers, also called knappers, to simultaneously take into account multiple varying factors, such as core morphology (Ashton and McNabb, 1994; Eren et al., 2011). Novice knappers fail to make good handaxes under short periods of time in experimental studies (Putt et al., 2014; Geribàs et al., 2010). While assessing rocks to pick out a suitable core for toolmaking is an important skill that a knapper must possess, it is not possible to determine visually whether a rock is of uniform quality throughout. Thus, another crucial skill that an expert handaxe maker must possess is knowing to deal with unexpected circumstances mid-knapping, such as a change in rock quality, or a core splitting in half. Thus, skilled handaxe production requires constant shifting of proximal goals, and readjustment of action plans. The complicated nature of handaxe making suggests the importance of teaching in the acquisition of this skill. Theories of high fidelity learning by imitation in humans suggest skills are transferred with a high degree of precision. However, not all individuals acquire skills in a similar manner. The kinds of information we internalize, and the behaviors to execute subsequently might speak to certain internal states, such as the emotional state, strength of memory, or prior experience. Few studies have focused on the behaviors associated with long-term acquisition of complex skills such as handaxe making. In this study, I examine whether novice knappers learning to make a handaxe use different strategies given the same quality of training, and whether these differences are apparent across their behaviors, as well as the handaxes they produce. Studying the behaviors of individuals learning to perform complex tasks over long-time periods will help shed light on the cognitive capacities that allow for learning, and how they differ between individuals.

Experimental Background

The Paleolithic Technology lab at Emory conducted a long-term study in which subjects with no experience making handaxes were given approximately 90 hours of training in handaxe-making by an expert knapper. All the subjects were given the same instructions during their training, although subjects were free to engage with the expert instructor however they wished to do so. These novice knappers were given an assessment after every 10 hours of training where they made a handaxe without any instructions or help from the instructor. All participants completed a pre-training survey, and a baseline-skills assessment session. The handaxes produced at each assessment stage, along with the associated flakes and debris were collected and analyzed.

Handaxe quality was assessed using model scores (Pargeter, 2019). In order to do this, handaxes from all assessments were measured on nine parameters (extent of the bifacial edge, flake scar density, the extent of unflaked area, symmetry in two planes, two shape parameters, the amount of flaked mass, and changes in the handaxe profile thickness). These metrics were compiled into a multivariate machine learning model that assigned each handaxe a quality rating on a scale from 1-5 measured against a subject skill rating given at each handaxe assessment. The learning curve, which shows handaxe scores as a function of training time, illustrates roughly three broad learning stages– an early phase of rapid increase in skill-scores which extends from assessment 1-3, followed a slight dip in the learning in the middle stage (assessments 4-6). Finally, there is a slight increase in skill-scores in the late-stage of learning (assessment 7-9). The individual learning curves for the subjects however are a lot more variable, illustrating that individuals acquire skills in different ways.

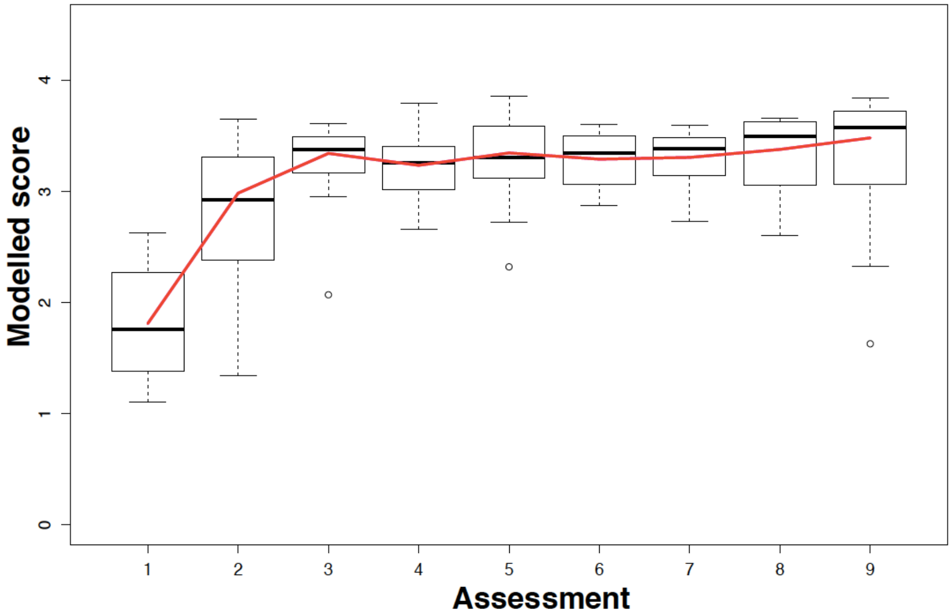

Figure 2: The learning curve of handaxe skill acquisition. The x-axis represents each of the handaxe-making assessments. The y-axis represents modelled scores given to each handaxe

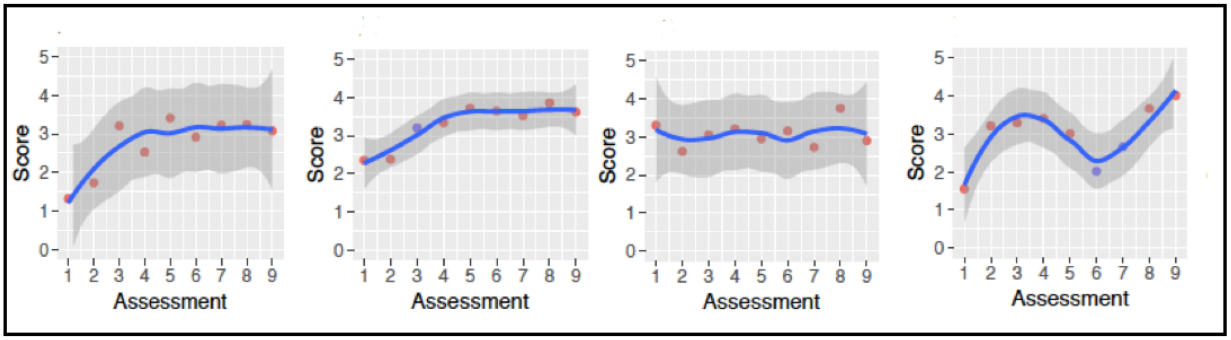

Figure 3: Some of the individual learning curves of handaxe skill acquisition generated in the study

Previous lithic studies

In a previous study, I recorded the number of complete flakes produced during each of the assessments. Complete flakes are defined as any debris greater than 20mm in maximum dimension with a complete platform of percussion. A platform is the surface on the flake that was struck to detach it from the core. Handaxe production requires the skillful removal of a few long, large flakes from the core (Newcomer, 1971). I refer to these large flakes as "outlier flakes." Outlier flakes are defined as complete flakes that have a maximum dimension of at least 50% of the length of the associated and finished handaxe. I also recorded the number of outlier flakes produced in every assessment.

Figure 4: A handaxe (left) and one of its outlier flakes

Methods

All training and assessment sessions were videotaped. The overall learning-curve based on handaxe-score model showed that, on average, the learning curve had roughly three broad stages. I focused on one assessment video from each of the three learning stages of the handaxe learning-curve, in order to have a clear understanding of the subjects' behaviors at each stage of learning. I included three subjects in this study, one of whom consistently produced good handaxes over the course of the study, one who produced fairly poor handaxes compared to their peers, and one who sat in the middle of the spectrum. Knapper performance was judged based on the model score of their handaxe. The subjects had nine assessments sessions in total. I analyzed assessment 2 from the early stage of learning, which is the first post-training assessment. I analyzed assessment 4 from the middle stage of learning, and assessment 9 (last assessment) from the final stage of learning. Assessment 9 for knapper two was not recorded. Hence, I analyzed assessment 8 in the last-stage of learning for knapper 2.

Table 1: Handaxe scores of the subjects by assessments included in the study. The last column provides the average of the handaxe scores over all the assessments throughout the training period

Knapper	Assessment	Handaxe Score	Average score over all assessments
2	2 (early)	1.622	2.822
	4 (middle)	2.359	
	8 (late)	3.338	
16	2 (early)	2.657	3.060
	4 (middle)	3.262	
	9 (late)	2.960	
14	2 (early)	2.249	3.324
	4 (middle)	3.922	
	9 (late)	.620	

I used a free, open-source event-logging and analysis software called BORIS to code for their actions and behaviors. BORIS allows for coding of two types of events– state events, which last over a period of time, and point events, which are momentary. The knapping process is complex, and subjects display several behaviors simultaneously at any given time. Given the time-consuming nature of coding actions, one of the main challenges of this project was to determine which actions would be most informative of knapping strategies. I did an initial evaluation of the most common behaviors and whether they change across knappers and across time in order to devise a rough ethogram of actions to focus on. The core-wielding hand performs actions such as core movement and manipulation, whereas the hammerstone-wielding hand is responsible to striking the core with different intensities. I adopted a core-centric approach towards action-coding, where I carefully observed how the core was being manipulated and struck. My ethogram contained different types of percussions on the core (same-point, laterally-adjacent, opposite-face, new-point), core movements (core movement with grip-shift, core movement without grip-shift, core flip), and flake detachment. The knapping sessions was broadly divided into states depending whether or not the subjects were actively striking the core. If they were not actively striking the core, they were engaged in activities such as switching hammerstones, inspecting the core, grinding the hammerstone against the core, or talking. Subjects sometimes performed idiosyncratic behaviors unrelated to knapping. These behaviors were put into the "other" category.

Table 2: The following is an ethogram of the actions I coded and how I defined them for the purposes of this study

Behavior	**Behavior Type**	**Description**
Inspection	State Event	Subject is inspecting the core without striking it
Talking	State Event	Subject is talking to the instructor
Other	State Event	Subject is displaying a behavior unrelated to knapping
Flake Detach	Point Event	A flake detaches from the core

Behavior	**Behavior Type**	**Description**
Light Percussion	Point Event	Subject strikes the core lightly in short strokes
Same Point Percussion	Point Event	Subject strikes the same point on the core as they had in their previous blow to the core
Laterally Adjacent Percussion	Point Event	Subject strikes a point laterally adjacent to their previous blow to the core
Opposite Face Percussion	Point Event	Subject strikes at a point on the opposite face relative to their previous blow to the core
New Point Percussion	Point Event	Subject strikes at a point that is not laterally adjacent, on opposite-face, or on same-point as previous blow
Core Movement without Grip Shift	Point Event	Subject changes the orientation of the core without changing their grip on the core
Core Movement with Grip Shift	Point Event	Subject changes the orientation of the core by changing their grip on the core

Behavior	Behavior Type	Description
Core Flip	Point Event	Subject turns the core over to the face opposite to the surface of the core they were previously working on

I coded for frequency of each of the behaviors and examined how they vary with training, and, by individual, using bar charts. Since bifacial flaking is characteristic of handaxe-production, I hypothesized that variables such as frequency of opposite-face percussions, and core-flips will increase as the subjects progressed through their training. To test whether behaviors coded for were reflected in the resulting stone tool assemblages, I created correlation plots between behavioral data and handaxe metrics. In particular, I focused of the covariation of number of opposite-face percussions and percent bifacially flaked (percentage of tool perimeter with alternating bifacial scars > 15mm). We would expect to see a positive correlation between the two variables assuming the subjects knap the core more bifacially as they gain practice.

