Investigating Indicators of Placental Mammal Birth Through Dental Neonatal Lines, and Perception of Accessibility and Disability in University Evolutionary Biology Courses

By

Taormina Lepore

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Abstract

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Here I present a first chapter manuscript relating to evidence of neonatal lines in the teeth of extant mammals; a second manuscript on quantitative evidence of the impact of Universal Design for Learning (UDL) on perception of accessibility in science media; and a third manuscript qualitative study on disability social justice and accessibility in science media through Universal Design for Learning (UDL). The first manuscript presents evidence of neonatal lines in the teeth of extant mammals, as a signature of live placental birth, compared across eutherian and metatherian phylogeny. This manuscript comprises a literature review of dental neonatal lines reported by other workers, as well as new analyses of neonatal lines in a selection of extant Carnivoran, rodent, and marsupial taxa. I conducted hard-tissue dental histology techniques at the UC Museum of Paleontology in Berkeley, USA, with Undergraduate Research Assistantship Program (URAP) students to slice over 40 thin sections of extant mammal teeth, comprising 9 taxa. This work was conducted after a pilot run at the Centro Nacional de Investigación sobre la Evolución Humana (CENIEH) in Burgos, Spain with the assistance of a petrology and histology lab technician there. Following high resolution slide photography and ImageJ analysis, my URAP research team and I developed a multimodal or integrative method for investigating putative dental neonatal lines in unexplored taxa, to be put forward in conjunction with other imaging methodologies for dental neonatal lines reported in the literature. We also compile mammalian dental neonatal lines reported in the literature, to our knowledge for the first time, and place this information into a phylogenetic and evolutionary context.

In the second manuscript, I analyze the impact of student implementation of Universal Design for Learning (UDL) core concepts, and focus specifically on UDL as a method of

promoting social justice and belonging in undergraduate science courses. This manuscript uses quantitative methods to assess this impact. I co-developed a pedagogical project which infused concepts of inclusive design and Universal Design for Learning (UDL) as central to student learning goals, hypothesizing this would increase awareness of accessibility and disability, and increase accessibility and inclusion for all.

In the third and final manuscript, I further explore questions related to disability perception and accessibility in four paleobiology-centered courses by assessing student open-ended responses for textual themes. This manuscript uses a qualitative methodology and framework. I analyzed student written responses to two survey questions asking students to reflect on their definition of accessibility, as well as their propensity to consider accessibility when interacting with science media, including academic journals, science documentaries, podcasts, or social media posts. Responses were analyzed using the qualitative method, reflexive thematic analysis, which allowed themes to be crafted through a recursive process of reading and annotating potential codes, correlating codes into candidate themes, and collecting themes into overarching themes. The thematic analysis data allowed me to generate four overarching themes with three themes each. These themes were developed using a mixture of latent and semantic coding, taking into account the face-value meaning of student's words (latent) as well as the occasional societally-influenced meaning (semantic).

Of note, this qualitative process centered the researcher's positionality and reflexivity as central to the data generation process, and took a so-called Big Q Qualitative approach which values the researcher as sculptor of themes, rather than the more positivist small q qualitative approach which upholds the researcher as uncovering pre-present themes (Braun and Clarke, 2022c), much like a paleontologist uncovering fossils.

Regarding the dental neonatal lines chapter, I sought to bridge techniques that have their genesis in dental anthropology with questions relevant to vertebrate paleobiology. This continued multidisciplinary synergy holds promise as we work to connect fields in an interdisciplinary manner, thinking outside the box of siloed academic labs, departments, and universities. Similarly, with regard to the quantitative and qualitative education research chapters, I set out to better understand the juxtaposition of so-called non-positivist views relevant to reflexive thematic analysis, with the objective positivist views of science writ large. I also believe this interconnected practice is important for future work in interdisciplinary research in paleobiology, especially as we reflect on the effectiveness of our pedagogy through a disability social justice lens.

These papers comprise a mixture of biological questions with a mix of social questions. I argue that rather than being strictly disparate topics, they are in fact deeply intertwined. I believe that biology simply does not exist separately from the social and personal perspectives of *biologists*. In shaping this dissertation, it has been my goal to acknowledge that the work we do as scientists cannot exist without our identities. As a disabled person with a family history of additional disability identity, working within a Department of Integrative Biology, the decision to interweave these themes was not without some trepidation and care. However, it's my hope that through this process, I can continue to advocate for a more equitable and just biology field that can take these challenging, introspective positions, interweave them, and help make this practice the norm rather than the exception.

Dedication

I dedicate this dissertation to everyone whom I am fortunate to call my *famiglia*, including by choice, by birth, or by community, and especially to my beautiful sister Katrina Lepore, and my inspiration of a mamma, Marlene LaFauci Lepore.

You are my sunshine.

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Acknowledgements

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I want to express my deep gratitude for my PhD mentors, Leslea Hlusko, Zhijie Jack Tseng, and Anne Baranger. Each one of you has taken the time to listen to my aspirations, guide me through frustrations and challenging times, and to celebrate with me during moments of success. I’ve learned so much from each of you and I feel so empowered by you to pay it forward with those I might mentor in the future.

Leslea, thank you so much for welcoming this former high school teacher and oddball fossil nerd (said with self-love) into your academic family. I’ve grown so much and learned so much from the first time we spoke, when I had this dream of maybe doing a PhD with interdisciplinary interests. I’m so honored to be one of your mentees - the last at Berkeley, no less! - and to be your colleague and friend.

Jack, I’m so grateful for all the time we’ve spent discussing mammals, mammal fossils, mammal evolution…all mammals, almost all the time! And occasionally, other fun topics as well. Being part of the Functional Anatomy and Vertebrate Evolution (FAVE) Lab has been such a blessing during my time at Cal, and I’m also so honored to call you my mentor, colleague, and friend. I’ve really learned so much working with you and hope to keep collaborating. I deeply appreciate that we have a very similar, snarky, sense of humor!

Anne, your Chemistry Education group became a second home for me, virtually on Zoom and then in person, all along the pandemic times and while I was navigating the world of science education research on campus. I'm so incredibly grateful for ChemEd, and for your constant support and guidance while I developed many new quantitative and qualitative research skills. I know this will come in handy during my science education post-doc at Western Michigan University, and beyond. I'm so grateful you took me under your lab's collective wing. Thank you as well for being a wonderful mentor, colleague, and indeed, friend.

Thank you to my student volunteers and my URAP and SURF SMART mentee students, especially Jenny Lu, Enya Deng, Colin Lowery, Catherine Kim, Jiho Kim, Kristin Song, Kevin Minter, and Harmani Verraich. Much of this work depended on your eagerness and willingness to participate in research and to be advocates for everyone deserving a space in science and medicine if they want to be here. You all have a very bright future. Thank you.

I want to thank my friends and family near and far, those in the IB graduate program and my dear friends from high school and college who have listened to me talk about fossils and science education equity and disability justice for way too many years. I want to mention Autumn Shaw and Iris Shaw, because we particularly miss one another, living on opposite sides of the country. Iris, when you grow up, I know you will follow your dreams and do hard things, because you're a wonderful 3-year-old and have a wonderful, supportive mom. Your mind is beautiful and unique. Auntie Tara loves you. You don't have to acknowledge her in your PhD dissertation (or whatever else you do!), however ;) I love you guys.

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Sid and Roving in our University Village apartment at UC Berkeley

Chapter 1: Introduction

This introductory chapter has three main sections. At first glance, these sections may seem somewhat unrelated, but they provide essential context for the three research chapters that follow (Chapters 2-4). I begin with a personal reflection ("Background and Rationale") that provides some of my background and the justification for why I chose to combine two seemingly disparate research projects (Chapter 2, versus Chapters 3 and 4). I then transition to a literature review on tooth development ("Relevant Background on Mammal Teeth and Dental Development") that provides deeper context for the hypotheses tested in Chapter 2. And lastly, I then provide a literature on disability and universal design studies that set the intellectual framework for Chapters 3 and 4. Each of the following chapters is linked by an abstract and bridging statement to guide the reader.

Background and Rationale

Never forget where you came from. This is something that my family, culture, and heritage has reinforced in me since my early childhood. I'm a first generation academic who comes from a working-class Sicilian-American family in suburban Boston. I am white. My family are settlers in the United States and Canada, and native Italians in Sicily. I am queer and disabled. I am neurodivergent. I am a person who walks between genders, rolls with a white cane between sight and blindness, and thinks slowly but powerfully. I value bringing community care and kindness to the places I call home, and to the communities that I call my family.

I never thought, in a million years, that I would pursue two Masters degrees and a PhD in the course of my lifetime. It's true that I had dreams of following a career path in paleontology from a young age, bitten with the "dinosaur bug". I knew on some level that I would probably need to go to college and do this "graduate school" thing I saw people talk about in science documentaries in order to do this. But when I made it to college, I wrote myself out of a career as an academic when I found myself stressed out, miserable, and generally invisible in the academic activities and biology major events I joined in college. I loved my vertebrate paleontology class; I felt lost and unprepared in my organic chemistry class. I made good friends in my dorm building and a couple of clubs; I felt like an impostor in many of my upper level science classes that assumed a heavy knowledge of math and evolutionary theory. I was so unhappy considering doing what my professors did for a job in large part because I thought that I had to change who I *was* in order to conform to what I saw as a largely male, white, heteronormative, and overall *competitive* paleontology field. I was scared of teaching because I had crushing anxiety. I was not competitive, and I cared about science and equity, but I didn't see many people holding space for *both* of these things at the same time. My first semester in college I experienced a big loss in my family, the sudden death of my grandfather who was like a second father to me, and the fallout of some family members who had a hard time coping with their grief. I became a family support person. My mental health tanked, and I thought about switching my major from biology to English, because I liked my English classes so much. It was a really confusing, tough time.

