Determining Whether Spectrophotometer CIE L*a*b* Color Analysis is an Effective Alternative to Munsell Soil Color Charts for the Study of Burnt Bones: Insights From Analysis of Bedh-Dhra EB II-III Burnt Bones
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- CIE L*a*b* spectrophotometers and cluster analysis should be adopted but require an experimental study comparable with Shipman et al. (1984)

## Literature Cited
Introduction

Project History

This project, which examines the mortuary practices of the Bronze Age residents of Bab edh-Dhra, began in the summer of 2010 as part of a National Science Foundation-Research Experience for Undergraduates (NSF-REU) at The University of Notre Dame. The NSF grant was awarded to Dr. Susan B. Sheridan, the director of the Bab edh-Dhra Bioarchaeology program. Dr. Sheridan and her associate Dr. Jamie Ullinger supervised all the research that went on that summer.

The program itself consisted of ten students conducting research on a single collection of bones from charnel house (or burial house) A22 from Bab edh-Dhra, an Early Bronze Age II-III site located in Jordan near the Dead Sea. The students were divided into research pairs, each given a specific predetermined research question and a specific type of bone to look at from the collection (e.g. humeri, femurs, crania, etc.). All the research questions were focused on examining whether the bones in the collection, which all exhibited some degree of burning, were burnt accidentally as a result of a building fire or intentionally as part of cremation practices. Though the research questions were broadly determined by the NSF faculty supervisors, it was necessary for each group to develop their own methodology and analysis.

My research partner, Theresa Gildner (undergraduate student at University of Notre Dame), and I used Munsell Soil Color Charts (see Fig. 7a) to conduct a bone color analysis of the humeri from the collection in order to investigate the possibility that fully articulated cremation took place at Bab edh-Dhra. As I explain
later in this paper, we did this through the comparison of bone color on the articular and non-articular surfaces of the distal ends of the humeri.

At the conclusion of the seven-week REU, my partner and I were offered the opportunity to continue the research with the aim of presenting a poster at the American Association of Physical Anthropologists (AAPA) annual meeting in April. Continuing the research necessitated adding a new element to the analysis of the bones. Theresa and I had previously discussed issues of subjectivity in the use of Munsell color charts. One of the other groups at the REU had worked with a handheld spectrophotometer to record bone color. This highly automated methodology removed all subjectivity from analyzing bone color. Theresa and I therefore decided that we would reexamine the humeri using this spectrophotometer and see whether we achieved the same results as when we used the Munsell color charts. If so, this would strengthen our conclusion from the Munsell study and also illustrate the utility of the new spectrophotometer technique.

I returned to Notre Dame during Fall Break of 2010 to meet with Theresa and help take spectrophotometer readings from the bone collection. Theresa also took additional readings during that following winter. It was decided between Theresa and I that the work would be divided so that I focus on the organization and analysis of the data, allowing me to also work on this thesis, and she focus on the production and presentation of the poster.

This thesis does not describe elements of the previous Munsell color analysis in which we examined bone color in relation to bone provenience within charnel house A22. These sections were excluded in order to address a research question
focused on the comparison of Munsell and spectrophotometer color measurements for use in burnt-bone studies. Through the comparison of the two color-measurement techniques I aim to make suggestions for future spectrophotometer studies in bioarchaeology as well as further the understanding of mortuary practices at Bab edh-Dhra during the Early Bronze Age.

*Bab edh-Dhra Site History*

Bab edh-Dhra is located in Jordan (Fig. 1a), at the southwestern end of the Dead Sea. The site overlooks the Wadi al-Kerak and includes a large cemetery 500 m southwest of the town (Schaub, 1993)(Fig. 1b). Bab edh-Dhra was first excavated in 1965-1967, in a project sponsored by the American Schools of Oriental Research (ASOR) and directed by the late Paul W. Lapp. Following Lapp's death in 1970, responsibility for the excavation fell to Dr. W.E. Rast (Valparaiso University) and Dr. R.T. Schaub (Indiana University of Pennsylvania), both staff members of the 1967 expedition. Excavation of the Bab edh-Dhra cemetery was carried out in four field seasons (1975, 1977, 1979, 1981) with joint sponsorship from ASOR and the Smithsonian Institute. These excavations were part of the larger expeditionary program “Expedition to the Dead Sea Plain” (EDSP), directed by Drs. Rast and Schaub. Recently, responsibility for publications related to this and other sites of the EDSP has been entrusted to Dr. Meredith Chesson (University of Notre Dame).
Figure 1 (a) Map of Early Bronze Age site Bab edh-Dhra, located on the Jordanian side of the Dead Sea, in the southwestern end. (b) Walled town of Bab edh-Dhra, overlooking the Wadi al-Kerak, with cemetery 500m southwest of the town.

The development of Bab edh-Dhra has been well documented by several authors (Schaub, 1993; Chesson, 1999; Rast, 1999). The site is one of many towns
that emerged throughout Palestine during the Early Bronze Age IB (3200-3100 BCE). During Early Bronze Age II (2900-2700 BCE) Bab edh-Dhra became more urban and fortified with the construction of large buildings and a stonewall enclosing the town. During the Early Bronze Age III (2700-2200 BCE) the town reached the peak of its development. At this point the town would have been large enough to support a population of 600-1000 people. The major crop grown was barley; but others were also produced including einkorn, emmer, wheat, grapes, olives, figs, chickpeas, lentils, flax, pistachios, and almonds. The large size of flax seeds excavated indicated that irrigation was utilized. The population also kept livestock such as goat, donkey, and cow.

The urban boom at Bab edh-Dhra ended around 2350 BCE, the beginning of Early Bronze Age IV (2300-2150 BCE) (Chesson, 1999; Schaub and Chesson, 2007). At this point, the gate to the city was hurriedly blocked and a massive conflagration took place causing significant damage to the gate superstructure (Schaub and Chesson, 2007). The site was abandoned for a short period of time following this disaster. It was eventually resettled as an un-walled village containing a sanctuary along the northern ridge of the town and houses and courtyards to the east and south (Schaub and Chesson, 2007).

Throughout the occupation of the site the changes in culture of Bab edh-Dhra residents are reflected in varying patterns of mortuary practice (Chesson, 1999; Rast, 1999; Chesson and Schaub, 2007). During EB IA, when the people of the region were seasonally mobile, all burials were secondary (i.e. remains were buried to decompose and then exhumed and re-buried) and took place in shaft tombs (Fig. 2).
Shafts were cut in the marl going straight down and tomb-chambers constructed at the bottoms. Disarticulated remains of the dead were deposited in the subterranean tomb-chambers. Post-cranial remains were placed on woven mats and crania were lined up on the edge of the mats.

![Figure 2 Artist’s depiction of an EB IA/B shaft tomb from Bab edh-Dhra.](image)

Generally four or five and no more than ten individuals were placed in a chamber. Between one and five chambers were placed at the end of a shaft. The size of the chamber ranged from 1.4-3.85 m² (Chesson, 1999). The remains were accompanied by various grave goods, including ceramic bowls and jars, stone vessels, shell bracelets, beads, wooden staffs, stone mace heads, unfired clay figurines, and textiles (Chesson and Schaub, 2007).

The use of shaft tombs continued, although with some modification, through EB IB and EB II. During this period, bricks for living structures and pottery were
found at the site, suggesting a more permanent settlement of Bab edh-Dhra (Rast et al., 1980). In EB IB the use of shaft tombs was modified as the number of tomb-chambers attached to a single shaft decreased, often to only a single tomb. Conversely, tomb-chamber size increased during this period, ranging from 3.6-7.0 m$^2$, increasing the maximum number of individuals per chamber to 15 (Chesson, 1999; Chesson and Schaub, 2007). Some tombs were also paved with large flat stones, foreshadowing the cobbled floors of the charnel houses in the next period (Chesson, 1999).

In addition to shaft tombs, above-ground circular charnel houses were also constructed during EB IB and early EB II. Within these charnel houses there is evidence of primary and secondary mortuary practices (Chesson, 1999; Rast, 1999; Chesson and Schaub, 2007). Grave goods similar to those found in the shaft tombs were also included among the remains of those buried in the circular charnel houses (Chesson, 1999). The circular charnel houses contained greater numbers of individuals than shaft tombs, with the house size ranging from 3.6-33.2 m$^2$.

The move to a sedentary lifestyle is most evident when the town of Bab edh-Dhra reached its peak population in EB II/III. EB II layers contain evidence signaling the expansion of fortifications and the construction of a 2.5 m wide mud brick town wall at the east end of the city and a sanctuary complex at the highest point of the town in the southwest sector (Rast et al., 1980; Schaub and Chesson, 2007). In the EB III stratum a 7 m wide stonewall containing at least two gates was uncovered (Chesson and Schaub, 2007; Schaub and Chesson, 2007). Two large guard towers at the northeast area overlooking Wadi al-Kerak were also discovered. Inside the city
itself, excavators found numerous closely spaced structures across the undulating interior of the town (Rast et al., 1980). These were understood to be domestic living spaces based in part on the presence of hearths. A sanctuary structure was also excavated in the southwest corner of the walled city.