I also created correlation plots of the total number of percussions, and handaxe metrics like flake scar density (measured as the number of scars > 15mm in length divided by the mass of the handaxe), percent unflaked area (measured as unflaked tool surface area divided by total surface area), delta weight (change in weight of the core), I hypothesized that the best knapper (the subject who made the best handaxes overall) will follow my predictions closely, while the while the poorest performer will deviate the most from these predictions.

Table 3: List of questions, along with the variables analyzed and predictions based on previous experimental data

Question	Video Data	Lithic Data	Prediction
How are the subjects partitioning their time across various tasks as they learn?	Ratio of inspection time to overall time spent knapping	-	Inspection times will decrease with skill acquisition. I expect subjects to spend less time inspecting the core as they get more familiar with the knapping process, the problems they might encounter, and how to deal with them.
Are the subjects working bifacially more as they learn?	Ratio of opposite-face percussions to other percussion types	-	I predict that ratios of opposite-face percussions will increase as the assessments progress. I expect subjects will get better at working with the core bifacially as the training progresses.

Question	**Video Data**	**Lithic Data**	**Prediction**
How does the way in which the subjects manipulate the core change over time?	Ratio of different core movements to total core movements	-	I predict that the ratio of core-flips to total number of core movements will increase with training reflecting an increased ability to flake bifacially
Are the subjects succeeding in reducing the core as they train?	Absolute number of flake detachment events	Ratio of number of strikes to complete flakes produced	I expect reduction intensities to increase with training. Since subjects will learn to reduce and thin the core with training, I expect to see an increase in the number of flakes produced, flake detachment events, or a steeper decrease in the mass of the core as the assessments progress.
	Ratio of the total number of strikes to the total number of detachments	Ratio of number of strikes to outlier flakes produced	
		Difference in mass of the core and mass of the handaxe	

Question	**Video Data**	**Lithic Data**	**Prediction**
Do the action patterns reflect the lithics produced?	Number of opposite-face percussions	Bifacially flaked area	I expect bifacially flaked area to increase with the number of opposite-face percussions.
	Total number of strikes	Flake scar density Delta weight Unflaked area	I expect reduction intensity to increase with number of strikes. I predict number of strikes to be positively correlated to flake scar density, and delta weight, and negatively correlated to unflaked area

In addition to collecting quantitative data, I also conducted a qualitative analysis of the knapping sessions, paying special attention to infrequent behaviors, such as incorrect striking methods, fidgeting, and talking. I also watched and analyzed the subjects' pre-training videos and surveys, to shed some light on how their pre-existing skills may have played a role in their ability to make handaxes.

Results

I. Results from Video Data

i) Inspection times

All subjects spend a majority of their time (greater than 50%) inspecting the core in the early stage assessment, with subjects 2 and 16 spending a similar amount of time inspecting. The time spent inspecting varies between subjects in the middle stage, with subject 2 spending the same amount of time, subject 14 spending less time, and subject 16 spending more time inspecting than they did in the early stage. Inspection times fall to below 45% for subjects 2 and 16 in the late stage of learning. Like the early-stage assessment, these subjects once again spend similar amounts of time inspecting in the late stage. Subject 14 on the other hand spends more time inspecting the core in the late-stage assessment than they did in either of their previous assessments.

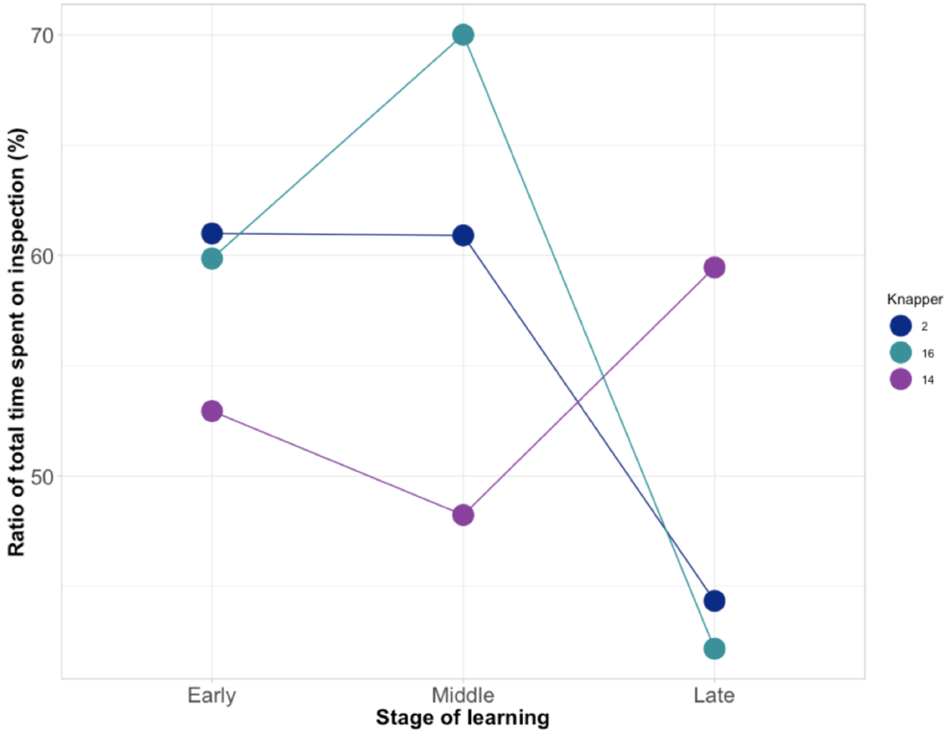

Figure 5: Ratio of total time spent on inspecting the core per stage of learning by each knapper

ii) Core Movement

All subjects perform more core flips in their late-stage assessments than they did in their early-stage assessments. The trend in the middle-stage assessments varies across knappers. Knappers 2 perform2 more flips in the middle stage than in the early stage, knapper 16 detached fewer, and knapper 14 about the same. Knapper 2 consistently performs less core flips than the other two knappers at all stages, and even at their highest number of core-flips, they perform fewer core-flips than the other two knappers. The largest jump in knapper 2's performance happens from early-stage to middle-stage, whereas for the other two knappers, the largest jump happens from middle-stage to late-stage.

Table 4: Absolute number of core flips performed by knappers at every stage, and ratio of core flips to all core movements

Knapper	2			16			14		
Stage	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
Absolute Number of Core Flips	49	68	49	96	66	85	52	60	62
Ratio of Core Flips to all Other Core Movements	0.140	0.189	0.205	0.294	0.203	0.411	0.286	0.296	0.392

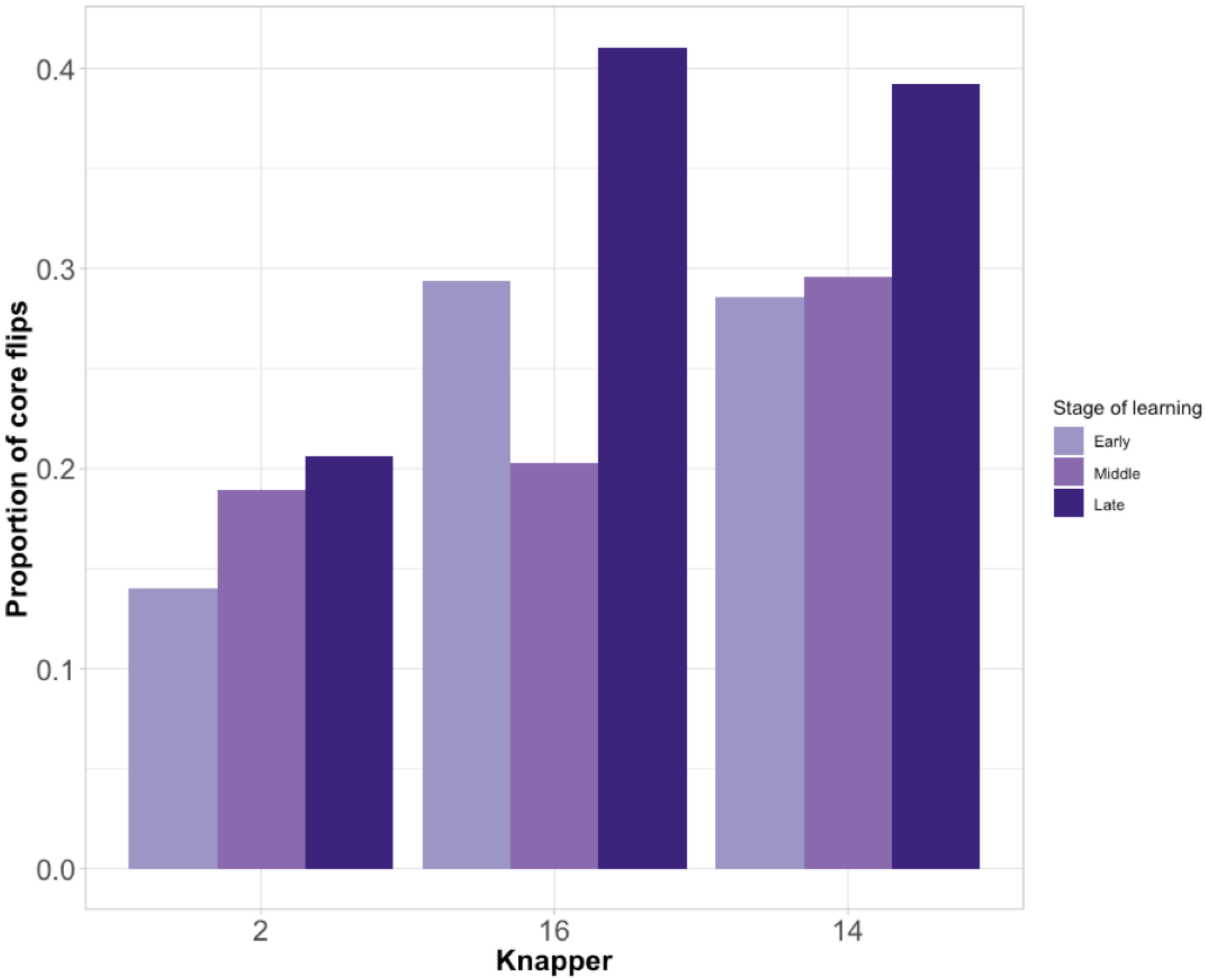

Figure 6: Proportion of core flips by stage of learning per knapper

iii) <u>Percussions</u>

There is an increase in opposite-face percussions as the stages progress across all subjects, except in the case of knapper 14, who performs fewer opposite-face percussions during the middle-stage assessment than they did in the early-stage. Similar to their performance in core-flips, knapper 2 consistently performs less opposite-face percussions than the other two knappers at all stages. Even at their highest number of opposite-face percussions, they perform fewer opposite-face percussions than the other two knappers in any of their assessments.