I climbed out of my GPA hole by my senior year, and finished a project on dinosaur trackways, but I still didn't feel like I had been trained on how to craft a hypothesis. I still had a lot to learn about the different ways in which people could do research. So when I got out of college I spent a few years working in the pharmaceutical industry and living at my parents' house. I was grateful for the time to think and save some money, but my living situation still wasn't very good in the protracted aftermath of family drama and loss. Eventually I realized that in order to test my boundaries and save a little of my sanity, I had to find a way to move out of my parents' house again and out of my destructive comfort zone. I applied to graduate school for the first time in 2008, got into some Masters programs in biology or geology, but didn't attend because I wasn't offered much funding. Then I applied again in 2009, and was lucky enough to have a full scholarship and funding to attend the Museum and Field Studies Masters program at the University of Colorado, Boulder. I picked up my belongings, stuffed them into my car, and drove with my then-partner from Boston to Boulder. I still remember my mom waving goodbye on the porch of our house, tears running down her face. I was the baby, the miracle kid who survived being 3 months premature. It was tough for her and the rest of my family, because I was a support person, and we did love each other. But I knew I had to make this change.

That change kick-started not just my science career, but a lifetime of continually reinventing myself, learning to grow into independence, and accepting and embracing communities of choice, people who loved me even though I was far from a nucleus of people and places I used to call "home". I went on to become a high school science teacher, a museum professional, a paleontology mitigation contractor - looking for fossils 60 feet underground beneath downtown Los Angeles - and I completed a second Master of Science degree in science education at Montana State University, focusing on the impact of field paleontology. Each of these experiences forced me to grow and change, and to advocate for my values and my communities, and to advocate for others.

So, why choose to do a PhD, and why study the evolution of birth? Why try to tease apart what people are saying or feeling about concepts like disability, neurodivergence, and accessibility in science fields? Obviously people don't need to have any kind of degree at all to live a fulfilling life; we've created a society that in some ways mandates this sort of academic pressure, in some cases because the training is needed to perform a certain career, and in other cases because a college degree or a graduate degree is considered a marker of "success". I never thought my life path would swing this way, and I'm writing this in my dissertation rationale to help readers, and myself, better understand my decision to undertake this imperfect work and share it with the world. This dissertation is an experiment. It's a combination of honoring where I come from, where I'd like my life and career to go, and ultimately asking questions about the natural world and our place within it. It doesn't mark my success, but it is a small part of my life journey that I am really proud of. I'm excited to take the readers of this dissertation on a part of that journey.

Relevant Background on Mammal Teeth and Dental Development

Here begins the relevant background on mammal teeth and dental development, pertaining to Chapter 2.

Dental development

What forms a tooth? Epithelial and mesenchymal interactions

The major tissue types in the vertebrate embryo are the endoderm, mesoderm, and ectoderm; these tissue types are the embryological precursors of all vertebrate tissue, and here, I outline how interactions between the epithelium (ectodermally derived) and the mesenchyme (ectodermally derived in tooth formation) produce oral teeth.

Teeth, hair, mammary glands, sweat glands, feathers and scales are among the vertebrate organ structures that are ectodermal in origin. These ectodermally-derived structures are produced through interactions between the epithelium (ectoderm) and the mesenchyme (derived either from mesoderm or ectodermal neural crest). In the case of teeth, mesenchyme is derived from ectodermal neural crest cells (Lumsden, 1988; Pispa & Thesleff 2003).

In mammals, cranial neural crest cells (those within the cranium) begin to emigrate to different places and purposes before, during, and after the closure of the neural tube, depending upon location along the vertebrate neuraxis (Lumsden, 1988) (Figure 1.1). But, Verwoard and Van Oostrom (1979) considered mouse neural crest cells to originate from the epidermal ectoderm, lateral to the neural plate margin, rather than more directly from the neural tube (see green labeled structures below). Neural crest cells migrate to form the sensory ganglia of cranial nerves V, VII, IX, and X; to the pharyngeal arches, contributing to face, neck, and heart mesenchyme; and, mesodermal mesenchyme forms more dorsal to the neural crest mesenchyme (work by Peter Ward, cited in Lumsden 1988).

What ultimately sets the stage for the growth of teeth and other ectodermally-derived organs is the settling of epithelium (epidermis) and neural-crest derived mesenchyme together in the same embryological spot wherein they can physically interact; with teeth specifically, this interaction occurs in the oral cavity. The cross-talk between epithelium and mesenchymal tissue allows specialized secretion to occur in an order and timing that ultimately determines spatial configuration and mature organ structure (Lumsden 1988).

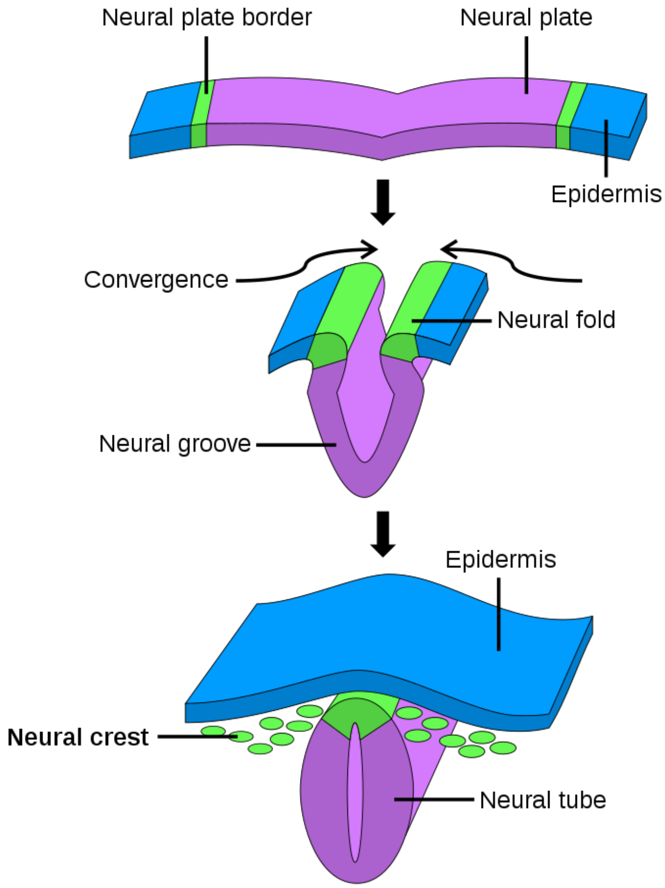


Figure 1.1. Neural Crest Development. Image from Public Domain, By NikNaks.

Tooth Morphogenesis

Teeth develop through interaction between epithelial and mesenchymal cells in a series of steps that represent observed timing of structure growth. The process begins with the initiation stage, during which the dental lamina epithelial cells thicken to form a dental placode, in conjunction with the underlying mesenchyme cells (Ten Cate *in* Nanci, 2007). The dental placode serves as a signaling center for further growth and development of the tooth. Morphogenesis occurs next, beginning with the bud stage, in which the overlying epithelium invaginates into the underlying mesenchyme, and the dental placode signaling center is centralized in the invagination of the epithelium (Figure 1.2). Next, the cap stage signifies the continuation of the invagination process; the enamel knot signaling center forms during the cap stage, along with the cervical loops that will lay the foundation for later development of enamel and dentin (Ten Cate *in* Nanci, 2007).

Following the cap stage, the bell stage may produce secondary enamel knots, furthering differentiation of cusps and the overall gross morphology of the tooth. The bell stage can be further subdivided into early and late bell stages; in the early bell stage, the tooth germ differentiates into layers such as the enamel organ (epithelial derived), the dental papilla (mesenchymal derived), and the dental follicle (mesenchymal), which will become the ameloblast producers, the odontoblast producers and the pulp, and the periodontal ligament, respectively (Ikeda and Tsuji, 2008). The late bell stage is ushered by the formation of ameloblasts and odontoblast cells, and the beginning of enamel and dentin formation. Following the late bell stage is the completion of the crown enamel and tooth maturation. Maturation occurs when the enamel-producing ameloblasts cease production of enamel matrix, and apoptose; and, enamel fully matures to its mineralized form (Ten Cate *in* Nanci, 2007). Teeth are comprised of additional tissues besides enamel and dentin, such as cementum, pulp, and associated anatomical structures such as the periodontal ligament; since this dissertation is focused on the presence of neonatal lines specifically within enamel and dentin, I highlight these two mineralized tissues here.