This urban development coincided with the abandonment of fully subterranean burial practices. Subterranean burials were replaced by above-ground, rectangular, mud brick charnel houses with stone thresholds and sometimes cobbled floors (Chesson and Schaub, 2007) (Fig. 3). These houses were filled predominantly with disarticulated skeletal material and grave goods made from ceramics, wood, and stone. Sizes of the charnel house ranged from 13.4-120.9 m². The Minimum Number of Individuals (MNI) calculated for the charnel houses ranged from 21-200 (Chesson, 1999).

Based on the presence of postholes in some of the charnel houses, it has been suggested that shelving units may have been present for storing remains and grave goods (Chesson, 1999; Chesson and Schaub, 2007). Examination of the grave goods has also revealed differences in access to non-local materials and prestige goods between charnel houses. Increasing access to non-local materials is correlated to increasing size of the charnel house and greater number of individuals. The unequal access to non-local materials and greater charnel house size is suggested to be an indication of status differentiation and possibly two broadly defined social groups (Chesson, 1999).
Figure 3 Artist’s depiction of an EB II-III charnel house at Bab edh-Dhra. The depiction includes the speculated shelving units suggested by the presence of post-holes. Remains of individuals and grave goods would have been stacked on these shelving units. Reproduced from Chesson (1999).

Since the charnel houses are located within several hundred meters of the city, it is very likely that an individual standing on the wall of Bab edh-Dhra could easily see the charnel houses in the cemetery near by. Either through the location of the building in relation to the natural geography, or through decoration of the charnel house, it would certainly have been possible for individuals to pick out the charnel houses in which members of their lineage were buried. The prominence and varying size of the charnel houses would have been visual reminders of one’s own status within the society. Whether the remains of the deceased ancestors were fully articulated or cremated, their placement in the charnel house offered a focal point for post-mortem rituals and likely made some statement about both the individual’s identity and the individual’s placement within the larger social structure.

It is still unclear whether burials in the charnel house were primary or secondary. Rast (1999) has argued that primary burial occurred and that older
remains were deposited on the edges of the room to make space for new fully articulated bodies. Chesson (1999) however, has suggested that the charnel houses were used to store disarticulated remains. This debate informs the core of my analysis: investigating whether skeletal remains recovered from the site were burned when articulated (i.e. in anatomical position) or disarticulated.

Around 2300 BCE, at the end of EB III and beginning of EBIV, a break occurred in the occupation at Bab edh-Dhra (Chesson and Schaub, 2007). The site was eventually resettled, but these residents were non-sedentary and did not rebuild the previous urban development. The cemetery continued to be used, but no more charnel houses were constructed. Instead, primary and secondary burials were practiced in stone-lined shaft tombs (Rast et al., 1980; Chesson, 1999; Chesson and Schaub, 2007).

Research Questions

Examine Bab edh-Dhra bones for evidence of cremation

Ultimately, the purpose of this investigation is to better understand the mortuary practices at Bab edh-Dhra during the Early Bronze Age (EB) II-III. Nearly all the bones recovered from charnel house A22 at Bab edh-Dhra exhibit some degree of burning. The most fundamental question is whether this burning was accidental or intentional. Intentional burning of the bones would suggest cremation was part of the mortuary customs at Bab edh-Dhra while unintentional burning would suggest that cremation was not practiced. While cremation was not unheard of in the Ancient Near East during the Early Bronze Age, there is very little evidence
of it and most cultures of the region did not favor the practice in their religious ceremonies (Davies, 1999). Furthermore, there is no evidence before the EB II-III period that the people of Bab edh-Dhra practiced cremation. Therefore, it is important to know whether these burnt bones represent the novel addition of cremation to the usual mortuary practices at Bab edh-Dhra. If it can be shown that the bones from Bab edh-Dhra exhibit burn patterns typical of intentional cremation, then this leads to questions regarding how and why cremation came to be adopted at Bab edh-Dhra. These questions would certainly involve a closer study of the relationships the people of Bab edh-Dhra had with other cultures in the Dead Sea Plain and in the larger geographic region of the Near East.

Only one aspect regarding the question of intentionality was examined in this study: the possibility of fully articulated burning. While fully articulated burning of the human remains does not conclusively demonstrate cremation, determining the state of the body during burning is a first step towards fully understanding the burial process.

The common adage “the dead do not bury themselves” is a reminder that mortuary practices, though focused on the dead, often reveal more about the living. Mortuary practices are often a prominent display of social relationships and cultural conceptualizations carried out by the living. The investigation of mortuary practices offers valuable insights into how a people perceive themselves and their relationship with those around them. Mortuary ceremonies may be viewed as a public arena for communication and assessment of individuals and social groups (Chesson, 2001b; Williams, 2004). Ian Morris described mortuary practices, and
especially burials, as “the material remains of self-representations of social structure through the agency of ceremony” (Davies, 1999). Furthermore, the study of mortuary practices is a means to explore how a culture conceptualizes death and their relationship with their deities and nature (Pearson, 1999).

The practice of cremation as part of burial has been linked with numerous ideologies and conceptualizations of death (Chesson, 1999; Davies, 1999; Pearson, 1999; Chesson, 2001a; Chesson, 2001b; Prothero, 2001; Chesson and Schaub, 2007). For example, in some cases it denotes a disregard for a permanent resting place or place for family members to visit and mourn. However, the opposite may be equally true if ashes are stored in a central structure rather than scattered. It is best to say that a universal causal relationship between doctrine and burial practice can never be found and that similar mortuary practices may appear in cultures that have vastly different social structures and conceptualizations of death (Davies, 1999).

The investigation of what intentional cremation might mean for the people of Bab edh-Dhra is beyond the scope of this paper. This research is simply a first step in studying the state of the body during burial and will only suggest whether the bones from A22 were fully articulated when burnt. More research will have to be conducted to determine whether cremation was a part of mortuary practices at Bab edh-Dhra and what that signifies for the culture of its residents.

In order to determine whether the bones from charnel house A22 were articulated during burning this research focused on the examination of bone color.
Determine if CIE L*a*b* is a good substitute for the Munsell color system in studies of burnt bone

The second intention of this paper is to determine whether a CIE L*a*b* (CIELAB) equipped spectrophotometer is an effective replacement for Munsell Soil Color charts in the analysis of burnt bone. Later sections will cover how both the CIELAB and Munsell systems work, but a short summary is presented here as an introduction. Munsell Soil Color charts, though originally designed for identifying soil color, have become the standard system for measuring color of burnt bones over the past several decades. Basically, they are a set of color palettes with a series of color swatches on each page that are used to identify an object’s color by direct comparison. CIELAB, in contrast, is a method that does not rely on the human eye. It requires that an object be scanned by a spectrophotometer and then the readings graphed in three-dimensional color-space.

If a CIELAB spectrophotometer can be validated for use in burnt-bone studies, it can serve as an effective alternative to the Munsell color system. Certain difficulties inherent to the Munsell color system, such as a high degree of subjectivity and variability between researchers, make finding an alternative an attractive prospect.

Since the archetypal burnt-bone-color study by Shipman et al. (1984), numerous studies have used the Munsell color system to catalogue the primary and secondary colors that can be expected to appear in bone at certain stages and temperatures of burning. It is therefore very easy for current researchers using the Munsell color system to examine their bones and make an estimate about what
stage and at what relative temperature a bone was burnt. For a study like this one, comparing two bone surfaces for difference in burnt temperature, this is particularly useful.

A major difficulty in working with Munsell color data is the process of analyzing and managing data. The Munsell color code produces data in a three variable system of *hue, value, chroma*. The variables *value* and *chroma* both theoretically follow a continuous range of 0-10 but in practice are often discrete and cover a limited range. The variable *hue* never follows a continuous metric system. Instead, it is a mix of numbers and letter abbreviations, e.g. 10YR, 2.5Y, Gley2. This non-continuous, non-metric data is difficult to statistically analyze or fit into a mathematical model. Translating the Munsell color code into actual color names (e.g. YELLOW, BROWN, BLACK) is sometimes used as a partial solution. Pages containing color names, which are included in the Munsell Soil Color Chart book, facilitate this process (see Fig. 7b). However, the translation inevitably results in a loss of information that can have a serious effect on the analysis of the data resulting in confounding results.

In contrast to Munsell, CIELAB uniform color space uses a three variable color system with each variable being numeric and continuous. This easily allows samples to be graphed in three-dimensional color space, statistically analyzed, and mathematically modeled. The data are more easily handled and managed in this form. Because of the level of precision available in color description, a CIELAB spectrophotometer captures more color information than is possible using Munsell color charts.
So far, however, no burnt-bone study has suggested a form of analysis that can fully utilize all the color data captured in a single CIELAB spectrophotometer reading. The only other CIELAB spectrophotometer study of burnt-bones (Devlin and Herrman, 2007) compared the three color variables (L*, a*, and b*) individually. This form of analysis has been carried over from Munsell color studies. It is impossible to compare all Munsell variables together because of the incompatibility of non-metric (hue) and metric data (value and chroma). In Munsell color studies, comparing only a single variable at a time could still be useful because most of the color information is represented in the hue and value designations. However, in CIELAB analysis all three variables are necessary to describe the full color. Comparing single variables to each other gives a very limited understanding of the data, failing to achieve the full potential of the CIELAB color system.