Table 5: Summary of ratio of the number of opposite-face percussions to total number of percussions per stage

Knapper	2			16			14		
Stage of learning	Early	Middle	Late	Early	Middle	Late	Early	Middle	Late
Ratio of opposite-face percussions to all percussion types	0	0.009	0.011	0.036	0.052	0.074	0.022	0.016	0.060

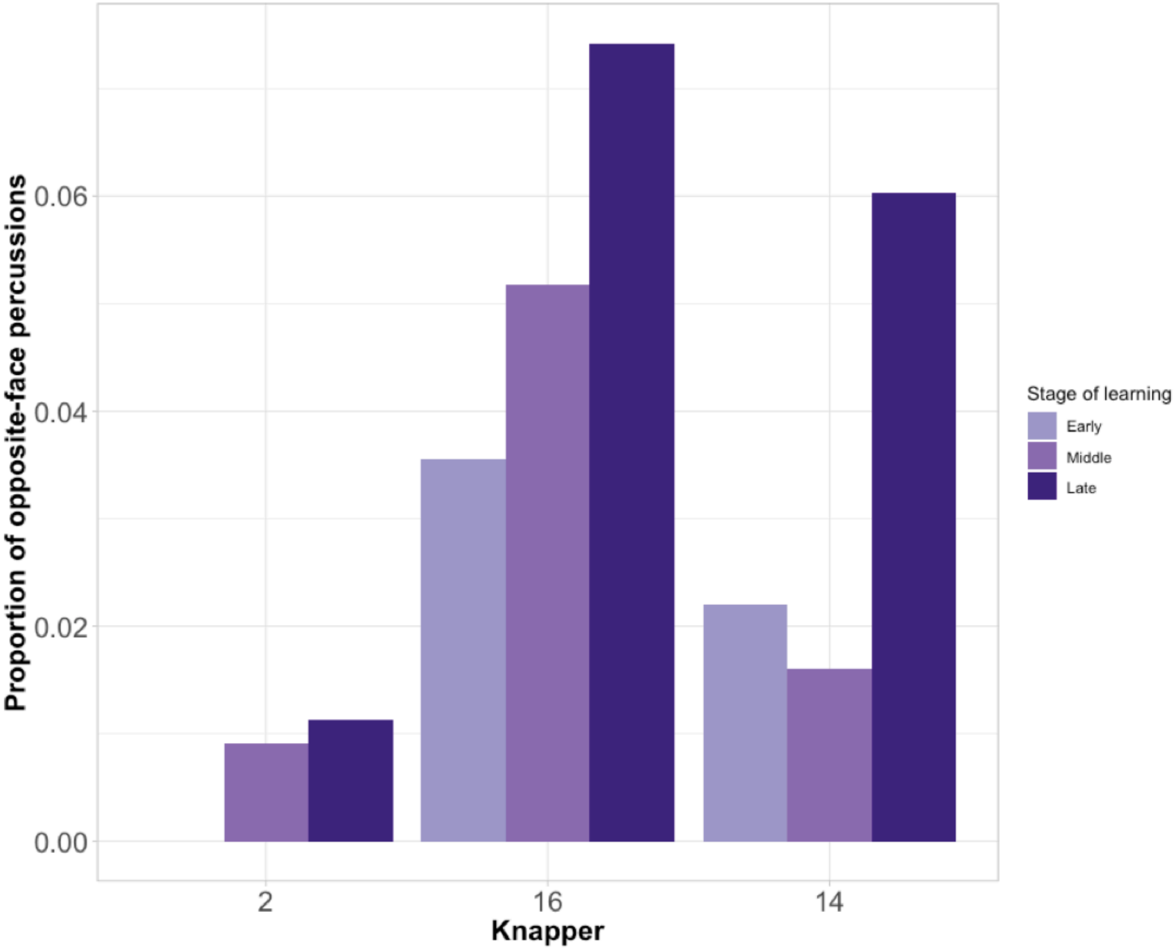

Figure 7: Proportion of opposite-face percussions per knapper

I also consolidated percussion proportion data on other kinds of percussions the knappers perform. These results have been presented in table 6. All knappers used light percussions most frequently in the early-stage, and same-point percussion in the middle-stage. Knappers 14 and 16 use light percussions most often in the late-stage assessment, while knapper 2 uses light percussions most often at that stage.

Table 6: Summary of ratio of different percussion types to total number of percussions per stage

Knapper	2			16			14		
Stage of learning	Early	Early	Early	Early	Middle	Late	Early	Middle	Late
Laterally Adjacent	0.066	0.031	0.031	0.031	0.074	0.048	0.057	0.074	0.048
Light Percussion	0.604	0.763	0.763	0.763	0.421	0.459	0.484	0.421	0.459
New-Point Percussion	0.022	0.027	0.027	0.027	0.041	0.062	0.033	0.041	0.062
Same-Point Percussion	0.307	0.144	0.144	0.144	0.447	0.371	0.403	0.447	0.371

iv) Flake Detachments

All subjects had more detachment events in their late-stage assessments than they did in their early-stage assessments. The trend in the middle-stage assessments varies across knappers. Knappers 14 and 16 detaching more flakes in the middle stage than in the early stage, whereas knapper 2 detached fewer. Furthermore, knappers 2 and 14 have more detachments in the late-stage than they do in the middle-stage, whereas knapper 16 has fewer.

Table 7: Number of flake detachments per stage

Knapper	2			16			14		
Stage	Early	Early	Early	Early	Early	Late	Early	Middle	Late
Absolute Number of Flake Detachments	41	32	57	57	57	71	32	53	81

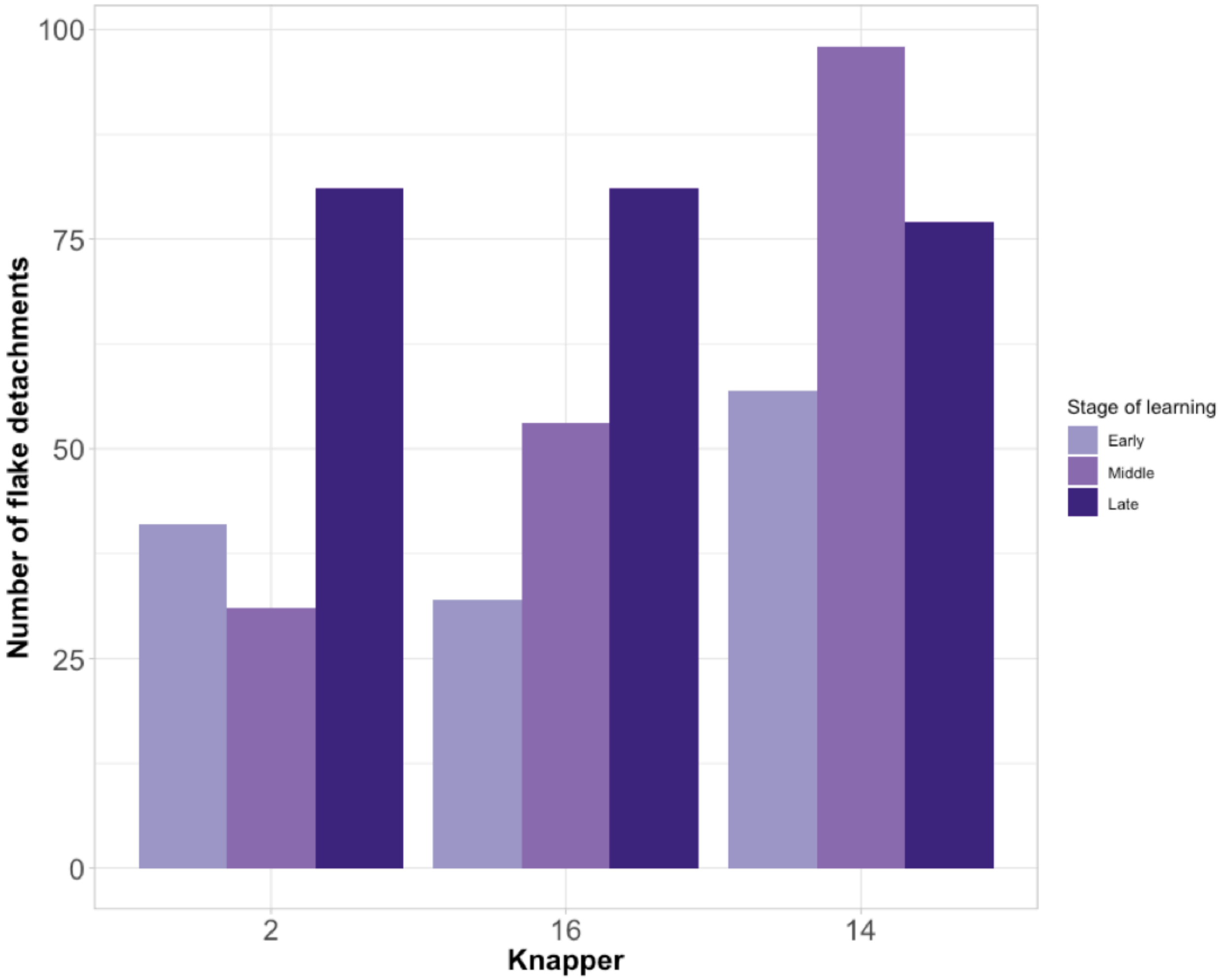

Figure 8: Total number of flake detachment events per stage of learning

All subjects take fewer strikes in their late-stage assessments to detach flakes than they did in their early-stage assessments. There is a sequential decrease in the strike to flake ratio as the stages progress with knappers 14 and 16. Knapper 2 deviates from this trend, with noticeable spike in the strike to flake ratio in the middle-stage assessment, followed by a drop in the late-stage.