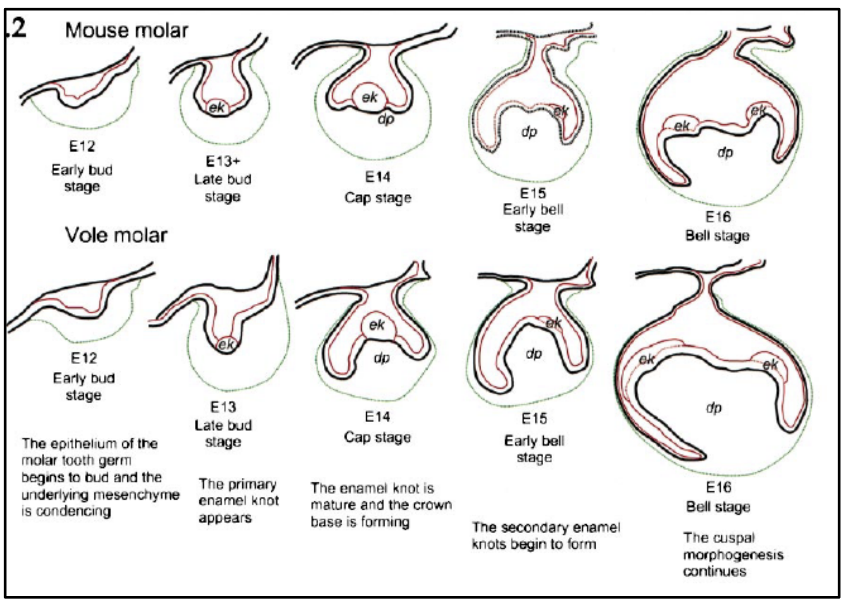


Figure 1.2. Tooth development through the bud, cap, and bell stages in the lab mouse molar. Figure from Keränen et al., 1998.

Enamel and Dentin Cells

The process of enamel formation, or amelogenesis, and dentin formation, or odontogenesis, occurs relatively late in the process of mammal tooth development. Following the late bell stage, maturation of the tooth occurs, which not only begins these processes but also initiates the formation of pulp, periodontal tissues such as cementum, alveolar bone development, and the continued formation of the periodontal ligament (Thesleff 2003, Ikeda and Tsuji, 2008). Eventually the tooth crown erupts from the gingival surface, and even later, roots solidify the connection to the tooth socket.

Tooth socket attachment or the presence of true sockets varies depending upon the vertebrate group.

The cross-talk that occurs to produce mineralized tooth tissue involves precursor cells on either side of the basement membrane, which then differentiate into odontoblasts, which produce dentin (from mesenchyme), and ameloblasts, which produce enamel (from epithelial cells). These cells deposit largely organic material against a growing soft tissue template, which is then “fossilized” by the mineralization and maturation of the crystalline dentin and hydroxyapatite enamel (Lumsden 1988).

What is enamel?

Enamel itself is produced by the ameloblasts, which are located in the internal enamel epithelium; these cells are narrow, cylindrical, closely packed with one narrow end in contact with the developing enamel, known as the Tomes’ process (Hillson 2005). Initially enamel is largely organic, containing enamel matrix proteins such as amelogenins, enamelin, tuftelin, and ameloblastin; and inorganic material such as hydroxyapatite, with some organic collagen and water. The process of amelogenesis occurs in three main stages: pre-secretory, secretory, and the maturation stage. During the pre-secretory stage, the inner enamel epithelium differentiates into ameloblasts. This corresponds to the bell morphogenetic stage; the low columnar or cuboidal cells of the inner enamel epithelium are directly underneath a layer of stratum intermedium cells, which begin to form the crown shape. Following this morphogenetic establishment is the cellular differentiation stage, during which the inner enamel epithelium differentiates into actual ameloblasts; the mitochondria of the cell cluster proximally, the cells elongate to tall columnar form,and the nucleus shifts proximally while the golgi shift distally (Hillson 2005).

The secretory stage occurs in the late bell morphogenetic stage, during which ameloblasts begin to secrete enamel organic matrix and give rise to the full enamel thickness of the eventual tooth crown. During this stage, the distal extension of the ameloblast known as the Tomes’ process forms, initiating the building of enamel matrix initially through prismless enamel foundation, and finally a mix of rod and interrod enamel which grows from secretory granules along the Tomes’ process (Hillson 2005).

Finally, maturation occurs as the ameloblast cells degrade the enamel matrix, and inorganic mineralization forms a mineral lattice of mainly hydroxyapatite (Hillson 2005). This occurs through a transitional phase, where ameloblasts undergo apoptosis and about a 25% reduction in number, prior to enamel mineralization; and then a maturation phase proper, where the bulk of water and organic matrix is removed, replaced by mineralized hydroxyapatite. This occurs through modulation of the cells which break down enamel matrix protein, while calcium-binding proteins and calcium ATPases mineralize the matrix layer in a switch-off between tight and leaky distal junctions (Hillson 2005, Ten Cate *in* Nanci, 2007).

What happens to enamel as it ages?

As enamel ages, it becomes less permeable due to a reduction in the crystalline spacing over time; senescence can also cause attrition (tooth-tooth contact) which ultimately wears down the enamel and cusps (if present). The hydroxyapatite crystals of enamel toughen and become harder with age, but these older crystals are also generally thinner, more predisposed to exposing dentin underneath, which has a darker yellowish color. The risk of dental caries (cavities) also increases with age, though ion exchanges (calcium out, fluoride in) with the environment through time may contribute to this wear (Ten Cate *in* Nanci, 2007).

What kinds of enamel are there?

Enamel comes in two broad flavors: prismatic and prismless. Prismatic enamel is comprised of hexagonal prisms of elongated enamel crystallites (von Koenigswald and Clemens 1992; von Koenigswald 2020; Clemens 2020; Mao et al. 2015), whereas prismless enamel may take on a number of prismless forms (reviewed in Sander 2000). Mammals generally have prismatic enamel, which may have arisen before the split with tritheolodontids, or independently and in parallel along cynodont and crown mammalian lineages (Grime et al. 1979, Sigogneau-Russell et al. 1984, Stern and Crompton 1995). Some workers have named a synapsid transitional enamel as seen in triconodontids or non-mammaliaform cynodonts, a plesiomorphic prismatic enamel (PPE) as described in extant and fossil didelphimorphs as well as fossil metatherians, and a derived prismatic enamel as seen in extant *Didelphis* (Wood and Stern 2020, von Koenigswald 2020, Wood et al. 1999, Sander 2000).

In contrast to many mammals, non-mammalian amniotes have an array of prismless enamel or a lack of any enamel whatsoever, the function taken up instead by softer dentin. Chondrichthyan fish lack enamel and ganoine, but do possess dermal enameloid structures known as denticles; genetically this group lacks the ability to produce enamel matrix proteins (EMP) (Qu et al. 2015).

Basal osteichthyes, conversely, bear enamel on the dermal scales in most fossil forms such as *Andreolepis* and *Psarolepis*, though the basal fossil form *Lophosteus* appears to lack dermal enamel (Qu et al. 2015). Enamel covers the teeth of almost all sarcopterygian fish, and ganoine scales appear in fossil actinopterygian forms such as *Cheirolepis*, fossil and extant gars, as well as fossil and extant bichirs; bichirs also have enamel surfaces on the oral teeth. Ganoine is lost on dermal scales in modern teleosts, though enamel teeth are common. Qu et al. (2015) propose that ganoine is a potential enamel homologue on the dermal surface.

Wood et al. (1999) caution that the presence or absence of these enamel types shouldn’t be taken on its own when considering the full scope of a taxon’s dentition; the crystallite structure, prism type, enamel type, schmelzmuster (organization of dental mineralized tissue), and overall dentition within the jaw should be considered.

What are the potential benefits of prismatic enamel? Enamel has been shown to provide resistance to cracking, greater force resistance, and greater durability through observations of differential enamel wear (Crompton, Wood, and Stern 1994; Grine 2005). But clearly, prismatic enamel is not the only way to build effective teeth.

What is dentin?

Dentin (alternative spelling: dentine) is a composite of mineral and organic material, estimated to be roughly 72% inorganic by dry weight, 18% collagen, and 2% additional organic material (Williams & Elliott, 1989; Hillson 2005). Much of the mineral content is apatite, and the crystallites are shorter than those in enamel, averaging 20-100nm in length (Hillson 2005). The organic matrix of dentin is composed largely of collagen, secreted in fine fiber mats, and within which the crystallite structure and orientation is determined. Unlike enamel, dentin tissue is living and can grow throughout life by way of odontoblast cells which grow inward from the EDJ to the pulp chamber, and eventually settle to line the pulp chamber in a mature tooth (Hillson 2005). Once dentin has formed, it does not remodel as in bone, similar to mature enamel. The first dentin to form during tooth development is called primary dentin, while secondary dentin continues to form after tooth maturation along the roof and walls of the pulp chamber (Hillson 2005). In human teeth, dentin forms slightly before enamel as predentin under the center of each cusp, followed by the first layer of enamel (Hillson 2005).