In this paper, I propose using cluster analysis, a statistical technique, on CIELAB data as an alternative to single variable analysis. I demonstrate that cluster analysis of CIELAB data using all three color variables describes color in a way that is useful for burnt bone studies and fits within the paradigm of previous burnt-bone color analyses.

A cluster analysis, based on L*a*b* values from the same sample of bones as the Munsell portion of the study was used to evaluate the utility of CIELAB spectrophotometer data for analyzing burnt-bone color.
Bone Burning

Understanding the changes that occur to bone color during burning requires some summary about the structure and composition of bone. In order to conceptualize the structure of bone, one can imagine deconstructing a large steel-wire cord. The very large steel-wire cord is composed of numerous medium sized steel-wire cords all wrapped around each other. These medium sized cords are composed of even smaller cords. Each set of cords is similarly reducible to a smaller set of steel-wires all wrapped together, getting progressively smaller and smaller until finally one reaches the most basic and irreducible component, a single and very narrow gauge wire of steel.

At its largest scale, bone is composed of dense cortical bone, which is found primarily in long bones and also as a shell around the cancellous (spongy) bone at the end of joints. This dense cortical bone is mostly composed of woven together secondary osteons, which we can liken to the large steel-wire cords. Secondary osteons are the most common higher-order structure in bone (Weiner and Traub, 1992). The secondary osteons are further reducible into arrays called lamellae. The lamellae are concentrically arranged around the blood vessels in the bone and can be arranged in a number of patterns. Further reduction of the lamellae reveals individual mineralized-collagen-fibrils. These fibrils form the lamella array and are the basic building block of bone. They are, in a sense, those very small and thin steel wires that begin the construction of the larger steel-wire cord.

The mineralized-collagen-fibril has three major components (Weiner and Wagner, 1998). First is the collagen protein, which accounts for more than 90% of
all the protein in bone, and is the fibrils primary constituent. The second major component is the mineral, hydroxyapatite (Ca$_{10}$(PO$_4$)$_6$(OH)$_2$). Hydroxyapatite forms plate-shaped crystals within and on the collagen matrix (Weiner and Traub, 1992; Weiner and Wagner, 1998). These crystals add rigidity and strength to the protein matrix. The last major component of bone is water. Water is located within the fibril, between fibrils, and between the larger fibers.

During burning, bone passes through several stages characterized by predictable alterations to its structure and composition. Thompson (2005) offers a concise summary of these stages. The first stage of burning results in dehydration of the bone as hydroxyl-bonds break and bounded water within and between the fibrils is lost. Following this is the decomposition stage in which organic components of the bone, namely the collagen and other proteins, are removed by paralysis. During the next stage, inversion, carbonates are lost and the hydroxyapatite crystal structure is converted to beta-tricalcium phosphate (Ca$_3$(PO$_4$)$_2$). Finally, fusion takes place with the melting and coalescence of the bone’s crystal matrix.

Previous studies by anthropologists have examined the alterations to bone that occur during burning (Baby, 1954; Binford, 1963; Buikstra and Swegel, 1989; Bennett, 1999; Walker et al., 2008). Many of the early studies focused on modification of bone morphology through warping and cracking and to a lesser extent changes in bone surface color (Baby, 1954; Binford, 1963). The utility of bone surface color analysis for the examination of burned bone assemblages was pioneered by the experimental studies of Shipman et al. (1984).
In their analysis, Shipman et al. (1984) standardized the description of surface color on experimentally burned bone through the use of Munsell Soil Color Charts. Their analysis produced five distinct color stages, each characterized by variation in hue, value, and chroma associated with specific increases in temperature. Shipman et al. recorded both dominant surface colors at specific temperatures as well as multiple secondary colors.

The first stage described by Shipman et al. (1984) occurs within the temperature range of $20^\circ C$—$285^\circ C$. During this phase the specimen is neutral white or yellow. From a temperature of $285^\circ C$—$525^\circ C$ the bone adopts a reddish brown, very dark grey-brown, neutral grey, or reddish yellow. In the third stage at $525^\circ C$—$645^\circ C$ specimens are neutral black or dark blue in appearance. At temperatures of $645^\circ C$—$940^\circ C$ the bones become neutral white, light blue-gray, or light gray. Finally, above $940^\circ C$ the bones become neutral white with some medium grey and reddish yellow (Fig. 4).
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<td>870</td>
<td>N9.5/0</td>
<td>N3.3-25/0, 2.5YR6/2</td>
</tr>
<tr>
<td>Bone</td>
<td>940</td>
<td>N9.5/0</td>
<td>7.5YR8/6</td>
</tr>
<tr>
<td>Tooth</td>
<td>940</td>
<td>N9.5/0</td>
<td>N3.5,4/0, 5YR7/6, 10YR8/3</td>
</tr>
</tbody>
</table>

Figure 4 Munsell colors on burnt bones and teeth from Shipman et al. (1984) experimental study. Note the greater frequency of browns (10YR, 7.5YR, 5Y) at low temperatures and the dominance of whites (N9.5/0) at higher temperatures. Reproduced from Shipman et al. (1984)

Despite their systematic analysis, Shipman et al. (1984) warned that reliance upon color as an indicator of exposure temperatures is an essentially imprecise criterion both because of differences in color perception ability of researchers and because burnt bones may change color if buried. Subsequent studies have demonstrated that variables other than just temperature, such as depositional environment, duration of burn, sediment type, and oxygen availability can all affect changes in bone surface color (Weiner et al., 1998; Bennett, 1999; Walker et al., 2008). Though color may not be exactly indicative of the temperature at which bone was burnt, the progression of color along a continuum is still dependable and
follows generally the pattern described by Shipman et al. even when considering these other variables.

When bone is burnt, the burn temperature the bone experiences is not necessarily consistent across the entire bone. The temperature that bone is exposed to varies depending on the bones placement and whether or not the bones were articulated or fleshed during burning. This process is referred to as shielding. Past studies, especially in forensics science, have indicated that the state a body is in during burning can be determined from the warping and coloring patterns present on the bones (Baby, 1954; Binford, 1963; Buikstra and Swegel, 1989; Baker and Nawrocki, 2008). Areas where bones articulate are often more shielded from burning due to the protection offered by the other bones (Schurr, 1987; Buikstra and Swegel, 1989; Stiner et al., 1995; Walker et al., 2008). This shielding often means that the articular surfaces in an articulated body are less burnt than the surrounding areas.

This difference in burn temperature reached is apparent through color differences between protected areas and non-protected areas of the bone. Therefore, if articulated bodies are burned, there should appear a set pattern to the bones’ coloration: the articular/protected regions will be less burnt and the non-articular/non-protected regions will be more burnt (Fig. 5a). If this pattern were identified in the bones of Bab edh-Dhra charnel house A22 it would indicate the burning of articulated bodies.
Figure 5 (a) Expected bone color pattern if body was articulated when burnt. The articular surface exhibits color indicative of a lower burn temperature (black) than the rest of the bone (neutral-white). (b) Example of expected bone color pattern if body was not articulated when burnt. The articular surface exhibits the same color as the rest of the bone (brown) indicating an even degree of exposure.

Articulated burning does not, however, conclusively demonstrate the intentional cremation of remains at Bab edh-Dhra. It is possible that fully articulated primary burial occurred in charnel house A22 and that all burning is due to an accidental fire that destroyed the charnel house. This unintentional burning of articulated bodies would still produce a pattern of burning where articular surfaces are less burnt than non-articular surfaces. Alternatively, it is also possible that intentional cremation may still have occurred as part of a secondary mortuary practice on disarticulated remains. This practice would produce equal burning on both bone surfaces (Fig. 5b).
For this paper bone color was analyzed using two methods: Munsell Soil Color Charts, and a spectrophotometer using CIE L*a*b* uniform color space. Since the Shipman et al. (1984) study, Munsell Soil Color Charts have been the standard system for color measurement of burnt bone (Bennett, 1999; Cain, 2005; Baker and Nawrocki, 2008; Asmussen, 2009; Scott et al., 2010). However, citing issues of subjectivity and incompatibility, Devlin and Herrmann (2007) suggested Munsell color charts be replaced by the use of spectrophotometers and CIE L*a*b* uniform color space in the analysis of burnt bone. Their analysis of burnt remains from the Walker-Noe site in Kentucky is one of very few, if not the only study, to use this new technique.

My own study will offer a new data set with which to examination this novel technique and will offer an alternative form of analysis to that used by Devlin and Herrmann (2007) for examining CIELAB data. Because the Bab edh-Dhra bones have also been examined with Munsell color charts, it is possible to compare results from both techniques and assess the extent to which they produce comparable results. This comparison will offer insight regarding the effectiveness of the CIE L*a*b* system for deciphering color in a way that is useful for burnt bone studies and fits within the paradigm of previous burnt bone color analyses. Additionally, having experience with both techniques, I can make a statement about preference for one technique or the other and offer future directions and improvements for other spectrophotometer studies.
Materials and Methods

The Skeletal Sample

The human skeletal material used in this study was excavated from an EB II-III charnel house, A22, in 1979 by Rast et al. and is currently housed in the lab of Dr. Sheridan at The University of Notre Dame. The total area of the charnel house from which the bones were excavated is calculated at 210.9 m² (Chesson, 1999). Based on its size and the presence of non-local, high-value items like gold jewelry, it has been grouped with the Greater Charnel Houses, possibly housing higher status individuals (Chesson, 1999). The minimum number of individuals calculated for house A22 is 170, and the number of vessels contained inside exceeds 450.