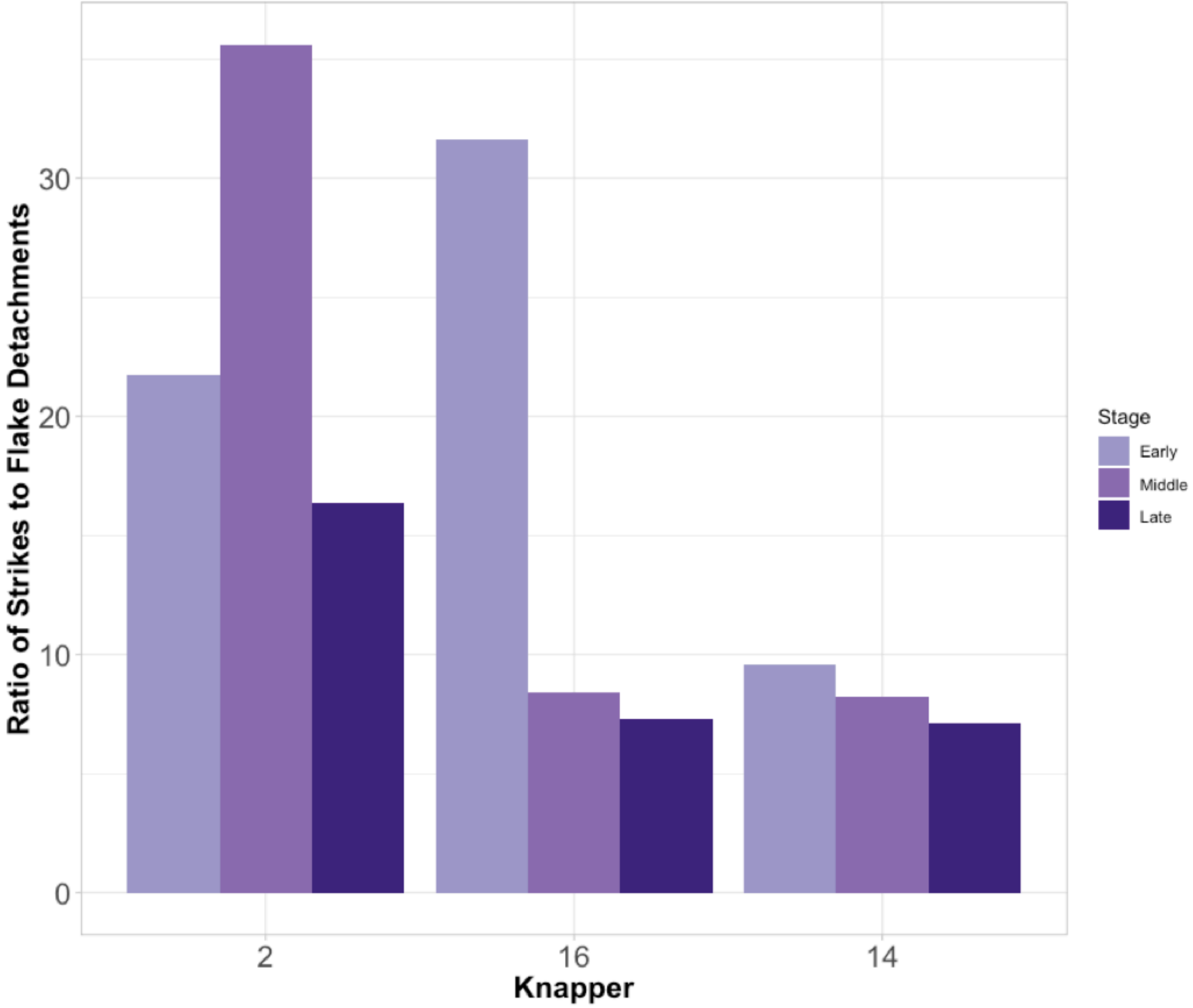

Figure 9: Ratio of total number of strikes to total number of flake detachment events per knapper

II. Results from Lithic Data

i) Flakes

There is a sequential decrease in the ratio of number of strikes to number of complete flakes produced as the stages progress for knappers 14 and 16. The trend is reversed in knapper 2, where we see an increase in the ratio as the assessments progress.

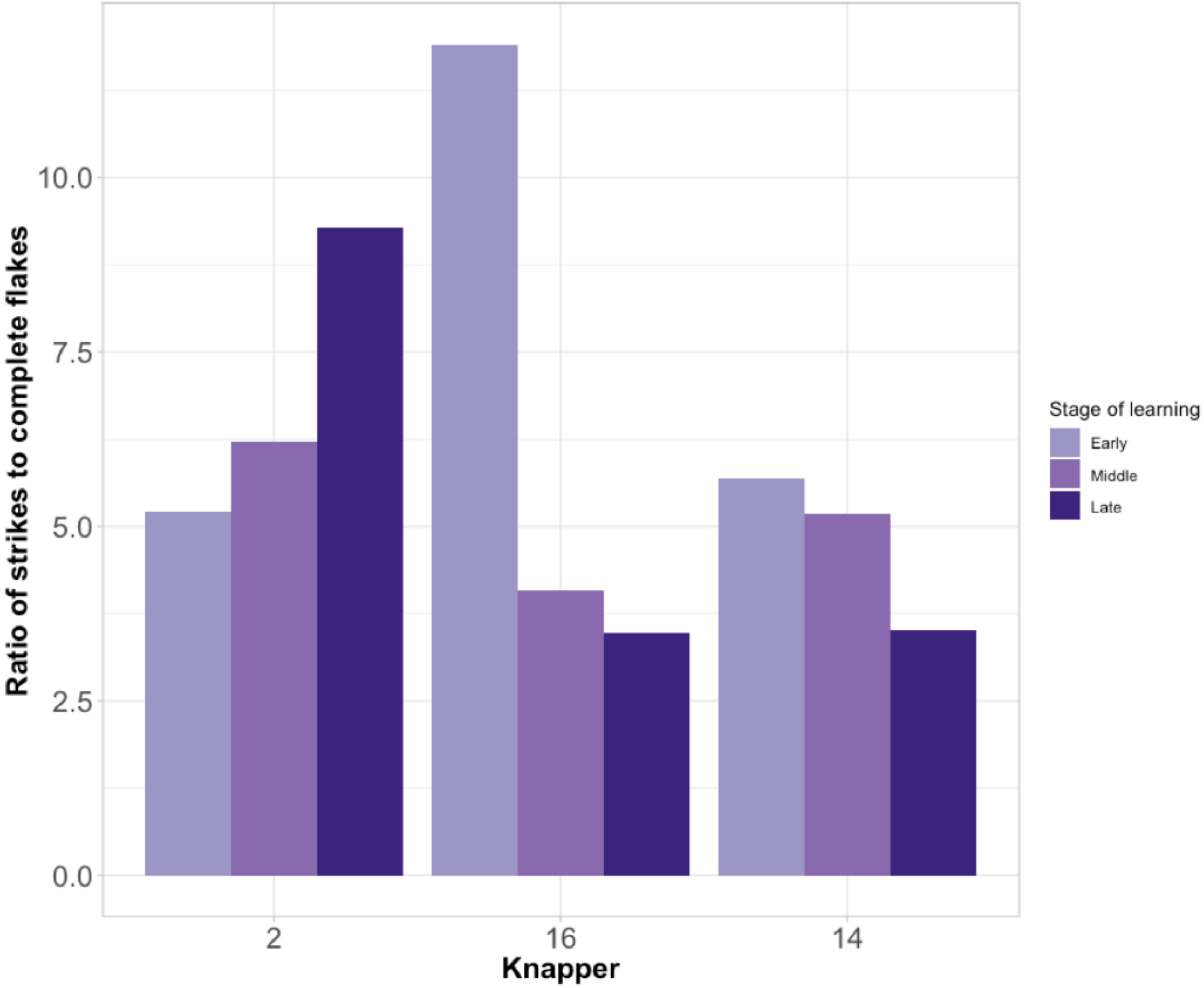

Figure 10: Ratio of total number of strikes to total number of complete flakes produced per knapper

All subjects take fewer strikes in their late-stage assessments to produce outlier flakes than they did in their early-stage assessments. While knappers 14 and 16 take more strikes to produce large, outlier flakes in their middle-stage assessments than in the early-assessments, knapper 2 takes fewer.

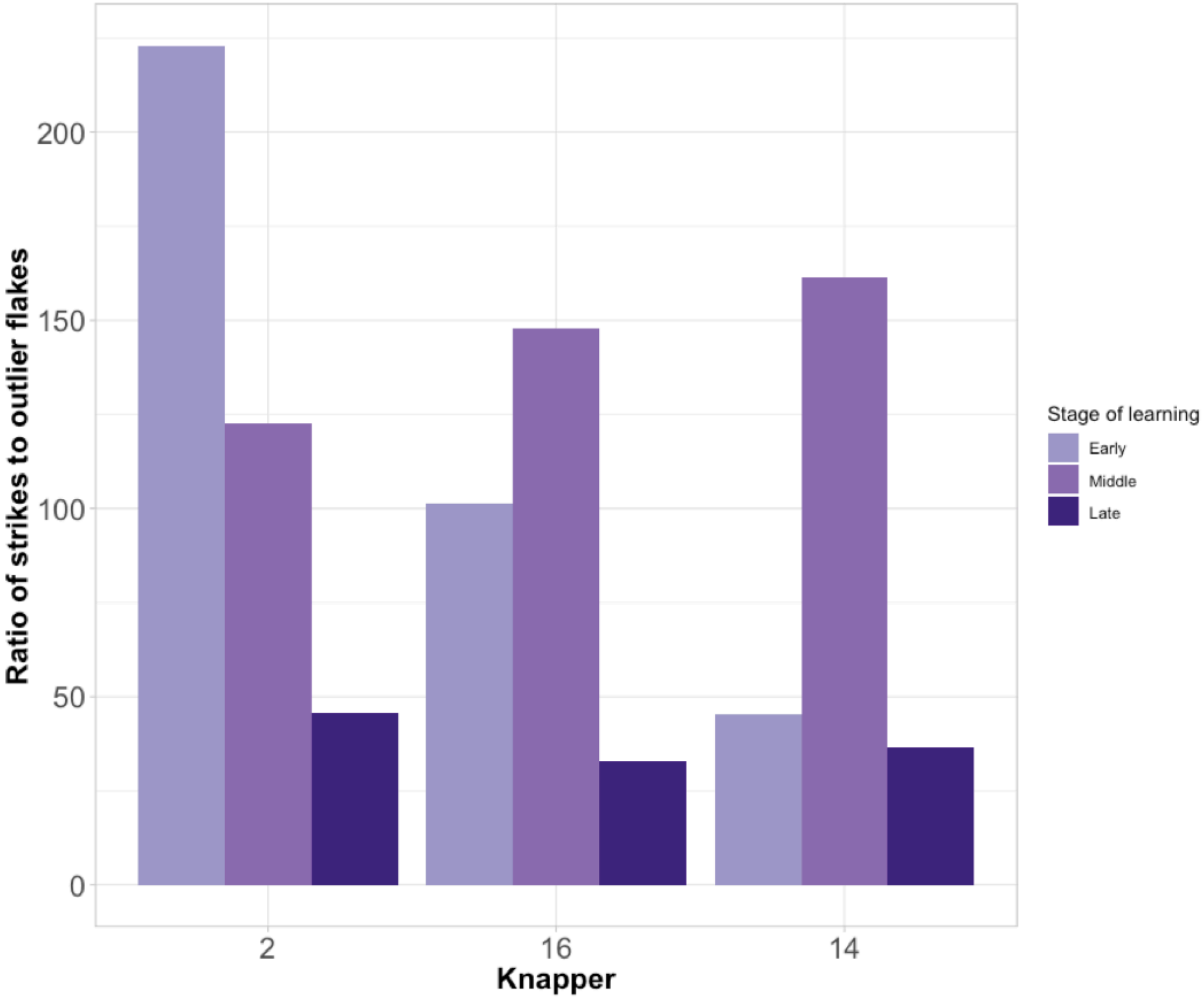

Figure 11: Ratio of total number of strikes to total number of outlier flakes produced per knapper

ii) Handaxes

There is a linear negative correlation between flake scar density, and delta weight (i.e. the difference between the mass of the initial core, and the handaxe); there exists a less steep linear, negative relationship between number of complete flakes produced and delta weight. There is no correlation between number of percussions, and handaxe metrics such as flake scar density, unflaked area, or delta weight. Knapper 14 and knapper 16 cluster together in performance in all these analyses. There is also no correlation between percent of handaxe bifacially flaked, and number of opposite-face percussions.