Anatomical terms for mammalian tooth crowns

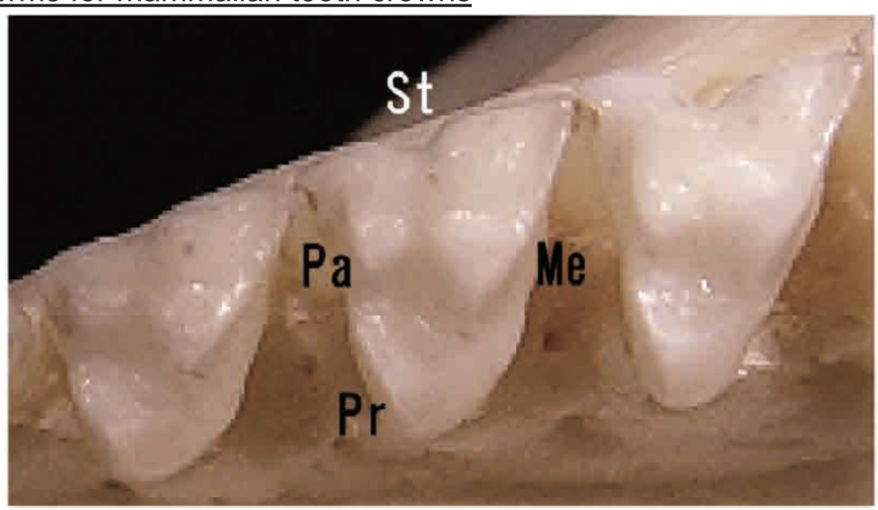


Figure 1.3. A standard tribosphenic molar, as seen in the labeled upper left M2 of *Monodelphis domestica* (From Suzuki et al. 2009), Pa = Paracone, Pr = Protocone, Me = Metacone, St = Stylar shelf. Stylar shelf is positioned buccally, while the protocone is positioned lingually.

To underpin the basic anatomy of the dental neonatal line chapter that follows, here I outline the terms relevant to a standard tribosphenic mammal molar; this review is not exhaustive. The three basic cusps of the tribosphenic molar are the paracone/paraconid, protocone/protoconid, and metacone/metaconid (upper/lower molars) (Figure 1.3). Dental sections were made in a buccolingual direction on embedded teeth, aiming for the paracone/protocone cusps (upper teeth) or the paraconid/protoconid cusps (lower teeth). As the most mesial cusps (towards the front of the mouth), they were deemed the best candidates for potential dental neonatal lines, based on literature from primate dental histology (Antoine et al. 2009). Occasionally dental histology slices were taken from more distal positions along the tooth, such as the metacone or metaconid.

Relevant Background on Disability and Universal Design for Learning (UDL)

Here begins the relevant background on disability and universal design for learning (UDL) which forms the underpinning for Chapters 3 and 4.

What is disability?

Disability is defined by the Americans with Disabilities Act (ADA) as: a physical or mental impairment that causes a substantial limitation of one or more life activities; a record of this kind of impairment; or, “being regarded as having such an impairment” (ADA Amendments Act, 2008). While this definition emphasizes some form of impairment that causes a limitation, disability literature reflects at least four models of disability that center the term in different ways. These are the moral model, the medical model, the social model, and the affirmation model.

The Moral Model of Disability

The moral model of disability has its roots in ancient recorded history worldwide, which often viewed disability as a moral issue that resulted from factors like sin or spiritual disease (Mackelprang and Salsgiver, 2021, p. 4). In this context, disabled people have been perceived as social pariahs, as the center of cure-based religious stories, and as reflections of the sins of parents or past lives, as well as opportunities for charitable acts by non-disabled people (Mackelprang and Salsgiver, 2021, p. 3-4). By the 19th century, European medical advancements sought to cure and treat these so-called deviations, which were largely viewed as undesirable (Mackelprang and Salsgiver, 2021, p. 6).

The Medical Model of Disability

The medical model developed out of the perception that disability is a deviation from the normal, which could be then cured or alleviated by medical interventions; the science of statistics encouraged the eugenic idea of “normal” (Mackelprang and Salsgiver, 2021, p. 6). For as long as humans have confronted mortality, disease, and injury, disability has been perceived as a medical or curative matter; the medical model defines disability as a defect within an individual person that must be cured in order for that person to achieve their full capacity or potential (Siebers, 2008, p. 3). Disability Studies professor and disabled advocate Mike Oliver refers to the medical model as the ‘individual model’, which locates the problems of disability in the individual themselves, stemming from limitations that have arisen from the disability (Oliver, 1990).This is sometimes referred to additionally as a personal tragedy theory of disability, painting an image of disability as universally unfortunate (Oliver, 1986; Oliver, 1990; French and Swain, 2004).

The Social Model of Disability

The social model of disability seeks to frame disability as identity, and empowers disabled people to challenge personal tragedy theory and the medical model (French and Swain, 2004). The social model was first proposed in the UK in the mid-1970s via the Fundamental Principles of Disability document (UPIAS, 1976). It was further elaborated by Oliver (1983), who argued that human beings are not disabled by their impairments, but rather by the disabling barriers imposed by society. Here, disability is defined not as a defect of the individual, or as a tragedy, but as the product of social injustice, which doesn't require a cure but instead requires "significant changes in the social and built environment" for disabled people to benefit from full access (Siebers, 2008, p. 3). Within this framing, disability can be understood as a cultural and minority identity (Siebers, 2008, p. 3). The social model therefore serves as a specific critique of the medical model (Cameron, 2014, p. 4).

The Affirmation Model of Disability

Further building upon the social model, the affirmation model of disability emphasizes its non-tragic nature and encompasses positive social identities for disabled people (Swain and French, 2000). While acknowledging that disability impairment can produce negative experiences, Swain and French (2000) assert that being disabled is not all about the pain or challenges of impairments, and that disability can be experienced as valuable, as a way of thinking differently about being different. They further insist that not all not all people with impairments will celebrate difference, nor does the affirmation model promote 'coming to terms' with disability or impairment, celebration of being oppressed in a disabling society, or aspects of disabled people being plucky or having 'can-do' attitudes (Swain and French, 2008). The affirmation model serves as a critique of the personal tragedy theory of disability, *affirming* the uniqueness of disability and an embrace of difference (Swain and French, 2008, p. 185; Cameron, 2014, p. 4).

Any number of these models of disability perception may be applied in numerous social contexts, depending upon individual training and lived experiences. Two definitions suggested by Cameron (2010; 2011; 2014, p. 6) that help reframe disability, in contrast to those provided by the ADA, are:

> Impairment: a physical, sensory, emotional, and cognitive difference, divergent from culturally valued norms of embodiment, to be expected and respected on its own terms in a diverse society.
>
> Disability: a personal and social role which simultaneously invalidates the subject position of people with impairments, and validates the subject position of those considered normal.

These definitions are provided again in the manuscripts below, to reaffirm the multifaceted nature of these terms. In assessing student perception of disability, we are interested in how students reflect a perception of Cameron's disability definition versus the ADA's definition - that is, will students reflect disability and accessibility as necessary components of diversity, or disability and accessibility as a substantial limitation, or both - or as something else, entirely?

Who is disabled?

Roughly 1 billion people worldwide are reported as having some form of disability (World Health Organization, p. xi). But what does it mean to be disabled in a modern global context?

Disabled people are a diverse and heterogeneous mixture, with myriad temporary or permanent disability characteristics, encompassing everything from a person with cerebral palsy, to a disabled war veteran, to a dementia patient, to an person with arthritis, to an autistic student, and many others (World Health Organization, 2011, p. 7-8). Not all disabled people are apparently or visibly disabled, and not all people with a disability perceive themselves as disabled. Disability, and disability identity, is therefore multifaceted. Personal views of disabled identity can vary widely. Disability is also compounded by additional social stigmas and systemic biases, such as racism, sexism, ageism, homophobia, and other systemic inequalities (Puar, 2017). Not all disabled people experience personal or social disadvantages, and disability disadvantages are not equal across the disabled population (World Health Organization, 2011, p. 8). Yet efforts exist to categorize disabled people in an attempt to provide adequate social support and services.

Each year, the researchers with the U.S. Disability and Health Data System (DHDS) survey citizens by telephone to determine their disability status. In 2019, DHDS reported that over 25% of adults in the United States identified as disabled (CDC, 2023) - over 65 million people. In the U.S. public school systems in 2019-2020, 7.3 million students aged 3-21 received some form of so-called special education services, comprising 14% of the total U.S. school-aged population (Irwin et al., 2021). Within these populations there are undoubtedly more individuals with disabilities than are reported, due to the medical and societal challenges associated with gaining access to care.

In the U.S. public education system, disabled students are mainly categorized as receiving special education. This construct was created with the intention of supporting students with "difficulties" at school, set within the larger landscape of what it means to be problematically different, and how to treat people who are different (Thomas and Loxley, 2022). While special education terminology is still utilized, shifting dynamics of disability identity pride and assessments of school conformity are changing this language and landscape (Thomas and Loxley, 2022).