At the beginning of the 2010 summer NSF-REU, my research partner and I were assigned by the program directors to examine only the humeri from the collection. After examining the humeri collection and consulting with the directors, we decided that our analysis would focus on examining only the distal ends of the humeri. The distal end of the bone was chosen for two reasons. First, it contained both an articular surface and a non-articular surface, as opposed to other regions of the humerus like the shaft. Second, distal ends offer articular and non-articular regions with surfaces that can be scored (i.e. color can be measured). This was distinct from the proximal end collection in which there were a large number of scoreable articular surfaces, but a low number of scoreable non-articular surfaces.
The two regions examined on the bones were:

a. Trochlear articular surface—the more distal portion of the articular surface was scored, that region which articulates with the ulna in the anatomical position (Fig. 6a)
b. Posterior, non-articular surface of the distal end of the humerus—the flattened area proximal to the olecranon fossa, at approximately the region where the curve of the distal portion of the humerus ends. The mid-point of this region was scored (Fig. 6b)

![Figure 6(a) Trochlear articular surface, distal portion of the articular surface where the humerus articulates with the ulna. (b) Posterior non-articular surface, the flattened area proximal to the olecranon fossa, at approximately the region where the curve of the distal end of the humerus ends.](image)

The same two regions were used in both the Munsell color analysis and the CIELAB spectrophotometer analysis.

Schurr (1987) and Symes et al. (2008) demonstrate the utility of articular and non-articular surfaces in examining burnt bones for evidence of cremation. During the burning of a fully articulated skeleton, the articular regions of the bones are protected and burn at a slower rate, achieving a lower temperature. Non-
articula\n  r	
  surfaces	
  of	
  the	
  bone	
  are	
  directly	
  exposed	
  to	
  the	
  fire	
  and	
  achieve	
  a	
  higher	
  temperature, burning at a faster rate. Therefore, if a body is fully articulated at the 
time of burning there should be a discrepancy in the degree of burning on the 
articular and non-articular surfaces. This discrepancy is measureable by the 
difference in bone color between the two surfaces. The articular surface would show 
a color corresponding to a low burn temperature and the non-articular surface 
would show a color corresponding to a high burn temperature. 

Based on the two regions of bone examined a sample size of $N=200$ distal 
humeri ends were picked from the collection. This sample included both rights 
($N=121$) and lefts ($N=79$). Specimens were selected based on the presence and 
scorability of at least one of the previously mentioned regions. Scorability was 
occasionally affected by dirt adhered to the bone by preservative or by preservative 
flaking off the bone. In situations where the preservative was flaking off, improving 
the clarity of the bone color was attempted by gently washing the region of the bone 
with cold water and a toothbrush. Bones were then allowed to dry before being 
scored. A preservative applied to all of the bones in general had a lightening effect 
on the bones color, often giving a grayish tinge. During Munsell scoring caution was 
taken to infer the underlying true bone color, but it is possible bones were still 
scored lighter than they actually were. It is unclear how the preservative might 
affect the spectrophotometer reading, but since all the bones were covered in the 
 preservative, the effect would at least be consistent.
Munsell Soil Color Charts

Burning on the bones was assessed independently using Munsell Soil Color Charts and CIELAB spectrophotometer. Though developed originally to determine soil color, Munsell color charts have become adapted in recent years for use in bone color analysis (Shipman et al., 1984; Bennett, 1999; Cain, 2005; Baker and Nawrocki, 2008; Asmussen, 2009; Scott et al., 2010). The eight charts in the collection comprise 450 different color standards. These color standards are systematically organized according to their Munsell notation (Munsell Color Company, 2009).

Figure 7 (a) 10YR page from Munsell Soil Color Chart book and (b) Corresponding color diagram page giving the color descriptor and actual color name for the Munsell Color codes. On both pages, hue is given in the top left corner, value is given along the left side, and chroma is given along the bottom. During the Munsell portion of this study, after recording the Munsell color code for a sample, the code was then translated into the color descriptor and actual color name using the corresponding color diagram page. From this translation process, bones could be placed within the 5 color categories YELLOW, BROWN, BLACK, GREY, and WHITE.
Three variables are combined to make up the Munsell color notation: *hue*, *value*, and *chroma* (Munsell Color Company, 2009). *Hue* indicates the color’s relation to red, yellow, green, blue, and purple. The symbol for *hue* is the letter abbreviation of the color, preceded by numbers from 0 to 10. For each letter range, the *hue* becomes more yellow and less red as the number increases. The second variable, *value*, indicates the colors lightness. The notation for *value* ranges from 0 (absolute black) to 10 (absolute white). The *chroma* indicates the color strength, or the departure of the color from a neutral of the same lightness. The notation for *chroma* ranges from 0, for light grays, to a maximum of 20. For absolute achromatic colors which have no *hue* or *chroma* (e.g. pure grays, white, and black) the letter *N* (neutral) is used in place of the *hue* designation. When recording with Munsell notation the standard order is *hue*, *value*, *chroma*.

Scoring with Munsell color charts involves matching a color swatch on the Munsell page to the color of the bone. In general, one page will contain colors all of one *hue*, with *value* and *chroma* both ranging from 1-8. Below each color swatch is a small circular opening through which one can view the targeted region of the specimen.

This highly subjective mode of analysis requires particular efforts be made in order to reduce interobserver error. It is recommended that the specimen be examined under dry condition and under natural sunlight (Munsell Color Company, 2009). For this study, observing the bones under sunlight was not practically possible. Instead, the bones were examined under fluorescent light in the lab. Great effort was taken to maintain a consistent level of lighting throughout the time it took
to score the bones. Other steps taken to reduce the chance of interobserver
disagreement included marking the bones with tape at the region of scoring, only
scoring the predominant color, and in case of multiple colors, scoring that color
which represented the highest burn temperature. The entire set of bones was
scored a total of three times, first with my partner and I working as a team, then
twice more as individuals. A concordance set of the data was then composed, and
bones for which there was disagreement in all three scoring-runs were reexamined
as a team.

Once each region on the bone was given a Munsell color score, the scores
were translated, through the use of the Munsell color charts, into five basic colors
consistent with colors reported in previous studies (Shipman et al., 1984; Buikstra
and Swegel, 1989; Stiner et al., 1995; Cain, 2005; Asmussen, 2009; Scott et al., 2010).
The color categories used were: YELLOW, BROWN, BLACK, GREY, WHITE (Fig. 8).
Figure 8 Examples of the five bone color categories used; (a) YELLOW, (b) BROWN, (c) BLACK, (d, e) GREY, including a grey with blue tinge, and (f) WHITE.

**CIE L*a*b* Uniform Color Space**

Color scoring with Munsell relies upon human perceived assessment of the three color-variables. The use of this system has been criticized due to its susceptibility to variation in lighting, which can affect color interpretation, as well as color perception ability. Additionally, a comparative assessment of colors is prohibited since the Munsell representation of color does not readily inform of actual color (Devlin and Herrmann, 2008). One must be fairly familiar with the Munsell system to immediately grasp from the notation the difference between, for example, a 5Y, 10YR, and GLEY2. Even then, colors within each of these hues may be remarkably similar to colors of different hues. It is therefore likely that for a single set of bones, two researchers in different labs may produce different color measurements. Comparison of data from two different studies is similarly difficult as the unique abilities of the researchers to determine color results in unaccountable variation. Furthermore, mathematical modeling and analysis of
Munsell data is prohibitively difficult due to the non-metric nature of the *hue* variable and the mostly discrete nature of the *value* and *chroma* variables.

A response to the subjectivity of color charts has been the adoption of spectrophotometers and colorimeters. Recent prosthetic dentistry studies have demonstrated human perception of color differences is routinely outperformed by spectrophotometric analysis, even in cases where those observing the color are highly trained prosthetic dental professionals (Rubino et al., 1994; Okubo et al., 1998; Paul et al., 2002; Lindsey and Wee, 2007).

Devlin and Herrmann (2008) were the first to use a spectrophotometer for color analysis of human cremains. The study focused on comingled remains; mostly bone fragments, excavated from a burial mound at the Walker-Noe site in the central Bluegrass region of Kentucky.

The spectrophotometer used by Devlin and Herrmann (2008) is an X-rite CA 22, a model similar to that used in this experiment, which is an X-rite SP60 (Fig. 9a). A spectrophotometer operates by shooting a beam of light at a sample, and then measuring with a photodetector, the amount and wavelengths of light reflected by the sample (Shimazaki et al., 2000). Light wavelength is indicative of the sample’s color, and the amount of light reflected is indicative of the sample’s lightness (more light reflected = lighter color sample).

There are a variety of ways to display the data acquired with the spectrophotometer. In this and the Devlin and Herrmann (2007) study, the spectrophotometer measures color in CIELAB uniform color space, an industry standard (Rubino et al., 1994; Melgosa, 1999; Paul et al., 2002; Lindsey and Wee,
The CIELAB “Color Space” is defined by three coordinates/axes, L*, a*, b*.