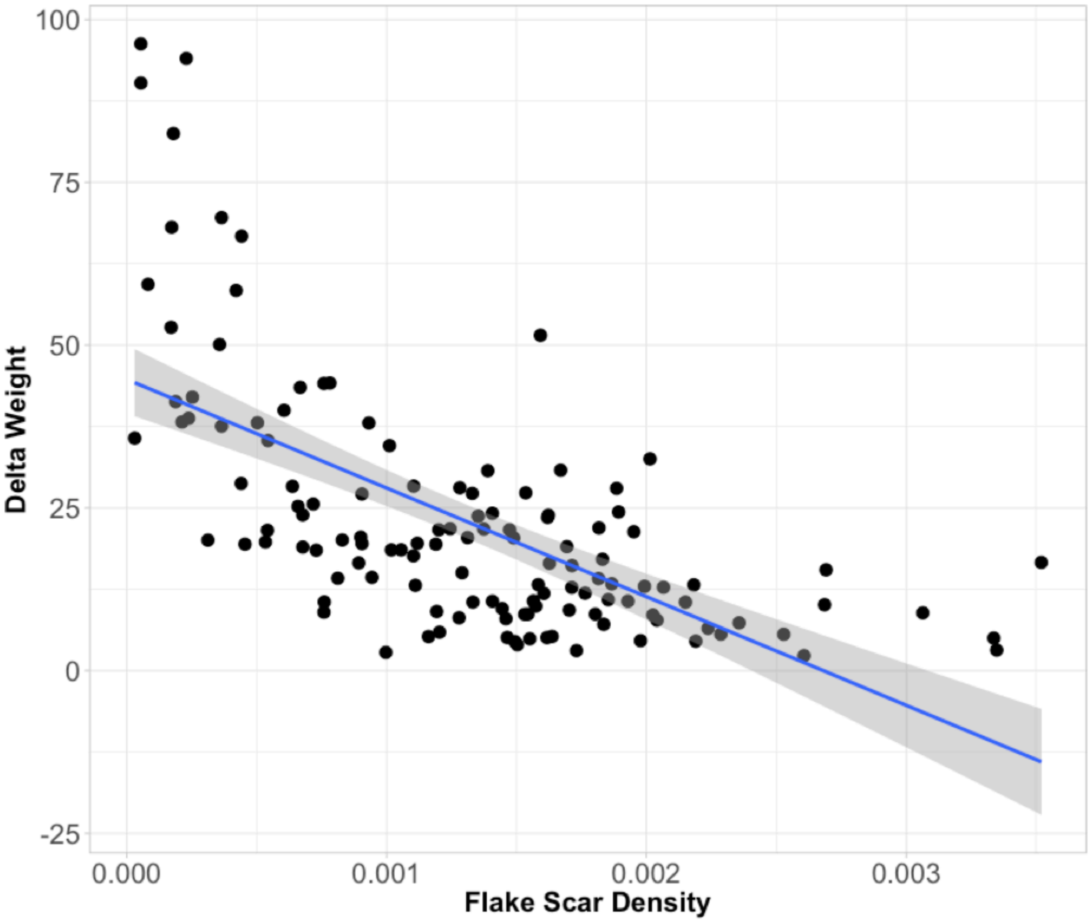

Figure 12: Correlation between delta weight and flake scar density across all knappers and assessments

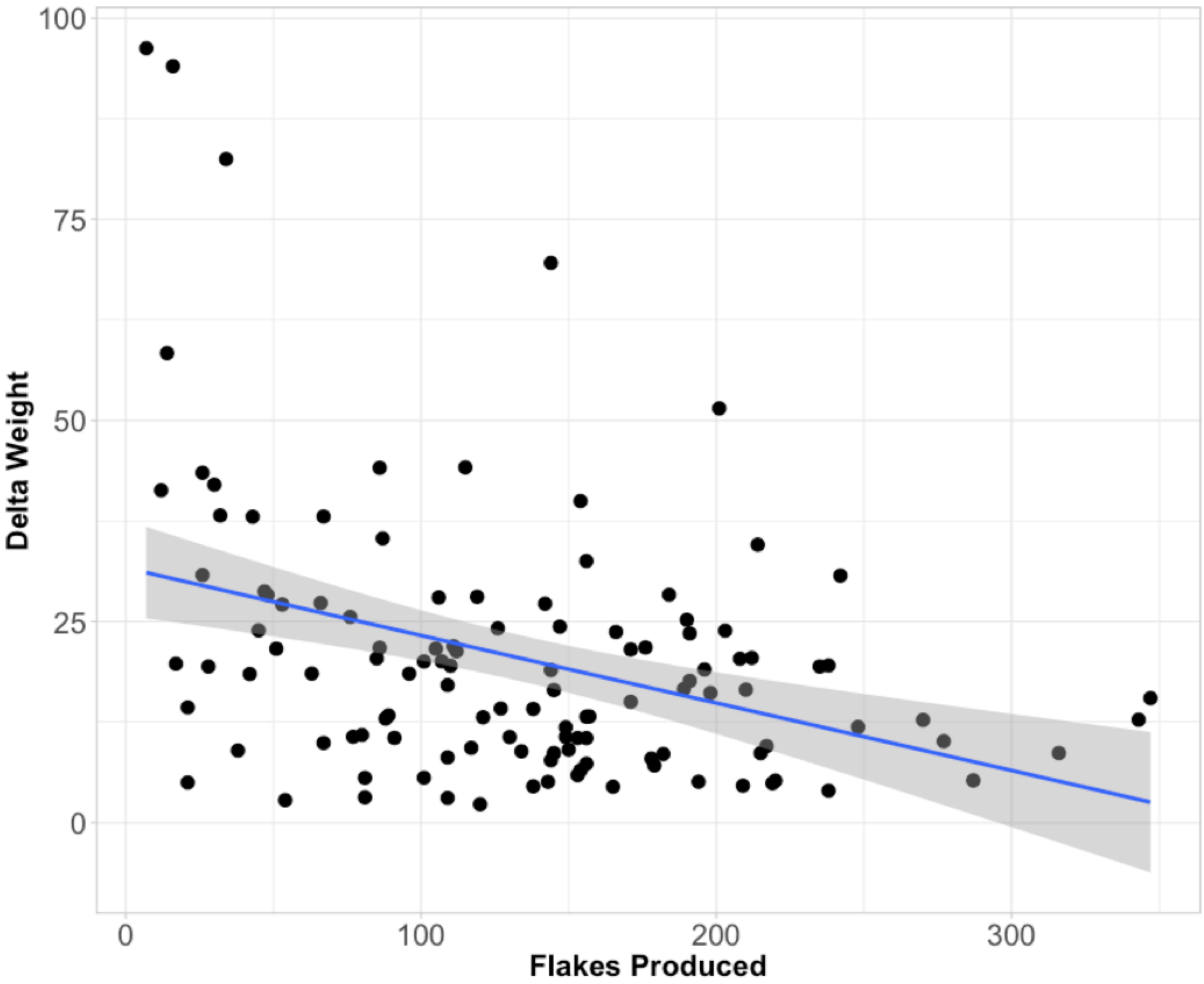

Figure 13: Correlation between delta weight and number of complete flakes produced by every knapper over all the assessments

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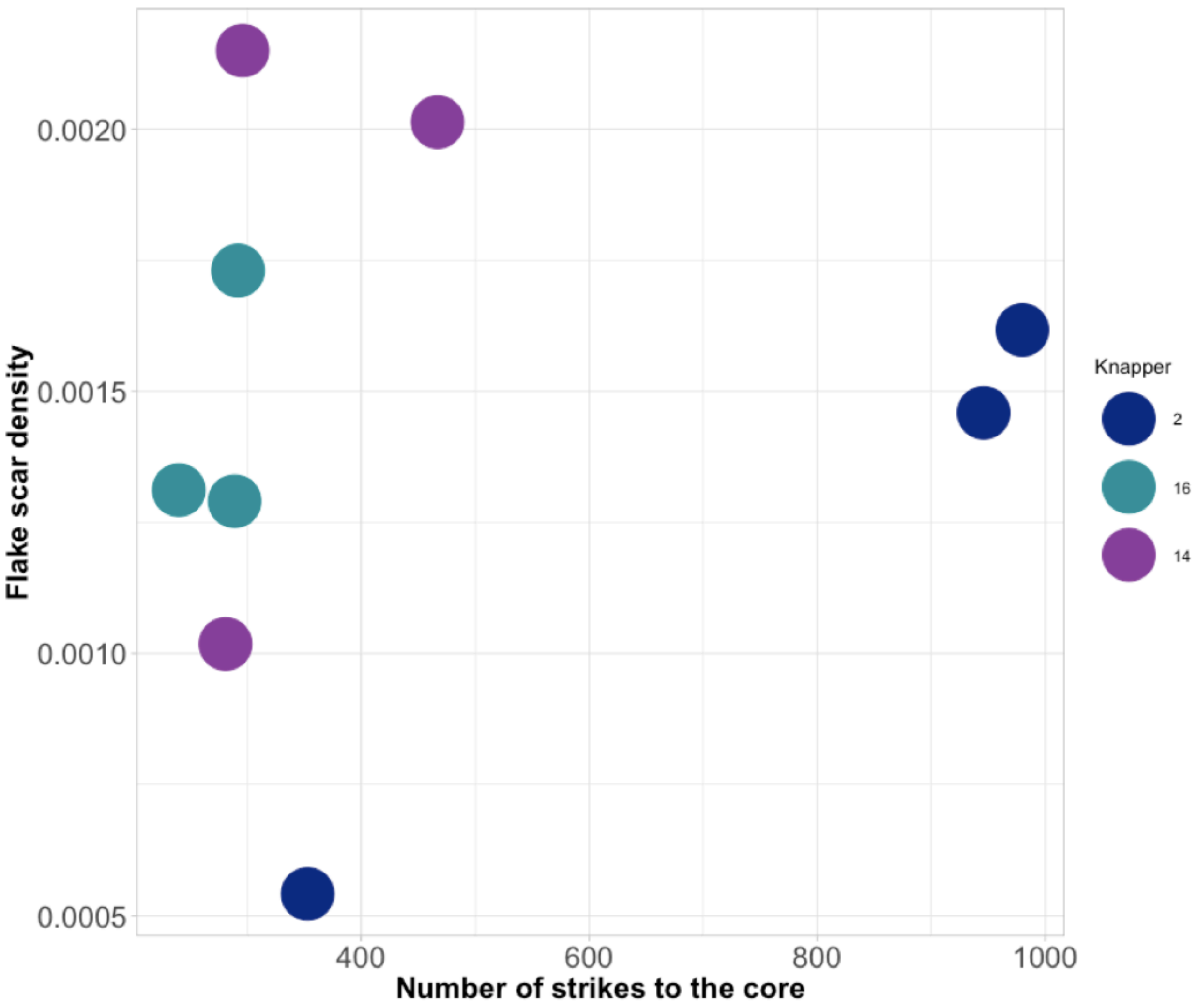