Disability identity is a unique phenomenon that can shape a person's sense of self, tied to the social model of disability; medical professionals are prompted to affirm this sense of self-identity and pride (Forber-Pratt et al. 2017)

Institutions in higher education with higher percentages of reported disabled students tended to have disability as part of diversity in their mission and/or diversity statements; some suggestions to promote the social model of disability at institutions of higher education include 1. Evaluating language that reinforces the "deficit" model, 2. Exploring accessibility delivery practices that "remove burdens not experienced by students without disabilities" (Scheef et al., 2020), 3. Supporting faculty in implementing equalizing practices such as UDL or inclusive design, 4. Building relationships across campus to bring in a variety of voices on accessibility decisions, and 5. Promoting the exploration of disability from a social justice perspective rather than a pity perspective (Scheef et al., 2020). Disabled students are reported to be less likely to feel welcome in engineering communities/departments (Lezotte et al. 2020). Personal reflections by disabled people have also underscored the ways in which the COVID-19 pandemic has impacted disability accessibility and awareness (Shew, 2020) and reviews have pointed out inherent ableism in academia (Vasquez, 2021; Powell, 2021; Spinney, 2022). Disability theory can help us rethink our teaching practices, with an emphasis on disability is "us" (Wood et al. 2014)

<u>Universal Design in Higher Education</u>

Inclusive instruction is necessary to provide full access to education for all students (Petersen 2020). Inclusive design means making a product available and usable by as many people as possible (Gilbert, 2019, p. 7). This framework arose from the work of Professor Jutta Treviranus, founder of the Inclusive Design Research Center (IDRC) in Toronto. Both inclusive design and universal design are closely related, with a set of basic steps and standard principles (Table 1.1). In the early 1990s, the IDRC put forward three basic steps to the inclusive design methodology:

1. Recognize and respect human uniqueness and variability, and design for that variability;
2. Use inclusive and transparent design processes, and co-design with people from diverse perspectives, including disabled people; and,
3. Recognize that experiences are designed in a "complex adaptive system", requiring us to think about design solutions that not only include the excluded, but also actively "propose ways of doing things that suit the needs of different people". (Treviranus, 2018; O'Neill, 2021, p. 10)

PRINCIPLES OF INCLUSIVE DESIGN (Shum et al., 2016)	1. Recognize exclusion 2. Learn from diversity 3. Solve for one, extend to many
PRINCIPLES OF UNIVERSAL DESIGN (Center for Universal Design, 1997)	1. Equitable Use 2. Flexibility in Use 3. Simple and Intuitive 4. Perceptible Information 5. Tolerance for Error 6. Low Physical Effort 7. Size and Space for Approach and Use

Table 1.1. Principles of Inclusive and Universal Design

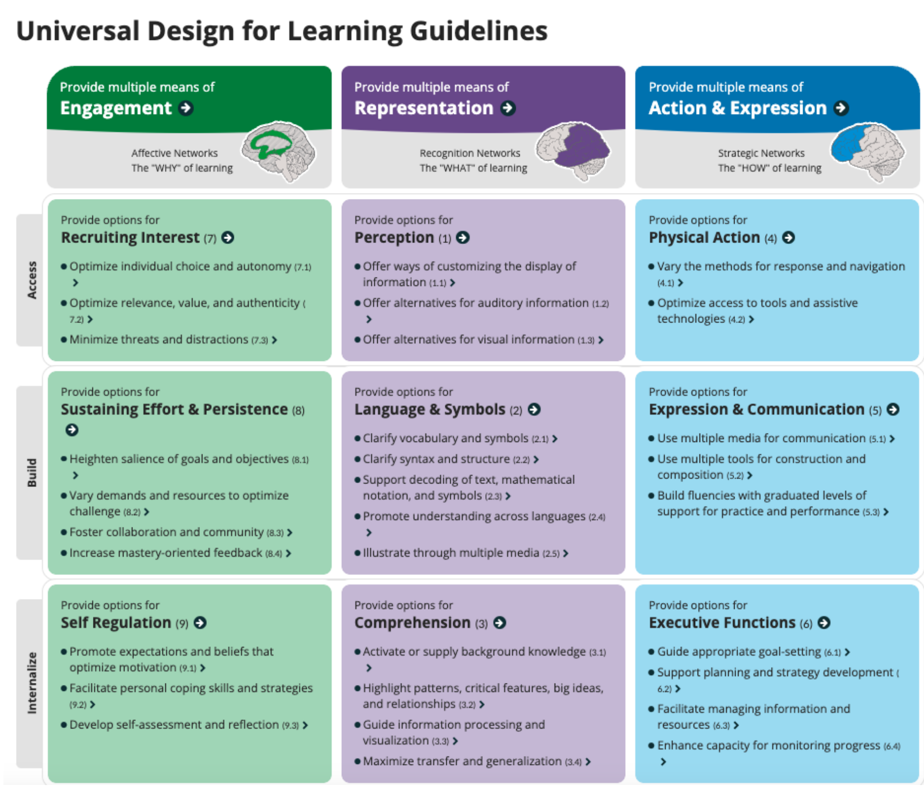


Figure 1.4. Universal Design for Learning (UDL) guidelines. Selected UDL guidelines were applied within this research. (from CAST, 2018)

How do we apply each of these principles? While at first glance the principles of universal design might appear skewed towards universal mobility and physical access, the principles can also be applied to a wide range of product design, including the design of digital products such as videos, podcasts, and social media posts.

Universal Design for Learning (UDL) (Figure 1.4) is a teaching methodology that aims for effective instruction of diverse audiences, based on the science of how people learn; while many singular UDL methods exist, the overarching goal is to provide flexibility in how students access and engage with material, and how they demonstrate their learning (Gilbert, 2019, p. 7). UDL is not a curriculum or technology, nor is it only one method of teaching, nor is it catered only to disabled learners (Gilbert, 2019, p. 7). In effect, all learners stand to benefit from the implementation of inclusive or universal design through the research-backed methodology of UDL.

The terms inclusive design, universal design, and Universal Design for Learning are subtly different, but here I use inclusive design as the umbrella term most closely aligned with digital or web-based learning experiences, as incorporated in this study.

The dissertation now segues into the evolutionary biology chapter on dental neonatal lines in mammal teeth, bringing the reader into the scope of this particular study. But we cannot leave our multifaceted identities behind, as we read on.

Note: Access to raw data is available to qualified researchers upon request.

Chapter 2 Abstract and Bridging Statement

Abstract

Certain placental mammal teeth record internal evidence of birth, known as the dental neonatal line. The neonatal line (NNL) is well-documented in humans and non-human primates as a dark band denoting temporary cessation of the incremental growth of enamel, a marker interpreted to be evidence of placental neonate birth stress. In humans, the NNL is influenced by neonatal birth weight and mode of delivery, and is often found in deciduous teeth and adult first molars. Although the NNL is also observed in other primates, the NNL has not been broadly identified across mammal taxa. We hypothesize that the NNL is present across placental mammals, given the similarities in the timing between birth and tooth formation across the clade. To test this, we conducted an expanded analysis of dental histology from a selection of non-primate mammalian molars that develop *in utero* and across the birth transition. We identified NNL signatures via analyses of polarized and non-polarized light microscopic observation of dental histology and laser ablation mass spectrometry for zinc and barium analysis. Results indicate an area of zinc enrichment in the raccoon dentin, and quantitative analyses of histological sections indicate areas of darker pigmentation attributable to incremental lines of growth in two additional placental taxa. We did not identify NNLs in the three outgroup marsupial taxa analyzed. Our study broadens the phylogenetic distribution of mammals with putative NNLs, especially litter-bearing extant mammals. Investigation of NNLs across extant and fossil mammals and proto-mammals promises to yield insight to the evolution of placental birth.

A modified version of chapter has been submitted for review to the Journal of Anatomy (2024); all co-authors are aware of this chapter's inclusion in my dissertation. I thank Leslea J. Hlusko, Z. Jack Tseng, Diego Fernandez, Christopher Anderson, Deming Yang, Narimane Chatar, Jiho Kim, Catherine Kim, Kevin Minter, Kristin Song, Colin Lowery, Enya Deng, and Harmani Verraich for their collaboration. Funded by: UC Berkeley Human Evolution Research Center (HERC); UC Berkeley URAP Program; UC Berkeley Museum of Paleontology and Department of Integrative Biology Graduate Student Research Awards.

Bridging Statement

Science research is conducted by human beings with our own positionality, values, and biases. This study opens my dissertation research by exploring a set of traditional scientific research questions on the phylogenetic extent of dental neonatal lines in mammalian taxa. This chapter shares results of new analyses as well as a review of dental neonatal lines described in the literature. The goal is to provide this information as a useful manuscript for future work on dental neonatal lines in mammal teeth, and to better understand how mammal birth is recorded, and ultimately, how it evolved. The two chapters that follow this one are centered in quantitative and qualitative research methods to better understand how students in evolutionary biology courses perceive, acknowledge, and advocate for disability and accessibility through direct practice with inclusive education. By combining these three chapters into one dissertation, I am happy to share multiple angles of interdisciplinary interest that I believe will have broad applicability to science education researchers and paleobiologists alike.