The L*-axis reflects the lightness of the color with values that range from 0 (absolute black) to 100 (absolute white). This coordinate is comparable with the Munsell value scale. The a*-axis reflects the red/green color scale. A strong green color has a very negative a*-value, while a strong red is given a very positive a*-value. The b*-axis indicates the yellow/blue color scale. Very strong blues are given negative b*-values, and strong yellows are given positive b*-values. The ability to plot these three color-values in a defined three-dimensional color space facilitates mathematical modeling and color comparison within and between studies.

Operation of the X-rite spectrophotometer is mostly a matter of “point-and-shoot.” The device is set to the appropriate color measurement system (L*a*b*) and illuminant observer conditions (fluorescent light) (X-Rite, 2007). The aperture for the device was left at 8mm diameter. Calibration of the device need only be done once a day based on the time since previous calibration and requires both a white calibration reading and a black trap reading. Taking a measurement entails centering the target window over the sample and pressing the “Read” key to initiate the measurement. A solid green LED lights up when the measurement is complete. The L*a*b* values are displayed on the built in graphic display following each reading (Fig. 9b). Readings were entered by hand into an Excel spreadsheet.
There are many benefits to using a spectrophotometer rather than Munsell colors charts for color analysis of burnt bone remains. First and foremost is the objectivity of analysis that the spectrophotometer permits. This negates concerns about variation in color perception ability as well as variation in illumination sources (e.g. fluorescent or natural light), which can be controlled through the settings of the device. Readings are also highly reproducible and displayed in a continuous measurement system. Both of these features facilitate comparison of results between data sets and ensure that when two different labs measure the same set of bones, they come up with near identical readings. Finally, analyzing color with a spectrophotometer does not require the same level of experience and expertise as does analyzing with Munsell color charts, where the ability to differentiate finely between colors takes practice.
There are, however, downsides to the use of spectrophotometers in the analysis of burnt bone remains. First is the large cost of the system compared with Munsell color charts. A Munsell color book costs approximately $200. An X-rite SP60 (the model used in this experiment) costs around $4,000. While both devices are portable (the spectrophotometer is a hand-held model), the risk associated with carrying a costly spectrophotometer into the field may mean that samples are brought back to the lab for analysis. Transporting samples from the field to the lab before analysis slows down the process and increases the risk of damaging the bones.

The greater problem associated with CIELAB examination of burnt bones is that a system of analysis that utilizes all of the color data at the same time has not been identified. In Munsell color studies, it is impossible to compare all the color data together because of the incompatibility of non-metric (hue) and metric (value and chroma) data in the same analysis. Munsell color studies therefore use only single variable comparisons. This method is useful because most of the color information is represented in the hue and value designations. Furthermore, translation of Munsell color data into actual color names (e.g. YELLOW, BLACK, GREY) can reduce all three variables into a single informative variable that is more easily analyzed.

When using CIELAB data, however, all three variables must be used together to describe the full color of the sample. Comparing single variables to each other gives a very limited understanding of the data. As an example, consider comparison of just the L*-values for a set of burnt bones. It is generally the case that low-burn
colors, such as brown and black, are darker and therefore have lower $L^*$-values that high-burn colors, such as grey and white. Comparison of differentially burnt surfaces should therefore result in significant differences when comparing just $L^*$-values.

This assumption is problematic because bone actually passes through a low-burn grey before achieving black, and then passes through a high-burn grey again before achieving white. Therefore, it is possible that two bones could both be classified as GREY (in the Munsell system) and have the same $L^*$-value, even though they were burned at two very different temperatures. Single-variable comparison of the $L^*$-value would show no significant difference between these two surfaces despite the difference in burn temperature. This type of analysis for CIELAB data can therefore produce an incomplete and even misleading interpretation of the data.

The solution to this problem, which I test in this study, is to use a cluster analysis to examine the CIELAB data obtained from the Bab edh-Dhra distal humeri. Cluster analysis has the advantage of being expressly designed to analyze data points using a multi-variable comparison. In the case of the two GREYs above, including differences in the $b^*$- and $a^*$-values for the two samples should reveal the difference in color and therefore burn temperature.

**Analyses**

The goal of the following analyses is to determine if there is evidence from articulated burning of the remains and to asses the comparability of the two color
measurement techniques; ascertaining if CIELAB is sensitive enough to distinguish different grades of burning with similar visual color profiles.

1. *Distinguishing articulated from non-articulated burning using Munsell color data*

   This analysis was intended to determine whether there was significant difference in the coloration, and therefore the degree of burning, of the articular versus the non-articular surfaces of the distal humeri from Bab edh-Dhra. If the articular regions were less burnt than the non-articular regions (Fig. 5a), this would suggest the cremation of fully articulated bodies. If no difference in coloration between the two surfaces (Fig. 5b), or if a reverse pattern is seen in which the articular region is more burnt, then the results would fail to indicate the burning of articulated bodies.

   For the Munsell color data, this analysis was performed using a Chi-square test on the translated actual color names. Three separate analyses compared articular to non-articular surfaces of the right distal humeri, left distal humeri, and combined right and left humeri. The samples included humeri with one or two scoreable surfaces. In order to have large enough samples for statistical analysis, three color-categories were used in the Chi-square test: Yellow/Brown, Black, Grey/White.
2. *Distinguishing articulated from non-articulated burning using single-variable comparison of L*a*b* values*

In order to ascertain the comparability of Munsell and CIELAB data, a two-tailed T-test was used to analyze the CIELAB data so as to determine whether a significant difference in coloration could be detected between the articular and non-articular surfaces of the bones. L*, a*, and b*-values from the articular surface were compared to the same value on the non-articular surface. A null-hypothesis of “no-difference” between the surfaces was used.

Evaluating the possibility of fully articulated cremation based upon a t-test of CIELAB values is based mostly upon a significant difference for the L* and b* values. If I discover that the articular surface has a significantly lower L*-value, and therefore a darker color, than the non-articular surface, this could be an indication of fully articulated cremation. If the articular surface is found to have a significantly higher b*-value, and therefore a less blue color, than the non-articular surface, this could also indicate fully articulated cremation. Both situations occurring simultaneously would strongly suggest fully articulated cremation.

3. *Cluster analysis of L*a*b* values*

Finally, a cluster analysis was performed on the CIELAB data to determine if interesting or significant groupings could be attained. I paid special attention to see if the data would fall into groups of articular and non-articular surfaces, or into groups that represented certain temperature ranges and Munsell color groupings as described by Shipman et al. (1984). I was also interested to see whether low-burn
Cluster analysis is generally used as a hypothesis generating form of analysis for data sets that have multiple variables for each data point. It is a means, essentially, to input a massive amount of data and see which measurements and variables are actually informative and produce patterns that warrant further investigation. In this way, cluster analysis offers an effective means to incorporate all three color-measurements of CIELAB data in a single analysis at one time. This should offer a more nuanced understanding of a bone’s color and therefore enable a researcher to assign bones to burn stages more accurately.

Clustering was performed in DATADESK version 6.0. A Euclidean distance metric (i.e. “as the crow flies” distance) was used to calculate the difference/relatedness between two points (Velleman, 1997; Fielding, 2007). Single linkage and complete linkage hierarchical clustering can both be used in DATADESK for the formation of groups (Velleman, 1997). The complete linkage hierarchical clustering, also called “the furthest-neighbor method” was used exclusively in this study because it minimizes the maximum intracluster distance at each stage, tending to find smaller, compact clusters and build them up in parallel (Velleman, 1997). This produced a greater number of distinct clusters, making for easier interpretation of the data.
Results

1. *Distinguishing articulated from non-articulated burning using Munsell color data*

This portion of the analysis was carried out in the summer of 2010 as part of a group project for the University of Notre Dame Bioarchaeology NSF-REU.

A sample of 200 distal humeri ends, comprised of 79 lefts and 121 rights, was scored with the Munsell Soil Color Chart. Of these bones, 146 specimens had an intact and scoreable articular surface and 155 had a scoreable non-articular surface containing the point of interest. This gave a total of 301 points scored.

For simplicity and ease of analysis, after recording the Munsell color code for a surface, the color code was translated, using the Munsell color chart (Fig. 7b), to the basic color name: YELLOW, BROWN, BLACK, GREY, WHITE. This was done at the suggestion of the program advisers and expert consultant. It was argued that it would be too difficult and only marginally more informative to use the full, non-metric, three-variables Munsell color code.

After collecting color codes and translation to color names, a chi-square test was run using the null hypothesis that there existed no difference in color frequency when comparing right to left humeri. The test had three degrees of freedom and resulted in a test statistic of 3.15. This did not exceed the critical value of 7.82, and gave a p-value of 0.37. Therefore, the null hypothesis was not rejected. In other words, there was no significant difference in color incidence comparing right to left humeri. Additionally, graphing color incidence in both right and left humeri showed that GREY was the most frequent color scored (Fig. 10), not surprising given that a grey color is produced at two separate burn stages.
Chi-square tests comparing color ratios for articular to non-articular surfaces were then run for three data sets: those containing only right humeri (Fig. 11a), those containing only left humeri (Fig. 11b), and those containing right and left humeri combined (Fig. 11c). In these analyses colors were grouped to form three larger categories: YELLOW/BROWN, BLACK, and GREY/WHITE. These groupings facilitated the statistical analysis by creating robust sample sizes. All analyses used the null hypothesis that no significant difference in color ratio existed between the articular and non-articular surface.