Figure 14: Correlation between flake scar density of the handaxes and the total number of strikes to the core. The different colors represent different knappers

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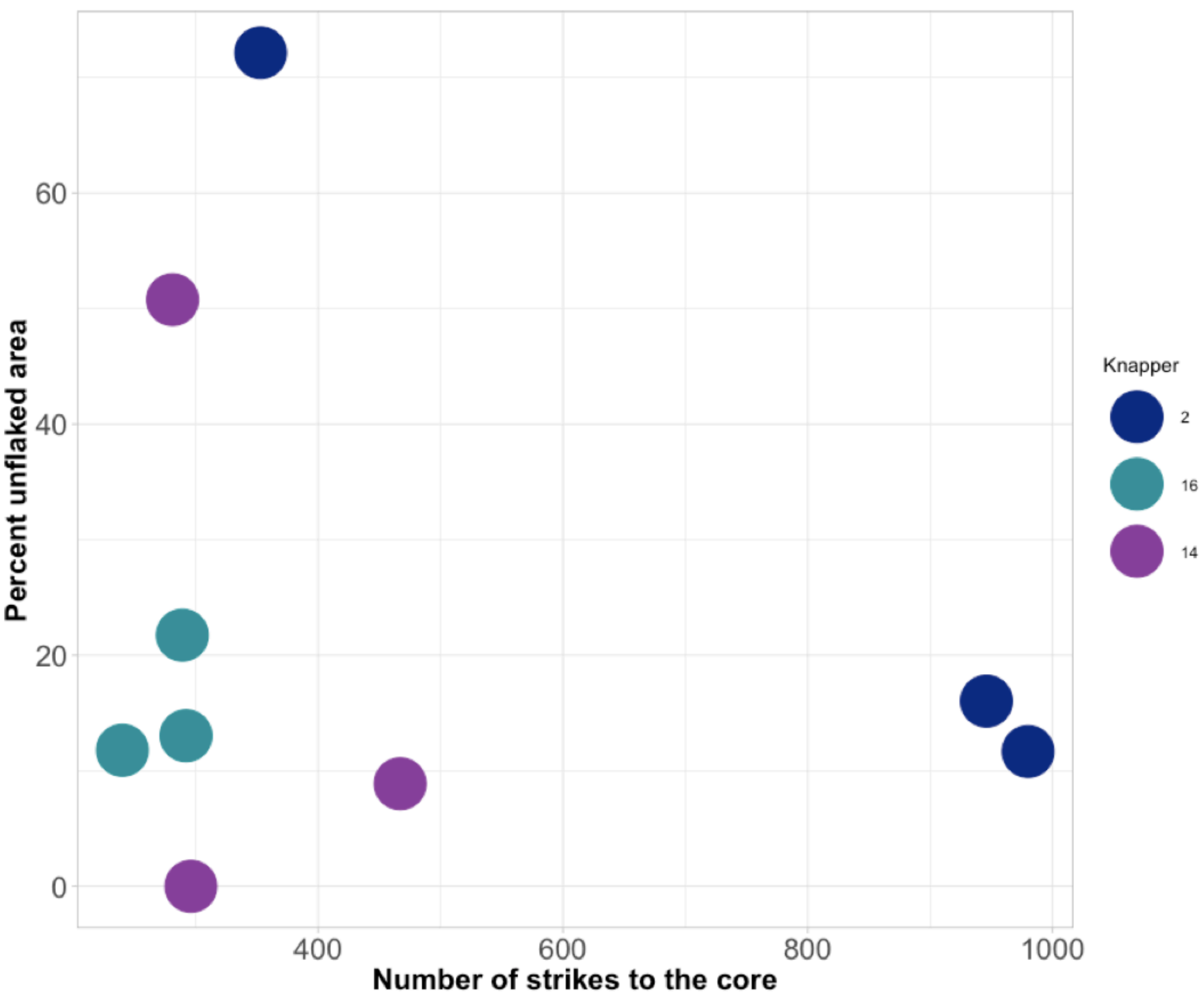

Figure 15: Correlation between percent of handaxe area left unflaked and the total number of strikes to the core. The different colors represent different knappers

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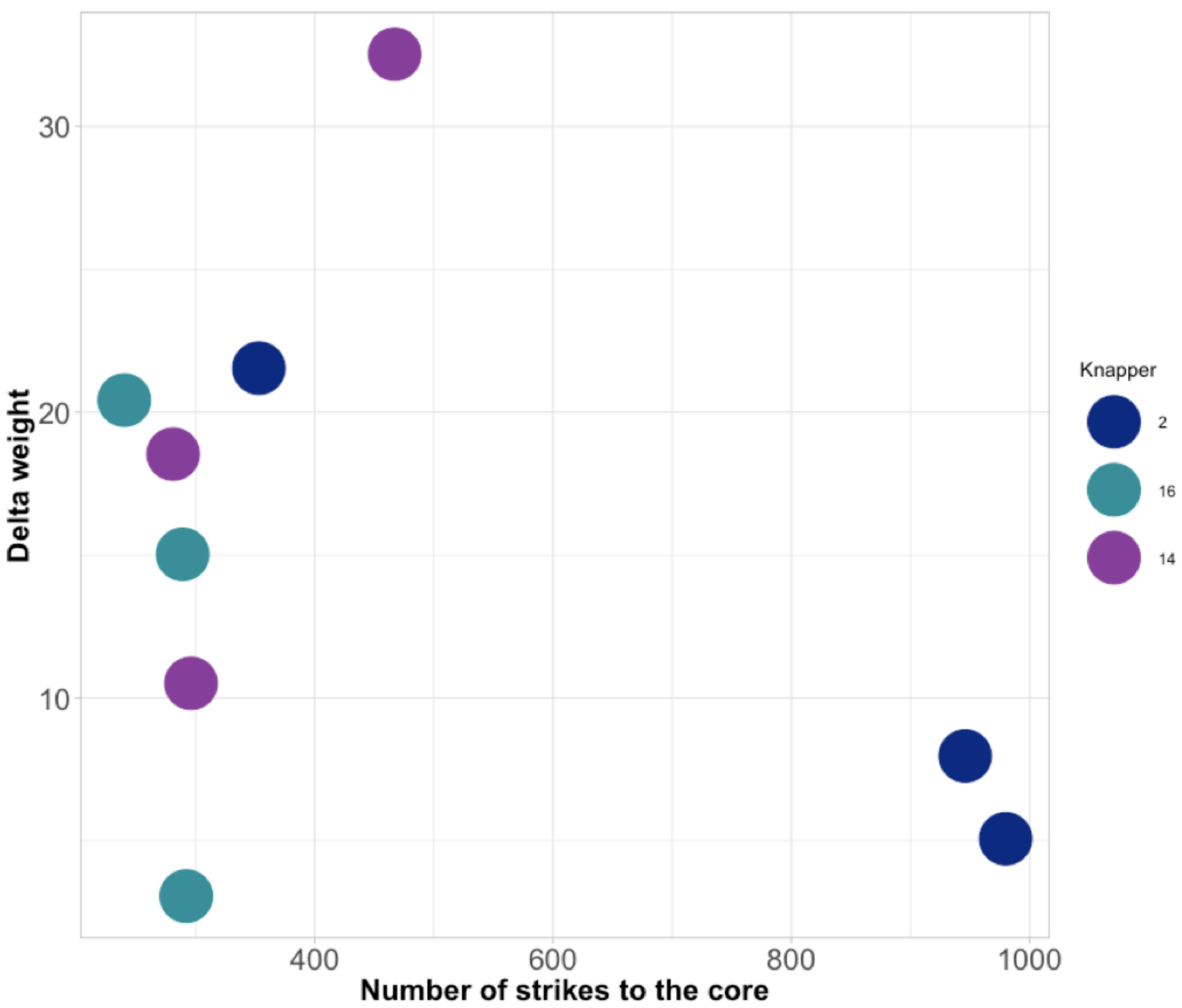

Figure 16: Correlation between delta weight, and the total number of strikes to the core. The different colors represent different knappers

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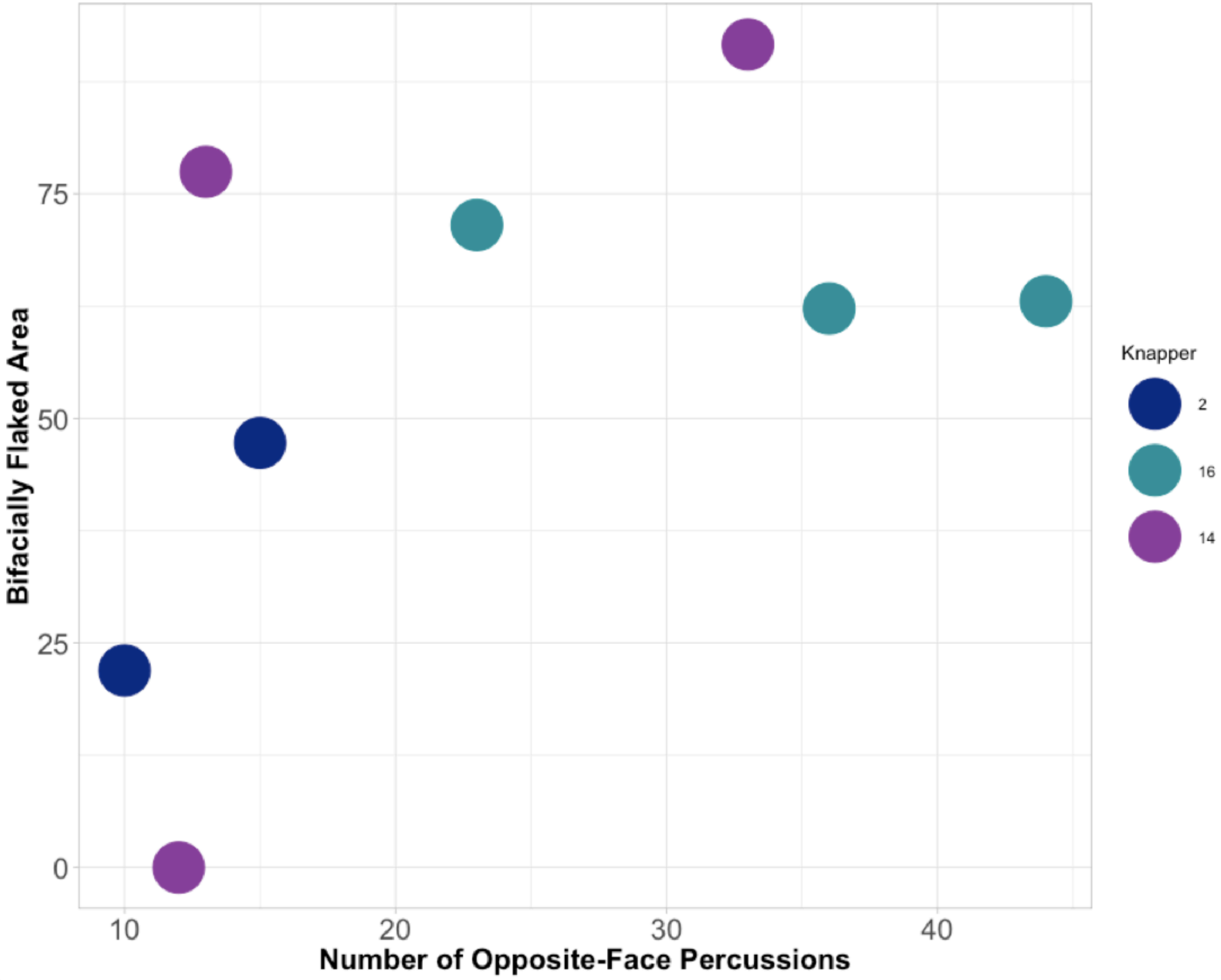