Chapter 2: Investigating Indicators of Placental Mammal Birth Through Dental Neonatal Lines

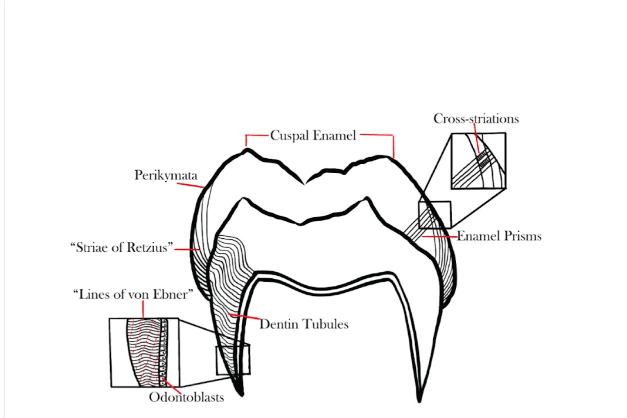
Introduction

Teeth are remarkable storytellers because they record life histories through their organogenesis. Dental life history markers in mammals can indicate stages in dental development, eruption, and maturation (Schultz, 1935; Smith, 1986; Smith, 1989; Smith, 1991; Smith et al., 2006; Antoine et al., 2009; Smith et al., 2015; Monson & Hlusko, 2018; Lanzetti et al., 2020); prenatal growth rate (Monson et al., 2022); development of sexual dimorphism (Leigh et al., 2005; Leigh et al., 2008), stress (Guatelli-Steinberg et al. 2012; Orellana-González et al. 2020; Austin et al., 2023), and milk weaning (Austin et al. 2013; Smith et al., 2021; Smith et al., 2022). One of the most remarkable of these life history markers is the dental neonatal line (NNL), a growth line that serves as a birth certificate inside the mouth, formed in teeth that mineralize across the placental birth transition. It may appear as an accentuated, darker line that occurs in the midst of other dental lines of incremental growth in dentin and enamel (Rushton 1933; Schour, 1936). Incremental lines were first observed at large by Retzius (1837) in dental thin sections and dental surfaces. The dental NNL is well-documented in primates (e.g., Beynon et al. 1991, Dirks 1998, Reid et al. 1998, Smith et al. 2006, Smith and Tafforeau 2008, Austin et al. 2013, Smith et al. 2015, Dean et al. 2019), and a broader investigation of its existence in other taxa has the potential to permit a deep-time reconstruction of the evolution of placental mammal birth. However, the presence of the NNL has not yet been studied across a broad sampling of mammalian taxa within a phylogenetic context. Since the NNL is a well-known birth marker in primates, we hypothesize that it should be present in extant and extinct placental taxa with birth stress equivalent to that exemplified by primates. Here, we examine the NNL across a sampling of extant mammal taxa, using multiple methods of identification to more confidently determine the presence/absence of this feature across mammal phylogeny. In addition, we review reports of extant and extinct mammal dental neonatal lines from the literature, enabling us to further understand the reproductive history of mammal taxa across deep time. To our knowledge no study to date has comprehensively compiled known or putative dental neonatal lines across such a broad range of mammal taxa.

Background

Mammalian tooth growth occurs through signaling interaction between the oral epithelium and the ectomesenchyme, in which the ameloblast cells differentiate from oral epithelium, and odontoblast cells differentiate from the mesenchyme (Figure 1) (Lumsden 1988; Ten Cate 1994). Fully formed ameloblast and odontoblast cells deposit enamel and dentin matrix, respectively, which matures into mineralized enamel and dentin tissue (Ten Cate 1994, Simmer et al. 2010). During this process, periodic pauses or disruptions in enamel and dentin secretion lead to linear features which are visible in thin section as incremental lines (Figure 2.1). Vital labeling and circadian experiments have suggested that incremental striations (daily cross-striations in human enamel and “lines of von Ebner” in dentine) are tied to circadian rhythm (Kawasaki 1975; Kawasaki et al. 1977; Dean, 1989, 1998; Simmer et al. 2010; Kierdorf et al. 2013; Kierdorf et al. 2019). Note that we use quotation marks around eponymic terms to affirm our desire to move away from anatomical terms named after scientists, emphasizing a commitment to inclusivity within medical and scientific discourse, while acknowledging historical figures and their strengths and biases.

a.



b.

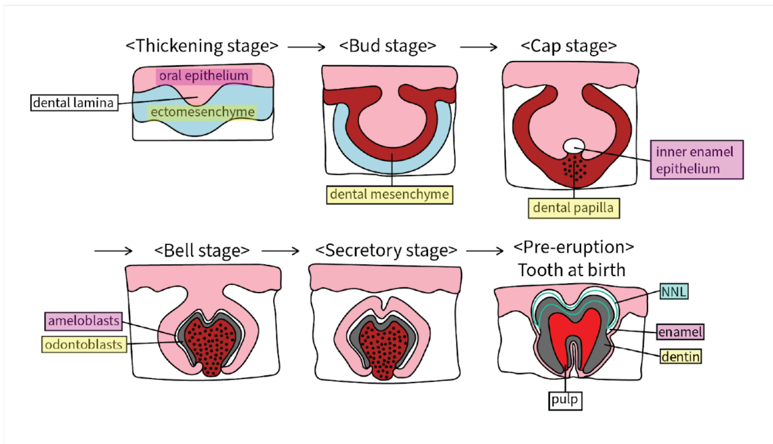


Figure 2.1 – Schematic of enamel and dentine formation: a. Weekly (enamel) and daily (dentine) incremental lines of a generic primate molar, represented by "striae of Retzius" and "lines of von Ebner" in enamel and dentine respectively. Daily enamel cross-striations are present between weekly enamel incremental lines of growth along the tracks of individual enamel prisms, representing daily matrix secretion and circadian pauses. When incremental growth lines reach the enamel surface, they can appear as thin grooves, or perikymata. (Modified from Smith et al. 2003 and Ramirez Rozzi 1994; image by Harmani Verraich) b. Dental development diagram highlighting dental neonatal lines in enamel and dentin, pre-eruption (Modified from Wolf et al. 2012 and Thesleff 2016; image by Catherine Kim).

Studies of incremental striation counts in thin section provide important insights into circadian rhythm during the dental development of primates. This rhythm appears as a series of brownish parallel lines in enamel and dentin under light microscopy (Dean, 1987; Boyde, 1989; Dean & Scandrett, 1996; Smith et al. 2007). In primates, the consistent pattern of cross-striations between these lines suggests a daily cycle in enamel formation (Smith 2006; Smith et al. 2006), with incremental growth lines or "Striae of Retzius" corresponding to multiday or weekly circadian patterns. In non-primate taxa, vital labelling has demonstrated a roughly 24-hour pattern of enamel incremental lamination, corresponding with cross-striations, in sheep (Kierdorf et al., 2013) and sika deer (Iinuma et al. 2004). The mechanism behind this difference in incremental growth line timing is not well understood (Kierdorf et al., 2013) but important to consider when making assumptions about the periodicity of incremental growth lines, and corresponding enamel and dentine extension rates.

The dental NNL has been documented in modern humans (Rushton 1933, Schour 1936, Weber and Eisenmann 1971, Whittaker and Richards 1978, Skinner and Dupras 1993, Behie et al. 2019, Dean et al. 2019) and our fossil ancestors (Macchiarelli et al. 2008, Tafforeau and Smith 2008, Smith and Tafforeau 2008, Smith et al. 2010a, Smith et al. 2015). The NNL is recorded in all teeth that are mineralizing across the birth transition (Dean 2006). NNLs have been observed in human deciduous teeth (incisors, canines, and molars) as well as in the first adult molars (Rushton 1933, Schour 1936, Jakobsen 1974, Dean et al. 2019).

A good deal of NNL literature has come from dental and medical sources, including forensic studies to assess live birth in humans, where the NNL is absent in stillborn infants (Janardhanan et al. 2011; Canturk et al. 2014; Srinivasan et al. 2017; Adserias-Garriga & Vishnapuu 2019) and has been noted in pre-term and at-term infants (Norén, 1982, Szpringer-Nodzak, 1984, Rythén et al. 2008, Mahoney 2012, Hassett et al. 2020). The width of the NNL has been reported as significantly thinner in children born by Cesarean section, and wider in those born by operative delivery (Eli et al. 1989, Canturk et al. 2014), although non-significant differences in Cesarean widths have also been reported (Zanolli et al. 2011, Hurnanen et al. 2017). These studies provide a known life history based on medical records to ground the timing of neonatal lines in teeth. Archaeological studies have also highlighted dental NNLs in ancient humans (FitzGerald and Saunders 2005, Kurek et al. 2015, Kurek et al. 2016, Peripoli et al. 2023). In non-human primates, the NNL has been identified in taxa with either known or unknown life histories: in chimpanzees (Reid et al. 1998; Smith et al. 2010b), pigtailed macaques (Smith et al. 2006), rhesus macaques (Bowman 1991; Austin et al. 2013), gibbons (Dirks 1998), mandrills (Lemmers et al. 2021), baboons (Dirks et al. 2010), orangutans and gorillas (Beynon et al. 1991).

Outside the primate Order, putative NNLs have also been identified in sika deer (Iinuma et al. 2004), domestic sheep (Smith et al. 2022), pigs (Kierdorf et al., 2019), rhinoceros (Tafforeau et al., 2007), Mediterranean monk seals and ringed seals (Murphy et al. 2012, Stewart et al. 1998), and odontocete cetaceans (Nishiwaki and Yagi, 1953, Gaskin and Blair 1977, Perrin et al. 2009, Stewart et al. 2018, Kemper et al. 2019). The methodology used to pinpoint each putative NNL varies widely (Table 2.1), and at times the putative NNL is noted as a “strongly accentuated” line in enamel and/or dentine that is “interpreted as” an NNL (e.g. Tafforeau et al., 2007). To our knowledge, it is unknown whether other extant mammal groups possess this birth marker in their teeth.