The chi-square test analyzing only the right distal humeri had two degrees of freedom and resulted in a test statistic of 0.97. This did not exceed the critical value of 5.9 and resulted in a p-value of 0.62. This failed to reject the null hypothesis.

Chi-square testing of only the left distal humeri used two degrees of freedom and resulted in a test statistic of 0.16. This did not exceed the critical value of 5.9 and resulted in a p-value of 0.92. This also failed to reject the null hypothesis.

Finally, I analyzed a data set that combined right and left distal humeri. The chi-square test had two degrees of freedom and resulted in a test statistic of 0.30. This did not exceed the critical value and resulted in a p-value of 0.86. Again, the null hypothesis was not rejected.
Figure 10 Comparison of right and left distal humeri examining the percent of each color category for the articular and non-articular surfaces. GREY was the most frequently scored color and WHITE the least frequently scored color. The high frequency of GREY may be a result of an inability to distinguish low-burn from high-burn grey colors.

2. Distinguishing articulated from non-articulated burning using single-variable comparison of L*a*b* values

The CIELAB data were separated into two tables in Excel, one for the articulated surface points and one for the non-articulated surface points. A sample size of N=145 data points were included in the articular surface data table, and N=154 data points were included in the non-articular surface data table. For each point, the L*, a*, and b* values were measured three times and then averaged. In the following calculations, only the average value for each point was used.

Within each table, average value and variance for all the points were calculated for L*, a*, and b* separately. The corresponding values are depicted in Table 1.
Figure 11 Comparison between percent of each color category present on the articular and non-articular surfaces of the (a) right distal humeri only, (b) left distal humeri only, and (c) combined right and left distal humeri. None of the groupings showed a significant difference in the percent of each color category when the articular surface was compared to the non-articular surface.
The data tables were then exported from Excel into DataDesk where the t-test could be run to compare for significant difference in color between the articular and non-articular surfaces.

### Table 1 Calculated averages and variance for L*, a*, b* values from examined Bab edh-Dhra distal humeri.

<table>
<thead>
<tr>
<th></th>
<th>Articular Data</th>
<th>Non-articular Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average; L</td>
<td>49.51</td>
<td>53.16</td>
</tr>
<tr>
<td>Variance; L</td>
<td>318.6489008</td>
<td>373.5785114</td>
</tr>
<tr>
<td>Sample size; L</td>
<td>145</td>
<td>154</td>
</tr>
<tr>
<td>Average; a</td>
<td>1.57</td>
<td>1.68</td>
</tr>
<tr>
<td>Variance; a</td>
<td>1.842442893</td>
<td>3.115326433</td>
</tr>
<tr>
<td>Sample size; a</td>
<td>145</td>
<td>154</td>
</tr>
<tr>
<td>Average; b</td>
<td>9.28</td>
<td>7.91</td>
</tr>
<tr>
<td>Variance; b</td>
<td>47.59848056</td>
<td>53.96719238</td>
</tr>
<tr>
<td>Sample size; b</td>
<td>145</td>
<td>154</td>
</tr>
</tbody>
</table>

A 2-sample t-Test was run comparing the average values for the articular surface to the non-articular surface for each variable, L*, a*, and b* (Fig. 12a, b, c). The null hypothesis was set as $\mu_1 - \mu_2 = 0$ and the alternative hypothesis was set as $\mu_1 - \mu_2 \neq 0$. The individual $\alpha$ was set at 0.05.

For all three color-variables, L*, a*, and b*, no significant differences were found between the articular and non-articular surfaces. The results are depicted in Figure 12.
Figure 12 Comparison of the articular and non-articular surfaces of humeri using a 2-sample t-test of CIE \( L^* \) (a), \( a^* \) (b), \( b^* \) (c) values. The p-values for \( L^* \), \( a^* \), and \( b^* \) respectively are \( p=0.0910 \) (t=1.696; df=296), \( p=0.5235 \) (t=0.6387; df=285), \( p=0.0982 \) (t=1.659; df=296). None of the CIELAB values show significant difference between articular and non-articular surfaces at the \( \alpha=0.05 \) level. Both \( L^* \) and \( b^* \) could be deemed significant at the level of \( \alpha=0.1 \), however this was not considered to be very informative because both were just barely significant at this level.

3. **Cluster analysis of \( L^*a^*b^* \) values**

The CIELAB data was separated into two tables in Excel, one for the articulated surface points and one for the non-articulated surface point. This was done so that three separate cluster analysis could be run, one for the articular surface points only, one for the non-articular surface points only, and one for all the surface points together. These tables contained columns with average \( L^* \), \( a^* \), and \( b^* \) values for each point. These columns were imported into DataDesk for cluster
analysis in that program along with each point's associated bone identification number.

DataDesk performs the cluster analysis using a Euclidean distance metric (i.e. “as the crow flies” distance) to calculate the difference/relatedness between points (Velleman, 1997; Fielding, 2007). DataDesk gives two options for data clustering and group formation: single linkage hierarchical or complete linkage hierarchical. After experimenting with both options on the data sets, I chose to use complete linkage hierarchical clustering exclusively. Complete linkage hierarchical clustering measures distance between clusters as the greatest distance between a member of each cluster. It is also known as the “furthest-neighbor method”. This method tends to produce very tight clusters of similar cases and performs well when cases form distinct clusters (Fielding, 2007).

The cluster analysis on DataDesk produces a dendrogram to represent the clustering. Identifying significant groupings based on this dendrogram is somewhat up to the discretion of the analyst. In general, the dendrogram was divided to produce between five and nine major groups.

After identifying the major groups, the data were exported from DataDesk to Excel. In Excel, I produced data tables for each grouping which consisted of the bone’s identification number, identification of its surface (articular or non-articular), provenience data, side of the body the bone was from, Munsell color code with each variable in its own column, Munsell color name, and the associated L*, a*, and b* values (see Supplemental Materials). With this format it was possible to identify general patterns within and between groups relating to Munsell color code,
Munsell color name, bone surface, and CIELAB values. This process was carried out on data for each bone surface separately and then both surfaces combined.

The data for the non-articular surface is the clearest of the three analyses and is fairly representative of the results in the other two analyses. From the 154 data points that make up the non-articular data set, I identified five distinct groupings in the cluster analysis (Fig. 13, fig. S13). All five groups were characterized by a predominant Munsell color, and three of the five consisted almost entirely of one color. The color groupings that appeared were BROWN (Group X), GREY (Group +), BLACK (Group |), GREY (Group \), and WHITE (Group 0). These groupings fit nicely with the basic color categories and stages of bone burning described by Shipman et al. (1984).

From the 145 data points comprising the articular surface data set I defined six groups (Fig. 14, figs. S14). Again, the groups were characterized by a predominant Munsell color. Unlike the non-articular data set, however, the articular data set did not have the same level of color variety. Of the six groups, two were predominantly BROWN (Groups X and 0), three were predominantly GREY (Groups \, +, and /), and one was predominantly BLACK (Group |).

By adding together the articular and non-articular data sets a combined data set consisting of 299 data points was produced. From the cluster analysis of this data set, I defined nine groups (Fig. 15, fig. S15). Of these nine groups, one was predominantly BROWN (Group X), one was predominantly WHITE (Group .), two were predominantly BLACK (Groups \ and 0), and five were predominantly GREY
(Groups $+,-,\|,$ and $\)$. In this analysis, articular and non-articular data points were equally distributed within groups even at a very fine level.

Figure 13 Cluster Analysis of CIELAB readings from Non-articular Surface points of Humeri. Group colors are: BROWN (Group $\times$), GREY (Group $+$), BLACK (Group $|$), GREY (Group $\|$), and WHITE (Group $0$). Note that the two GREY groupings are separated from each other with Group $\|$ being placed sister to the WHITE Group $0$. Group $\|$ contains predominantly the hue GLEY1 and GLEY2, while Group $+$ contains predominantly the hue 10YR or 7.5YR. This separation suggests an ability to differentiate low-burn from high-burn grays using CIELAB data.
Figure 14 Cluster Analysis of CIELAB readings from Articular Surface points of Humeri. Groups colors are: predominantly BROWN (Groups X and 0), predominantly GREY (Groups \, +, and /), and predominantly BLACK (Group |). Groups + and / represent low- and high-burn grays, respectively. Though the two groupings are placed sister to each other, they are still identifiable as distinct and are defined by the predominance of 10YR in Group + and the predominance of GLEY1 and GLEY 2 in Groups /. 
Figure 15 Cluster Analysis of CIELAB readings from combined Articular and Non-Articular Surface points of Humeri. Groups colors are: predominantly BROWN (Group X), predominantly WHITE (Group .), predominantly BLACK (Groups \ and 0), and GREY (Groups +, , -, and /). Though
there are 5 GREY groups, only 2 are considered truly GREY. The two GREY groups (Groups -- and /) are placed sister to each other but are differentiable by their hue values. Group – is defined by a high incidence of GLEY1 and GLEY2 while Group / is defined by a high incidence of 10YR and 7.5YR. These two groups represent the high- and low-burn grays respectively. Their separation demonstrates the ability of Cluster Analysis to differentiate between the two burn temperatures based on CIELAB data.