Figure 17: Correlation between bifacially flaked area on the handaxe and the total number of opposite-face percussions. The different colors represent different knappers

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III. Results from Qualitative Analysis

Knappers displayed several idiosyncratic and infrequent behaviors that are very prominent in the pre-training handaxe making session, but quickly disappeared in subsequent sessions. These behaviors include changing postures, and percussion supports, fidgeting with the hammerstone, core, or mat, and humming. Actions I classified as "fidgeting" were not directly benefiting the goal of flake-production. For example, some knappers would throw the hammerstone into the air and catch it, as one would do with a ball. Another example of fidgeting would be instances where subjects excessively wipe away dust from the core either using their hand, or by blowing on the core. These actions usually occurred in the early assessments.

I also analyzed the contents of the knappers' conversations during the knapping session. Most conversations were less than a minute long, and mainly revolved around the knapping activity. Sometimes knappers would try to explain out loud to the instructor why their handaxe turned out a certain way, or even predict how the core would break.

An analysis of the pre-training survey revealed some of the motor skills the subjects already knew to perform, and how proficient the subjects considered themselves to be at the task.

Table 8: Overview of motor skills the subjects had knowledge of prior to participating in the experiment

Knapper	**Skill**	**Years of practice**	**Level of proficiency**
2	Beading	1	1
16	Carpentry	30	4
	Woodworking	5	3
	Welding	2-3	1
14	Printmaking/Book Binding	30	4-5
	Carpentry	35	3
	Metal Work (sculpture)	30	3

Discussion

I coded for actions performed by novice knappers in order to analyze the strategies and behaviors they adopt as they learn to make handaxes, and link them to the lithic artifacts they produced over those assessments. Firstly, results illustrated that there is a wide variability in the behaviors and knapping strategies of each of the knappers despite being given similar training over an extended period of time. Poor performance could be traced across the handaxes, flakes, as well as the behaviors. In particular, the poorest performer struggled to work bifacially, and detach flakes from the core even towards the end of their 90-hour training periods. The behavioral variability across knappers might be a result of their variable toolmaking aptitudes, determined at least in part by prior experience. Secondly, our results highlight that while there exists a correlation between handaxe metrics, and between handaxe metrics and lithic debris, knapping behaviors don't correlate with handaxe metrics. This indicates that observable artifact features are not always good predictors of behavior, especially when variable behaviors result in equifinal lithic products. These findings demonstrate the value of behavioral analysis in experimental archeology, and open doors to new avenues of methodological approaches towards answering more questions about toolmaking, and skill-acquisition.

I. Behavioral variation

I predicted that subjects would spend more time inspecting the core in the early stages of training, and they would spend less time inspecting the core towards the end of their training period. This expectation was based on the hypothesis that as they progressed through their training and gained hours of practice, they would be able to employ knapping strategies without having to consciously think through them every time. In the case of subjects 2 and 16, this prediction holds true, with both spending roughly 60% of the time inspecting the core in the early-stage, and dropping to about 45% in the late-stage. Subject 14 however, does not follow this trend, spending roughly 53% of their time in the early-stage, and 60% of their time in the late-stage inspecting.

Subjects show the most variable inspection times during the middle-stage assessment. Subject 2 spent the same amount of time inspecting the core in the middle-stage as they did the early-stage. Subject 14 spent slightly less time inspecting the core in the middle-stage compared to the early-stage (48% vs. 53%), whereas subject 16 spent a lot more time inspecting their core in the middle-stage than in the early stage (70% vs. 60%).

Subject 16's performance in the middle-stage assessment, and subject 14's performance in the late-stage assessment, do not fit my prediction of reducing inspection times with practice and training. Instead in both those cases we see an increase in inspection times. These observations can be explained in the light of accidental core splitting. In both these assessment sessions, the core broke in half mid-knapping. According to the experimental protocol, if the subject's core broke in half, they were asked to choose one half of the core and continue to make a handaxe out of that. They could not switch out once they had decided on work with one half. Thus, the subjects spent many minutes evaluating each of the broken halves carefully to assess which one showed most potential to be turned into a handaxe. Thus, the deviation from the expected trend in inspection times could be due to the occurrence of the unexpected core-splitting event, requiring the subjects to re-evaluate their knapping strategies.

Bifaciality is a defining characteristic of the handaxe. Core-flips, and opposite-face percussions are both good measures of whether an individual is working on both faces of the core. Thus, I predicted that we would observe more core-flips, and opposite-face percussions as the stages progressed, since I hypothesized that with training and practice, the subjects would learn to work the core more bifacially. The data show that knapper 2, who made the poorest handaxes, also consistently performed fewer core flips and opposite-face percussions than the other two subjects. This suggests that their poor handaxes might be a result of them not working bifacially. Thus, video analysis yields similar results about knapper performance as lithic analysis of the handaxes.

Flake removal is a basic aspect of handaxe making, since the core cannot be shaped unless mass is taken off it. I expected to see more flake detachments as the subjects gain practice. Similarly, I expected lower strike to flake ratios as subjects as the assessments progressed, meaning they were able to get more flakes with a fewer number of strikes to the core. While we do see an increase in flake detachments between the early-stage and late-stage assessments, the middle-stage assessments are more variable. Knappers 14 and 16 show similar trends in their ratios of strikes to flakes produced across assessments, while knapper 2 once again follows a different trajectory.

The video data also shed light on how strategies adopted by the three subjects compare to one another across stages. All knappers used light percussions most in the early stage, and same-point percussions in the middle-stage. This suggests that they have similar strategies in the early-stages. While knapper 2 keeps using same-point percussions for the most part in the late-stage, the other two knappers switch back to using light-percussions. This could be understood in the context of give-up times. An important aspect of the knapping strategy is to gauge if and when to give-up working on a particular part of the core, judging whether the energy and time being put into striking the same part of the core repeatedly is worth the results it will produce, if any. In this context, it would seem that knapper 2 takes longer to give-up on working one point on the core. They tend to stay fixated on a certain point on the core more than the other two subjects, who move onto another point on the core faster. This observation is also corroborated by the higher proportion of new-point percussions in knappers 14 and 16 compared to knapper 2. Given knapper 2's poor handaxe scores, it suggests that giving up quicker on striking repeatedly at one point, and instead using that time and energy to move on to another point or another task such as platform-preparation is a more productive strategy. The correlation plots of strikes and reduction intensity metrics also show that knapper 2, the knapper who performed most poorly, did not cluster with the other two knappers, suggesting once again that this subject employed different strategies compared to the other two, who cluster together relatively closely.

Qualitative analysis also revealed variable behaviors. In the pre-training assessments for example, some subjects switched hammerstones often (15+ times over the span of an hour), others 5-6 times over a half hour, while others still never switched their hammerstones. This variation in hammerstone-switching decreased as training progressed. We could hypothesize that the reason for this pattern is that at the outset of the training, some subjects were more inclined to investigate and familiarize themselves with the range of hammerstones available. Towards the end of the experiment, they were familiar enough with the task and equipment to know which hammerstones they preferred. Sometimes, instead of switching-out a hammerstone, subjects would turn their hammerstone in-hand to exploit a different hammering edge. This is indicative of an understanding of how striking with different angles on the hammerstone would affect flake production on the core. The subjects' postures, on the other hand, were more fixed in the early assessments than in later ones. For example, in the earlier assessments, subjects placed the cores firmly on the protective mat, supporting them on their thigh, and almost never lifted the core up, even during inspection. One could posit that the size of the core plays a role in whether it is held in-hand or placed on the mat. However, in the first assessment, the core was supported on the mat even when it had been reduced to a manageable size for holding in-hand. Percussion support has been highlighted as being significantly different between novice and experienced knappers in another smaller-scale experimental study (Geribàs et al., 2010). Qualitative analysis of subjects in my study suggests that as knappers grew more familiar with the task, they moved between postures more, switching between placing the core on the mat, and holding it in their hand.

Some knappers fidgeted by gently throwing the hammerstone and catching it. Bingham and colleagues (Bingham et al., 1989) describe this kind of 'hefting' behavior in individuals preparing to throwing a rock far distances. They reason that participants display hefting behavior to judge the dynamic properties of the rock. Predictive processing framework (Clark, 2013) posits that we are constantly generating certain predictions about the environment based on prior knowledge, and reacting to the dissonance between expected and observed events. We could hypothesize that we notice hefting behavior in our subjects for similar reasons as Bingham et. al. did, where participants are making an effort to familiarize themselves with the physical properties of the hammerstone, while simultaneously implicitly learning and committing to memory how hammerstones with different properties interact with the core in various ways, thereby enhancing their predictive powers about the given task. Another form of fidgeting was excessively wiping away dust from the core. These actions usually occurred in the early assessments. They also coincided with inspection of the core, while the knapper was trying to plan their next steps. Some knappers also occasionally whistled and hummed while knapping. Feltovich and colleagues (Feltovich et al., 2006) discuss the "limit of attention" as a constraint on performance of novices in laboratory-based tasks. They state that we can only engage with a region of time, and space at once. When faced with a novel task, we can only focus our attention on solving one problem or making one decision at a time. Usually, we can retrieve information from long-term memory and bring relevant knowledge forward to working memory based on the data collected from the environment using the perceptual systems. However, in cases where there is a dearth relevant data to pull from in long-term memory (i.e. in a case where they are inexperienced at a task), attention switches quickly to a different task. Thus, some of the behaviors categorized as "fidgeting" may be due to an attention deficit caused by lack of experience with the task at hand. It is possible that these behaviors are a combination of attention deficits and information gathering for predictive processing.