As a potential marker of placental birth evolution, exploration of dental markers of birth in geologically older specimens has the potential to add significantly to our understanding of the evolutionary origins of placental mammals. A fossil Miocene notoungulate *Toxodon* had a putative neonatal line identified in a deciduous lower 4th premolar through scanning electron microscopy (Braun et al. 2021), as well as fossil *Mammuthus primigenius* specimens (Rountrey et al. 2012; Fisher et al. 2014a, 2014b) and *Mammut americanus* specimens (Fisher et al. 2014b) through light microscopy and examination of disruptions of the outer tooth surface. A fossil mammal specimen of the pantodont genus *Pantolambda bathmodon* had dental neonatal lines identified via dental histology and laser ablation spectrometry in the enamel and dentin of the adult lower 1st and 2nd molars in multiple cusps (Funston et al. 2022), where the dental NNL was identified as zinc-enriched. This is the geologically oldest dental neonatal line identified to date, at 62 million years ago (Funston et al. 2022). Pantodonts are an enigmatic group of eutherian herbivores and were among the first mammalian groups to reach relatively large body sizes during the Paleogene as compared to their Mesozoic ancestors (Kemp 2005, p. 238; Funston et al. 2021, 2022). Pantodonts have been found globally in China, North America, South America, and Antarctica, and their phylogeny is debated, though they may be related to the Cretaceous paleoryctid insectivorous mammals (Kemp 2005, p.239-240).

Dental neonatal lines have been visualized using a number of different methods (Table 1). Neonatal line microstructure has been referred to as a "staircase" or "tortuous path", as the pause in ameloblast secretion or change in prism configuration associated with birth leaves a complex histological structure (Weber & Eisenmann, 1971; Pantke et al., 1983; Hurnanen et al. 2019). This microstructure has been observed through scanning electron microscopy (Whittaker & Richards, 1978; Sabel et al., 2008), where individual enamel prisms appear to change direction across the enamel surface in the region corresponding to the putative birth period. Sabel et al. (2008) also point out that visual identification alone is not always a concrete method of pinpointing the neonatal line, due to wide variation in sample preparation methods and visualization methodologies; microradiographs display the neonatal line as a darker line, and corresponding digital image analysis of histology thin sections have measured a reduced radiolucency (less brightness) at the NNL, potentially indicating hypomineralization. Postnatal enamel prisms also appear to have a more regular structure than those same tracts prenatally; the irregular or wavy prenatal prisms may be an indicator of incomplete mineralization pre-birth (Sabel et al., 2008). Locating the NNL in a thin section can be a matter of careful practice and luck, as slight changes in thin section angle can obscure it, and it is best visualized in primates when molars are sectioned at the mesiobuccal cusp (Antoine et al. 2009). Because the dental NNL can be difficult to identify and is inconsistently visible in different teeth or cusps, we explore a variety of protocols that may enable investigators to broaden the study of this dental feature.

Table 2.1. Dental Incremental Line Visualization Approaches, Resolution, and Destructiveness

Visualization Approach	Taxon	Destructive?	Resolution	NNL Identification Reported
Laser Ablation	*Pantolambda bathmodon*†[1] *Ovis aries*[2] *Macaca macaca*[3]	Yes (histology, and micro-level ablation)	Micron scale, elemental	Enamel and Dentin
Hard Tissue Histology - Transmitted Light Microscopy	*Delphinapterus leucas*[4] *Homo sapiens*[5,6]	Yes	Sub-millimeter scale, visual interpretation of NNL	Enamel and Dentin
Decalcified Microtome Histology and Staining - Light Microscopy	*Phoca hispida*[7]	Yes	Sub-millimeter scale, visual interpretation of NNL	Dentin
Scanning Electron Microscopy	*Homo sapiens*[8,9,10,11]	Partial (histology, gold coating)	Micron scale, visual interpretation of NNL	Enamel
Perikymata/External Grooves	*Mammuthus primigenius*†[12, 13] *Mammut americanus*†[14]	No	Sub-millimeter scale, visual interpretation of NNL	External Surface of Dentin
Pixel Density or Grey Values Mapping - Light Microscopy	This work	Yes (histology)	N/A, pixel and grey value visual interpretation of NNL	Indeterminate
Propagation Phase Contrast (PPC) Synchrotron Radiation nanoCT	*Homo sapiens*[15]	No* *may cause reversible discoloration	Micron scale, visual and elemental interpretation of NNL	Enamel

[1] Funston et al., 2022; [2] Smith et al., 2022; [3] Smith et al., 2021; [4] Stewart and Stewart, 2018; [5] Hurnanen et al., 2017; [6] Peripoli et al., 2023; [7] Stewart et al., 1998; [8] Whittaker & Richards, 1978; [9] Kodaka et al. 1996; [10] Sabel et al., 2008; [11] Merglova et al., 2021; [12]Rountrey et al. 2012; [13] Fisher et al. 2014a, [14] Fisher et al. 2014b; [15] Tafforeau and Smith, 2008.

Recently, investigators have turned to the enrichment of zinc and barium as evidence of the NNL. Elevated zinc levels have been noted in the outer enamel surface, secondary dentin, and neonatal lines in humans (Dean et al., 2023) along with a distinct decrease in sodium and magnesium at the neonatal line as well (Sabel et al., 2008). Neonatal lines have been identified as enriched in zinc in both fossil (Funston et al., 2022) and extant dental specimens (Dean et al., 2019; Smith et al., 2021; Smith et al., 2022); the cause of this zinc enrichment has been attributed to partitioning of zinc-heavy umbilical cord blood, and zinc-enriched colostrum milk, to neonates as seen in humans (Dean et al., 2023). The distribution of zinc in the dental tissues of fossil teeth has been demonstrated to resemble that of modern teeth, suggesting that zinc preservation and distribution on the outer enamel surface of fossil teeth remains stable over millions of years (Dean et al., 2023). One fossil non-primate tooth, to our knowledge, has been analyzed for zinc enrichment within the NNL in dentin and enamel - the pantodont, *Pantolambda bathmodon* (Funston et al., 2022). Barium/Calcium elemental ratios have also been noted to increase post-birth in the extant human and macaque teeth, and in Neanderthal fossil teeth (Austin et al., 2013). Barium/Calcium ratios were noted as potential indicators of milk weaning in *Pantolambda bathmodon*, but no increase was noted specifically at the dental NNL (Funston et al., 2022).

Regions of elevated zinc levels in the neonatal line and secondary dentine suggest transference from maternal parent to fetus; in humans, zinc stored in the fetal liver is released after birth (Dean et al., 2023), which may combine with zinc-enriched colostrum and umbilical cord zinc to influence the signal of zinc enrichment at the NNL. This zinc liver storage mechanism is not well understood outside of primates. Zinc is also present in matrix metalloproteinase 20 (MMP-20), a protease that regulates enamel maturation; the presence of zinc in the outer enamel surface, within secondary dentin, and also at the EDJ may be a result of the metalloprotease's role in dental tissue mineralization and maturation (Dean et al., 2023). Shin et al. (2014) were able to genetically induce an area of hypomineralization similar in structure to the NNL with 25% reduction of MMP-20 protein expression in transgenic mice (Shin et al. 2014, de Andrade Dantas et al. 2020), though identifying the NNL was not a focus of the study. Finally, work has been conducted on zinc's presence within areas of compressive stress, such as the tooth socket (Ho et al., 2013), indicating areas of high compression may play an additional role in the expression of zinc signatures within teeth.

The biogenic apatite of enamel is largely resistant to diagenetic alteration (Wang and Cerling, 1994), making teeth especially durable, and thereby, relatively more abundant in the fossil record compared to other skeletal elements. Further, while birth lines can be recorded in bone (Nacarino-Meneses and Kohler, 2018), enamel and dentin do not undergo remodeling as seen in bone – though dentin and cementum have some regenerative capability (Boskey 2007; Abou Neel et al. 2016), making teeth a particularly useful time capsule for recording life history events such as birth. Therefore, investigation of putative NNLs across extant taxa provides an important baseline for investigating putative NNLs in the fossil record. An understanding of the visual presence, width where measurable, and chemical composition of putative dental NNLs in a wider range of fossilized taxa will provide a more empirical understanding of the evolution of mammalian birth. As the dental neonatal line is one of a suite of correlates that can be used when assessing the evolution of mammalian birth, paleobiology is on the brink of unveiling incredible new insight to the origins and evolution of this important characteristic of mammals. Other anatomical correlates associated with placental birth evolution through genetic or skeletal evidence are listed in Appendix Table 2.1, Mammal Trait Evolution Table. Here, however, we focus solely on the NNL.

In light of what has to-date been observed for the neonatal line in dental histology, reviewed above, we proposed two hypotheses to test:

H1: The putative neonatal line will be present in representatives of the Carnivora and Rodentia.
H2: The putative neonatal line exists across all placental mammals, and is absent in marsupials.

In the sections that follow, we describe our tests for these hypotheses.

Materials and Methods

Materials: Hypothesis 1: We looked for evidence of NNLs in one tooth from each of 10 species that represent carnivores, rodents, and marsupials. All teeth were sourced from IACUC-approved lab specimens at the University of California Berkeley (*Microtus*, *Mus*) from the labs of Dr. Annaliese Beery and Dr. Michael Nachman; from the University of California Los Angeles (*Monodelphis*) from the lab of Dr. Karen Sears; or from taxidermy specimens (Skulls Unlimited, n.d.) which are recorded as “legally and ethically obtained” by the vendor. The prairie vole specimen (*Microtus*) originates from the UC San Francisco transgenic line of oxytocin receptor knockout animals. All lab animals were managed and culled according to standard Institutional Animal Care and Use Committee (IACUC) protocols by the individual labs, in line with established guidelines (National Research Council, 2003).