**Discussion**

The results of the analyses are discussed below in three separate parts, beginning with the Munsell study and then the two CIELAB studies.

*Munsell Color Analysis shows no difference in coloration of bone surfaces*

The three analyses of humeri color based upon the Munsell basic color names show there is no significant difference in the coloration of the articular and the non-articular surfaces of the distal humeral ends. I did not find the pattern expected for articulated cremation in which the non-articular surface is more burnt than the protected articular surface. Hence, these data do not support the possibility that the remains at Bab edh-Dhra were fully articulated when burnt.

These findings require a caveat, however. Translation of three-variable Munsell color codes to basic color names may produce misleading results. It is possible this reduction may cause the color information to be misrepresented during the analysis phase. Along with the **basic color names** (YELLOW, BROWN, BLACK, GREY, WHITE) the Munsell color charts also give **color descriptors**. For example, translation of a 10YR 5/2 would be the color grayish brown. Is this classified as a GREY or a BROWN? Is there a brown tinge because of dirt and staining from the sediment? Is it grayish because of the preservative used to cover the bone? There may be grays that fell into the brown category, and there may be browns that
fell into the gray category. This confusion of color may explain why GREY is consistently the majority color in all of the Munsell color analyses.

*Single variable analysis of $L^*$, $a^*$, and $b^*$-values show no statistically significant difference between bone surfaces*

In the 2-sample t-test comparing the average values for the articular surface to the non-articular surface for each variable, $L^*$, $a^*$, and $b^*$, no significant differences were found. Since there is no significant difference for any of the color-variables in the comparison of articular to non-articular surface, it is not possible to conclude the surfaces experienced differences in burn temperatures. As with the Munsell data, the CIELAB results do not support the notion of fully articulated remains being burnt at Bab edh-Dhra.

The results from this test have to be considered with some caution because of an inherent flaw in the analysis of CIELAB data using a single variable comparison through a 2-sample t-test. As mentioned previously, single variable comparisons of the CIELAB data give incomplete and possibly misleading interpretations of the data. For example, in the case of $L^*$-values, it is possible for two bones to be burnt at very different temperatures, but both be categorized as GREY and have similar $L^*$-values. In some ways this is a similar problem to that encountered with the Munsell color data. Though we may be able to capture all the data through the color measurement system, accessing this data during analysis requires a process of simplification, which can produce misleading results.
The solution to this problem is to add more information through an additional variable. In the case of CIELAB t-test, this additional information comes in the form of the b*-value. High-burn grays often adopt a bluish tinge, while low-burn grays often maintain a brown or yellowish tinge. This difference can be measured through the b*-value where a strong negative value indicates a strong blue color and a strong positive value indicates a strong yellow color. A significantly negative b*-value for the non-articular surface could be used as a check when no significant difference in L*-values is uncovered. Even if there was no difference in L*-values comparing articular to non-articular surfaces, if the non-articular surface had a significantly negative b*-value this could suggest fully articulated burning.

This solution, however, is problematic since there is no easy way to check that the strongly negative b*-values are attached to bones with grey color.

The ultimate difficulty is that we lack a system with which to assess all of the color data at the same time. Cluster analysis offers a possible solution to this problem, as it is a system expressly designed to handle a vast number of variables related to a single data set.

*Cluster analysis of L*a*b* values does discriminate low- from high-burn GREYs and does not separate articular from non-articular bone surfaces*

The most significant result of the cluster analysis using both articular and non-articular data points is the nearly equal distribution of these points among all the color groupings. It was hypothesized that fully articulated cremation would cause a significant difference in the coloration of the articular and non-articular
surfaces. Based on this difference in coloration, a cluster analysis of data points from the two surfaces should separate the articular and non-articular points into different groups. If the bones were burnt in a non-articulated state then no significant difference in the coloration of the articular and non-articular bone surfaces should exist. In this case, during a cluster analysis data points from both surfaces would be equally distributed among groups.

In the combined cluster analysis, even at the nearly lowest level of grouping, articular and non-articular data points are closely related and placed within the same groups (see Supplemental Material). These results strongly suggest that there is no difference in the coloration of articular and non-articular points. These findings do not support the possibility of fully articulated remains being burnt at Bab edh-Dhra.

The strength of this conclusion based on CIELAB cluster analysis is bolstered by other results from the cluster analysis that show the system’s ability to discriminate between colors at a very fine level. In conducting a t-test analysis of the CIELAB data I was initially concerned that two bones burned at different temperatures (i.e. a high-burn and a low-burn) could adopt the same gray color. In analyzing the CIELAB data with a t-test it would be impossible to differentiate these two bones. A cluster analysis of CIELAB data was therefore performed to see if this method of analysis could distinguish between the high-burn and low-burn GREYs.

During the cluster analysis of the non-articular surface CIELAB data (Fig. 13) the two different types of GREY (low-burn and high-burn) separate out. The difference is apparent on two levels. First, the two GREYs (Group +, and Group \) are
only distantly related to each other in the dendrogram with one group (Group \) placed sister to the WHITE group (Group 0). The close association of this GREY group to the WHITE groups suggests it may represent the high-burn grays.

Second, examining the Munsell color-codes for each grouping further supports the expectation that the two GREY groups represent the high- and low-burn grays. In Group +, the grays are associated with the Munsell hue 10YR, denoting a yellow/brown tinge. This brown tinge is associated with low-burn temperatures. In Group \, which was placed sister to the WHITE group, the grays are coded for using mostly GLEY1, a neutral gray, or GLEY2, a gray with a bluish tinge. This neutral or bluish tinge of the second GREY group is associated with high-burn temperatures.

These two pieces of evidence together suggest that the two groups represent two distinct grays, one produced from low burn-temperatures and a second produced from high burn-temperatures.

Cluster analysis of the articular surface points produces comparable results to the non-articular data points, although with less color variety (Fig. 14). The identification of three distinct GREY clusters (Groups \, +, and /) is particularly interesting because we expect only two GREY categories, low-burn and high-burn. Closer examination of the 3 GREY groupings reveals why they may not have fit in only two groups. Groups \, with sample size of N=21, is composed of barely 50% GREY data points. The remainder of the groups consists of approximately 20% BROWN, 20% WHITE, and 10% YELLOW. Furthermore, though the Munsell hue is a mix of 10YR, GLEY, and 2.5Y, the average score for Munsell value (the Munsell
measure of lightness) is above 7, with some points scoring at 8.5. These scores indicate especially light colors even when classified as BROWN or YELLOW. This group therefore seems more of a “grab-bag” of light colors, and would perhaps be better classified as WHITE/LIGHT. It is possible that in this case the preservative on the bones produced the gray tinge observed.

Examining the other two GREY groupings (Groups + and /) in the articular data set, we see that the level of separation that occurred in the non-articular data set is still occurring, but at a lower degree. In the articular data set, the two GREY categories are placed as sister to each other, indicating a close degree of association, while in the non-articular data set they were more separated in the dendrogram. However, the two groups are still differentiable based on Munsell color code. Group + is predominantly 10YR, while Group / is predominantly GLEY1 or GLEY2. The cluster analysis has still separated the high-burn from low-burn grays.

Cluster analysis of the combined articular and non-articular CIELAB data (Fig. 15) produced five distinct GREY groups (Groups +, −, |, −−, and /), as opposed to the expected two groups for differentiation of high-burn from low-burn GREYS. However, closer examination of the five GREY groups suggests several be relabeled or discarded.

One of the five GREY groups (Group |) was exceptionally small, consisting of only four data points. For a data set of this size I think this is anomalous and believe this group should be ignored. Another group (Group +) had nearly as many BROWN (N=9) as GREY (N=10) and also had a considerable number of WHITE (N=6) and some YELLOW (N=2). This group seemed to be like the WHITE/LIGHT group
described from the articular data set, containing an average score of 7.7 for the Munsell value. This group therefore seems to be better characterized as WHITE/LIGHT rather than GREY.

Of the remaining three GREY groups, two (Groups -- and /) are sister to each other and form a monophyletic group with the abnormally small GREY group and the WHITE group. Though these two GREY groups are sister to each other, they are distinguished from each other based upon their Munsell hue values. Group -- is characterized by scores mostly of GLEY1 or GLEY2, and the Group / is characterized by scores of 10YR. Therefore, though the groups are sister to each other, they are still distinguishable as high- and low-burn groups based on cluster analysis of the CIELAB data.

The third and last of the GREY groups (Group _) poses an interesting problem. It is not located anywhere near the other two GREY groups and instead is sister to the WHITE/LIGHT group. The formation of this polyphyletic group of GREYs is troubling and difficult to explain. This outlying GREY group is characterized by Munsell hue scores of 10YR and 7.5YR, suggesting a low burn-temperature. One would expect that this characteristic would group these data points with the other low-burn GREYs (Group /). However, it is interesting to note that within this outlying GREY group (N= 46), 30% of the data points are coded as BROWN, whereas in the other low-burn GREY (N=48) only 10% of the data points were coded as something other than GREY. This pattern suggests that the outlying GREY group could be closer to BROWN, explaining its separation from the other two GREY groups.
The inability of the CIELAB cluster analysis to consistently produce only two groupings of GREY as well as the fact that groupings often do not contain only a single color raises questions about the usefulness of this analytical system for investigating patterns in burnt bone collections. However, it is important to remember that the utility of the CIELAB cluster analysis is being judged by its ability to match results from Munsell color analysis: a highly subjective and potentially misleading system. The fact that several GREYs and BROWNs show up in a group that is predominantly BLACK may not indicate a flaw in the cluster analysis, but rather suggest that the Munsell scores given to those GREY and BROWN data points was incorrect.