The best knapper included in this study (knapper 14), who consistently performed better than the rest of the cohort in all assessments, reported having more than 30 years of experience in metalworking (sculpting), carpentry, printmaking and bookbinding. Both metal sculpting and carpentry require gross motor skills, whereas booking-binding and printmaking require a mixture of gross and fine motor skills. The intermediate knapper (knapper 16) reported three-five years of experience with painting, welding, and carpentry. The knapper with the poorest performance in the study (knapper 2) reported having one year of experience with beading as their only skill, which is an activity that relies only on fine motor techniques. The ability to produce even simple flakes by striking the core requires a certain level of familiarity with the given materials, and basic fracture mechanics, which most people might not be exposed to in their day-to-day lives.

II. Relation to artifacts

Due to the positive relationship between flake production, and core reduction, I expected lower strike to flake ratios as subjects as the assessments progressed, meaning that the subjects were able to produce more flakes with a fewer number of strikes to the core. While we do see an increase in flake detachments between the early-stage and late-stage assessments, the middle-stage assessments are more variable.

Overall, there is a dip in the learning curves of the subjects based on handaxe model scores. This dip occurs in the middle-stage assessments, and might help explain some of the patterns we notice when considering performance in the middle-stage assessments. For example, it is at this stage that both knappers 14 and 16 struggle to produce large flakes, and flake detachment becomes progressively harder for knapper 2.

Shipton and colleagues (2015) argue flake scar density to be a good predictor of how heavily the core has been reduced. The correlation plot of delta weight (as a measure of reduction intensity) and flake scar density (figure 12) yields a linear negative trend, thus verifying the claim made by Shipton and colleagues. Both delta weight, and flake scar density are measurements collected using the core alone. The correlation plot of delta weight and number of flakes produced every assessment (figure 13) follows the predicted trend, but there is more variability in the plot than in the delta weight ~ flake scar density plot. Finally, correlation plots between number of strikes to the core and measures of core reduction (flake scar density, delta weight, percent unflaked area) follow no noticeable trend, and are highly variable. For a given number of strikes, there is a large amount of variability in delta weight, meaning the knappers are often striking the core with varying amounts of success. Similarly, a variable amount of strikes may result in the same change in handaxe metrics.

There appears to be no correlation between number of opposite-flake percussions and percent of bifaciality. We can interpret this result in two ways. Firstly, the result could highlight a dissonance between lithic, and behavioral data. Our data from frequency of opposite-flake percussions (refer to Figure 7) suggest that the knappers are, on average, performing more opposite-flake percussions as they gained practice. Since the correlation plot between percent of handaxe bifacially flaked, and number of opposite-percussion performed show no relationship, this suggests that thought the knappers may have been performing the actions associated with bifacial knapping, their behavior did not translate onto the core. Secondly, we would expect to see a positive correlation between these two variables assuming knappers were continuously switching between the two faces on the core such that they were taking off flakes from each face alternatingly. Since we do not see a correlation, this could suggest that knappers are able to create bifacial edges without employing opposite-face percussion. For example, the knappers could be performing multiple strikes on one face, working their way around the edge before turning it over and repeating the process. The final product in this case would be the same as one produced due to alternating percussions on opposite faces. The archeological record is susceptible to the problem of equifinality (Hiscock, 2004), meaning different processes yield similar products. The data presented above illustrate that fact, in addition to the fact that relationships between lithic metrics become harder to interpret as you move from handaxe, to flakes, and finally to behavior. A variety of behaviors can be implemented to arrive at the same lithic product. Thus, researchers must adopt caution when interpreting behaviors based on lithics alone in the archeological record.

The gap between lithic and behavior can also be observed in the difference of the Y-axis scales across the graphs representing strikes to flake detachment, strikes to complete flakes, and strikes to outlier flakes (refer to figures 9, 10, and 11). For example, looking at knapper 14's early-stage assessments across the three graphs, we see that they took roughly 10 strikes to detach a flake, 6 strikes to produce a complete flake, and 50 strikes to produce an outlier flake. Firstly, this reveals that multiple complete flakes are produced during each flake detachment event. It also tells us that producing outlier flakes, which are instrumental to thinning and shaping the handaxe, is a skilled task that novice knappers seldom perform. Once again, these results present a cautionary tale about using lithics as the direct proxy for behavior when interpreting lithics from archeological sites.

III. Methodological lessons

The observed deviation of inspection times from the predicted trend is a good example of why reliance on quantitative data alone is not sufficient to provide a clear picture of the knapping process. An unforeseen event such as the core splitting in two can throw the knapper considerably off course, presenting them with a new challenge, and disrupting their flow of thought. It introduces a major change to the course of the session. For example, the predicted trend for opposite face percussions is disrupted in the case of the middle-stage assessment for knapper 14. This could be explained in light of the core-split event during the session, following which the knapper chose to work with the split half of the core that was already thin to start with. Thus, perhaps they did not need to manipulate and thin the core bifacially as much since it was already thinned.

There are several ways for researchers to deal with a core-splitting event during an experiment. For one, we could just ignore the time the subjects spent deciding between the two halves. However, this would not be true to the knapping process for two reasons. Firstly, we cannot predict how the session would have progressed had the core not split. The session may have run longer because the unbroken, larger core would have to be reduced more than the split half. Alternatively, it could have run shorter because the subject was not faced with a challenging situation. Secondly, unexpected events such as core-splitting are a part of the knapping process.

Cores are often non-uniform, and it is often impossible to gauge the quality of the inside of the core based on its cortical appearance. How knappers approach solutions to a challenging situation can be informative of how they understand the problem at hand, and of the characteristics of the core they think will aid them in turning it into a handaxe. For example, both knappers chose to continue working on the half that had a more pointed end. Subject 16 states his reason for picking the thinner half with a somewhat pointed end over the larger, chunkier other half of the core as, "... go with this one. This is at least closer to the shape [of the handaxe] than that one...," demonstrating that their reason for picking the half they did was its physical resemblance to the end goal. One way to avoid encountering a situation like this in an experiment is to set up the experimental protocol such that the subjects can choose to switch out to a new core when the core they are working on splits in half. But once again, this runs the risk of bypassing a realistic, challenging situation that any knapper can run into, that ultimately speaks to the expertise-level of the knapper. Thus, data collection and analysis should be taking into account both the absolute quantitative data (i.e. amount of time spent inspecting), as well as the qualitative data (i.e. how did the knappers react to the situation) from the videos of the knapping sessions.

Qualitative analysis of the contents of the subjects' speech during the sessions is a novel contribution of this project, providing insight into some of their thoughts while knapping. While most subjects talked to the instructor, one subject often talked or muttered to themselves about how the core fractured, or where to strike it next. How often, and how much different subjects talked to the instructor varied from knapper to knapper throughout the study. Topics of conversation also varied. While most subjects would talk to the instructor about their thought process or next steps, others have a more casual conversation about things unrelated to knapping.

It is important to keep in mind that the knappers were never prompted to talk about the knapping process during the assessments. They volunteered the information themselves. It is interesting to note that knappers talking about the knapping process were often either justifying why they were not able to perform the way they wanted to (“Is this a bad rock?”, “There is a huge crack in this core…”), or preempting why something they planned on doing might not work.

Analyzing the contents of conversation can also provide a window into the factors that motivate knappers, experts and novices alike. One knapper for example, finding themselves in a dilemma about how to proceed with knapping exclaimed, “I can’t give up now. I’ll look terrible.” Clearly, some participants were more heavily personally invested in the learning process and its outcomes. In many ways, tool-making is a performative task, even in environments where the tools have a practical function. Ethnographic work with the adze makers in New Guinea highlights the importance of the social dimension of knapping in communities that still practice stone toolmaking (Stout, 2005). Aspiring toolmakers must prove their seriousness, and dedication towards the craft to an expert if they wish to be taken under their wing as apprentices. Despite the shift from heavy reliance on the tool, adze-makers attach a sense of pride and identity with the craft. The subject in my study airing her concern about how an examiner might view her based on her handaxe points to the same phenomenon of motivation to do well being intertwined with emotions like prestige. While we might expect this from adze-makers who have a long history of cultural inheritance of the skill, we do not expect to see it much in the cultural context within which our experiment was conducted. Unlike the adze-makers, our subjects did not come from a background where handaxes have a socio-cultural value. Yet we see them adopt similar attitudes towards toolmaking in the way they associate the skill with self-worth. These results show that one isn’t just focused on the core and the hammerstone while making tools, but also on one’s surroundings, including the people in it. Learning to make tools is not always just about seeing the goal of making tools to completion by having certain internalized, mental strategies, but rather a complex interaction between multiple factors, both internal and external to the knapper.

Future Directions

The behavioral data highlight that the variation in handaxe quality is due to the different strategies employed by different individuals, and poorer handaxes are not just the result of fewer hours of practice. This raises the question of how individuals receiving the same training for the same amount of time choose to approach the same task is various ways. Analysis of previous experience with manual skills strongly suggests that aptitude of the knappers, determined at least partly by their past experiences, plays an important role in predicting performance. Analysis of their training sessions will shed light on what kinds of behaviors the subjects displayed and how that might have affected the learning process, leading to differential performance. Skill-acquisition experiments similar to this one must adopt base-line cognitive tests to quantify factors that might affect aptitude such as attention-span, maturity, and self-worth assessments, among others. It would also be fruitful to control for the age, and sex of subjects included in the study.

Analysis of sequential data is another avenue of future work. Certain knapping processes are dependent on actions being performed in order. For example, platform preparation requires the knapper to employ a series of light percussions to create a favorable angle on the core for flake removal (Stout et al., 2014). Analysis of the flakes produced in the assessments reveals minimal to no platform preparation at any stage. Whether the knappers employed the method of platform preparation and failed to do it successfully, or didn't use it at all to produce flakes can only be revealed by analyzing the sequence of actions.

A drawback of this study is its small sample-size, which limited the use of statistics to test hypotheses. Thus, adding more subjects to the study is another direction for future work.

Conclusion

The goals of this study were manifold. Firstly, I established a methodology to approach behavioral data is stone toolmaking experiments, and examined how these data speak to the ability of the handaxe makers. Secondly, I also strived to understand the relationship between the behaviors, and the lithics produced. Finally, I wished to highlight that variability in handaxes is reflective of the variability in knapping behaviors. The data illustrate actual behaviors behind different knapping outcomes, point to some factors that might lead to differential skill acquisition amongst knappers, and revealed many behaviors that the lithic fail to capture, such as how the knappers interact with their surroundings, and how their previous experience with other motor skills may impact their performance. Ultimately, analysis of behavioral data provides us with a realistic picture of the knapping process, allowing us to form more robust inferences about toolmaking processes, while also closing the gap between artifact and behavior.

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