The trouble in this comparison of techniques is that it attempts to match up results from an unknown technique with subjective and questionable results from another technique. If an error occurs, it is difficult to say in which system of color measurement the error occurred. The error in one system compounds the error in the other system. For this reason, despite some inconsistencies and lack of clean separation of colors, the fact that general trends in the color composition of groups are discernable and that at some level separation of colors and burn-temperatures are consistent gives me confidence that cluster analysis of CIELAB data is a useful tool.

The consistent separation of low- and high-burn GREYs from each other based on cluster analysis of CIELAB data suggests that this technique is capable of making distinctions between very closely related colors and thereby distinguishing between burn-temperatures. Therefore, if it cannot make any distinction between
the colors of the articular surface data points and the non-articular surface data points, then it seems safe to conclude that no difference exists in the coloration of these two surfaces. These results agree with the Munsell color analysis.

**Implications for Reconstructing Mortuary Practices at Bab edh-Dhra**

Based on the results from the Munsell color analyses and the two CIELAB data analyses, it seems unlikely that the bones from charnel house A22 at Bab edh-Dhra during EB II-III were fully articulated when burnt. All three analyses agree that there is no difference in the coloration of the articular and non-articular surfaces.

What these results mean for the possibility of intentional cremation as part of mortuary practice at Bab edh-Dhra during EB II-III is less clear. Cremation can be practiced on the fully articulated body of the recently deceased or it is also possible for cremation to be part of a secondary mortuary practice, carried out on de-fleshed and disarticulated remains. Cremation as part of secondary-mortuary practices might produce equivalent burning patterns on articular and non-articular surfaces.

Furthermore, it is clear from the excavation reports that there was substantial burning to the structure of charnel house A22, likely causing its destruction (Rast et al., 1980). There has not been extensive research on the effects of a second burning event on burnt remains. It is possible that a second burn event could mask or distort evidence that would be present following cremation of fully articulated bodies.

As has been emphasized before, this research is only a first step in describing the state of the body during burial at Bab edh-Dhra during EB II-III. Future research
will have to determine what this evidence of disarticulated burning means for the possibility of cremation at Bab edh-Dhra and how this informs our the understanding of mortuary practice and the greater culture at Bab edh-Dhra during EB II-III.

Bab edh-Dhra was one of only two walled Early Bronze Age settlement in the Dead Sea Plains to have a substantial cemetery (Chesson and Schaub, 2007). While the archaeological record shows the people of Bab edh-Dhra participated in complex mortuary practices for centuries, there is no evidence that they practiced in any type of cremation in the period leading up to and including EB II-III. If these bones can be clearly identified as cremated remains, then it is important to identify how this novel practice was adopted. While not unheard of in the Ancient Near East, cremation was indeed rare (Davies, 1999). Therefore, the appearance of cremation as part of the mortuary customs used by the people of Bab edh-Dhra signifies an important exchange of culture or local innovation, either of which would merit significant additional research to investigate the larger social practices at work.

Implications for the Use of Munsell and CIELAB in Burnt Bone Studies

* CIEL*a*b* cluster analysis is a highly discriminative tool for burnt-bone color studies

Since the burnt-bone color study conducted by Shipman et al. (1984), the Munsell color system has been the primary tool for characterizing burnt bone. Researcher’s extensive use of this system has produced numerous comparable data sets, facilitating the examination and interpretation of their own bone collections. However, issues of subjectivity and difficulty in the analysis and management of
Munsell color data have led some (Devlin and Herrmann, 2007) to criticize the system's use for studies of burnt bone. Devlin and Herrmann suggest that spectrophotometers, specifically those using CIE L*a*b* color space, be used as an alternative to the Munsell Soil Color Charts. This alternative offers a much more objective system of measurement with a high degree of reproducibility and also records data that are much easier to model and manage.

The use of CIELAB spectrophotometer color analysis comes with two significant drawbacks. First is the extreme difference in cost between a book of Munsell Soil Color Charts and a spectrophotometer equipped with CIELAB software. The former costs only several hundred dollars, while the later costs several thousand dollars. The second major drawback to using a CIELAB spectrophotometer is that so far no form of analysis for burnt-bone studies has been suggested that can fully utilize at once all the color data captured by the system. It was the intention of this study to demonstrate the utility of cluster analysis for this purpose.

The utility of the CIELAB spectrophotometer system for burnt bone analysis can be measured in two ways. The first is by whether its results regarding the possibility of fully-articulated burning matched those of the Munsell color study. The second is whether it was able to discern between grays produced by high- and low-burn temperatures, a feat possible to some extent with Munsell color data. Both the single-variable comparison and cluster analysis of CIELAB data revealed no significant difference in coloration of the articular and non-articular surface points of the humeri. These results matched with those of the Munsell color study. Though the single-variable analysis was unable to differentiate between high- and low-burn
grays, the cluster analysis of CIELAB data proved able to finely discriminate between the two burn temperatures. During the cluster analysis some inconsistencies occurred and a clean separation of colors was sometimes lacking, but general trends in the color composition of groups were discernable and separation of characteristic burn-temperature colors were consistent. These results strongly demonstrate the utility of CIELAB cluster analysis in burnt-bone studies.

*CIE L*<sup>a</sup>*<sup>b</sup>* spectrophotometers and cluster analysis should be adopted but require an experimental study comparable with Shipman et al. (1984)*

What remains to be answered is whether CIELAB cluster analysis offers a significant enough improvement over Munsell color analysis to warrant purchasing a several thousand-dollar spectrophotometer. Future studies will likely reveal that the answer to this question is “Yes.”

This conclusion will be based on the ability to easily model and manage CIELAB data. Using the results from a cluster analysis of burnt bone data, it seems very possible that a standardized equation could be produced establishing parameters for color values in a way that categorizes points by color and might suggest ranges for burn-temperature. A researcher who had taken CIELAB spectrophotometer readings of burnt bones could input the CIELAB values into this equation and be given a color description of the bone, as well as a suggested temperature for which the bone was burnt. A complex system could even offer different equations for different burn conditions, such as varying types of sediment, fleshed or unfleshed bone, and buried or unburied burning. A researcher who knew
the conditions under which the bones were burnt could arrive at very specific
temperature ranges for the colors of the bones.

The development of this technique would require a very systematic
approach, similar to that used by Shipman et al. (1984). In order to complete a
reference set of data, bone fragments would have to be burnt at a wide range of
temperatures and under precise conditions. A wide range of temperatures is
necessary to ensure that the data cover all possible colors achievable during bone
burning. The bones would then be scored independently using Munsell color charts
by a large number of experienced and skilled researchers and the results pooled to
limit inter-observer subjectivity. Following this a separate group would measure the
CIELAB values for the bones. The order of Munsell scoring first, then
spectrophotometer reading is important so that the CIELAB data does not influence
the Munsell scoring process. Cluster analysis of the CIELAB data would then
facilitate mathematical modeling and the development of a predictive equation.

If an equation could not be produced, it would still be possible to use this
extensive data set as a predictive tool in itself. In their geochemical analysis of
Roman lava quarries, Gluhak and Hofmeister (2009) used the cluster analysis of
their experimental data set for later millstone provenance analyses. They were able
to test whether new millstone samples integrated into existing clusters or formed
their own cluster, suggesting they did not derive from any of the examined quarries.
A similar methodology could be used to determine bone color and get at burn
temperature. A sample of bones of unknown color/burn temperature could be put
into the data set and tracked during the clustering to see into which existing clusters
they integrate. This could then similarly inform about the color and burn
temperature range of the bone.

As a final note I offer a critique of the two systems based on my personal
experience with both. I found working with the Munsell Soil Color Charts to be
consistently frustrating and slow work as I often became stuck agonizing over which
shade of brown or gray or white described the bone best. Furthermore, the data
produced were difficult to analyze thoroughly with a robust statistical analysis. In
contrast, I found working with the spectrophotometer and the resulting CIELAB
data to be a much simpler process and more amenable to thorough statistical
analysis. However, any current burnt bone study using CIELAB data is hindered by
the lack of experimental research using this technique. Burnt bone studies using
CIELAB data still have to rely on Munsell color data in order to interpret the
readings that are obtained from the spectrophotometer. The sheer volume of burnt
bone studies that have used Munsell color data makes this technique much more
useful during interpretation and analysis of results. Until an experiment comparable
to that of Shipman et al. (1984) is conducted using CIELAB data, the use of CIELAB
data and spectrophotometers in burnt bone studies will be limited. It is paramount
that such a study be carried out with CIELAB data so that this technique, which
offers valuable opportunities and improvements in the recording and analysis of
burnt bone data, can move forward and become established in the field of
bioarchaeology.
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