Materials: Hypothesis 2: We conducted an extensive literature review, looking for published accounts of the NNL across mammalian taxa. To build the phylogeny, phylogenetic data were compiled via TimeTree 5 (Kumar et al., 2022), and life history trait data were compiled via PanTHERIA (Jones et al., 2009), a species-level dataset of life history traits from extant species. We extracted data on the log average adult body mass (grams) and log average neonate mass (grams) from the database, and calculated the ratio of neonate mass to adult mass. For *Tursiops aduncus* and *Felis catus,* no litter size was available via PanTHERIA, but average calf number (N=1) for *Tursiops aduncus* and average litter size for *Felis catus* (N=4) was added according to the literature (Jefferson et al., 2008; Bradshaw et al., 1999). No adult body mass was available for *Tursiops aduncus* via PanTHERIA. *Rhinoceros unicornis* data were similarly unavailable within the database. The topology and heatmaps were generated using the ggtree and gheatmap functions from the ggtree package (Yu et al., 2017). Red stars indicate taxa with reported dental NNLs in the enamel and/or dentin.

Table 2.2 - Specimens sampled for the test of Hypothesis 1.

			NNL Identification Method			
Taxon*	**Specimen Number**	**Tooth Sampled (Cusp)**	**Method 1: Pixel Density**	**Method 2: LA-ICP-MS**	**Method 3: Light Microscopy**	**NNL Present?**
Rodentia						
Muridae: *Mus musculus*	MVZ 245702	RM (whole tooth)	n	n	y	No
Cricetidae: *Microtus ochrogaster*	MVZ 245701	RM (whole tooth)	n	n	y	No
Carnivora						
Canidae: *Canis latrans*	UCMP 297646	Lm (protoconid)	y	y	y	No
Felidae: *Felis catus*	UCMP 297648	Lm (protoconid)	n	n	y	No
Felidae: *Lynx rufus*	UCMP 297647	Rm (protoconid)	y	y	y	Equivocal
Mustelidae: *Lontra canadensis*	UCMP 297651	Lm (metaconid)	y	y	y	Equivocal
Procyonidae: *Procyon lotor*	UCMP 297645	Lm (protoconid)	y	y	y	Likely, dentin
Marsupialia						
Phalangeridae: *Trichosurus vulpecula*	MVZ 245700	LM (metacone)	y	n	y	No
Didelphidae: *Didelphis virginiana*	UCMP 297649	Lm (paraconid)	y	y	y	No
Didelphidae: *Monodelphis domestica*	UCMP 297650	Rm (metaconid)	y	n	y	No

* *Mus* and *Microtus* were sampled at CENIEH; all others were sampled at UCMP. UCMP = University of California Museum of Paleontology; MVZ = University of California Museum of Vertebrate Zoology; CENIEH = Spanish National Center for Research on Human Evolution; M = maxillary molar; m = mandibular molar; R = right; L = left; all teeth are first molars

Methods: Hypothesis 1: We used three methodological approaches to test the first hypothesis: quantitative assessment of pixel density in photomicrographs, laser ablation of enamel and dentin to assess zinc and barium enrichment, and a qualitative visual assessment using a microscope at a minimum of 100x magnification. All of these methods were done on thin sections of the teeth. We first describe how the thin sections were made, and then describe the three approaches for identifying the NNL in detail.

Dental Histology Thin Sections.

We prepared dental histology thin sections from single teeth of four carnivorans and three marsupials (Table 2.2) using the hard tissue histology lab at the University of California Museum of Paleontology (see Appendix Fig. 2.1 - Histology and Illustration Methods). Teeth were documented prior to destructive analysis using multiple angles of photography and/or CT scanning. We mixed Buehler Epothin II mix in a 100:45 (epoxy:hardener) weight/weight ratio until thickened, then poured epoxy over samples in their silicone rubber mold containers, enough to cover the specimens. No chemical release agent was used due to the flexible nature of the silicone rubber mold. We then applied a minimum of 1-2 rounds of minimum 12 psi vacuum to the point where epoxy bubbling and off-gassing was visible. The silicone mold samples were removed from the vacuum chamber and left to set on lab counter space while the epoxy cured, for approximately 24 hours. Embedded teeth were then sectioned in a buccolingual direction on a Buehler Isomet diamond wafer blade saw to create serial section billets of roughly 700-1000 microns in width. Billets were sketched and documented to ensure accurate tracking of tooth cusp location. These billets were affixed to glass petrographic slides using 2-ton epoxy, pressed gently by hand to remove bubbles, and compressed using the edge of a small circular weight. After 24 hours curing time, the weight was carefully removed and the billet slide visually assessed for quality, such as cracks or under-glued areas. Next, the mounted billets were ground sequentially by hand using a petrographic slide holder, applying the slide to a Buehler lapping machine with 600-grit silicon carbide lapping pad, with frequent light microscopy checks for optical clarity and abrasion. Lapping occurred in a roughly figure-eight motion to ensure even grinding of the billet. If needed, billets were ground and polished using a 1200-grit silicon carbide lapping pad on a second Buehler lapping machine. Final thin section width ranged between 100-300 microns, depending upon size and fragility of the tooth specimen, though some final thin sections were slightly thinner than 100 microns. Once optical clarity was achieved, the thin section was polished by hand to remove lapping pad scratching using sequential 7000 and 10,000 grit polishing pads with a thin layer of water applied to each pad.

An additional pair of *Mus* and *Microtus* dental histology slides were prepared at CENIEH (Burgos, Spain) using a related method, wherein individual block sections of skulls were cut buccolingually along the peaks of mesial cusps when possible, and distal cusps when necessary due to angle of the cut. For these specimens, the fresh cut surface was placed on a 60 degree warming plate for about half an hour; then, we applied a thin layer of resin to the heated cut surface. The samples were allowed to warm overnight in a 40 degree incubator. Then, individual block sections were ground sequentially using a Logitech lapping machine with 600-grit carbide slurry, then two rounds of 800-grit carbide slurry, with resin and 40 degree incubator heating applied between grinding sequences. The polished block sections were then trimmed using a Buehler Isomet diamond blade to achieve desired thickness for optimal contrast. Contrast was checked sequentially using a light microscope.

NNL identification method 1: ImageJ Transects. A Keyence VHX-7000 (Keyence Corporation of America, Itasca, Illinois) light microscope was used to generate photographs of histological slices for Methodological Approaches 1 and 3, with slices taken through left or right lower or upper first molars. Each image was saved as a .jpg file using Keyence VHX microscope software and converted to lossless .tif format. We then opened the corresponding .tif file in ImageJ (Schneider et al., 2012), ran FFT Bandpass Filter function on the file to remove excess noise, and to filter large- and small- scale features between 40 and 3 pixels. This has been established through work with proboscidean teeth to diminish differences in luminance due to “Hunter-Schreger bands”, first-order (annual) increments, and ccd noise (Fisher et al., 2003; Rountrey, 2009). “Hunter-Schreger bands” are undulating visual features comprised of enamel prisms, in which layers of prisms run parallel to one another and are oriented at various angles to the prisms of adjacent layers (Stefen, 2020).

The FFT Bandpass Filter function also suppressed vertical stripes with a tolerance direction of 5%, to reduce artifacts resulting from image scanning by the Keyence scope. Autoscale and saturate were also enabled to increase image contrast. We standardized our images by converting them to 16-bit greyscale. As a result, we could most effectively visualize second-order (daily) or weekly increments (Figure 1). Four transects were then drawn along sections of enamel spanning from the enamel-dentin junction (EDJ) to the outer enamel surface (OES), and measurements of integrated pixel density were taken at set intervals corresponding to the visual boundaries of dark incremental growth lines. One experienced researcher (TL) produced the transect and intervals, and two other researchers (CL and ED) independently measured the same number of interval clicks for each transect. The resulting three transect measures were averaged and graphed along a percentage distance from the EDJ to the OES surface. Any incongruent measurements were removed or discussed and re-measured accordingly. Then, each transect was exported in a comma-separated values (.csv) format. The .csv files were imported into R version 4.3.1 (R Core Team, 2023) and each transect was stored into a list to be plotted individually along the EDJ-OES surface percentage. Finally, the average density was also plotted against the percentage across the EDJ to OES surface using the ggplot function from the ggplot2 package (Wickham, 2011). Utilizing ImageJ to produce quantitative measures of integrated pixel density across the enamel surface can allow us to assess darker, accentuated incremental patterns that may be challenging to pinpoint by eyesight alone. We describe pixel density results for four carnivoran taxa: *Lynx rufus, Canis latrans, Lontra canadensis*, and *Procyon lotor*, and for three marsupial taxa: *Didelphis virginiana, Monodelphis domestica*, and *Trichosurus vulpecula*.

NNL identification method 2: Laser Ablation Inductively Coupled Plasma Mass-Spectrometry (LA-ICP-MS). Elemental quantification was performed using laser ablation with inductively coupled plasma mass-spectrometry (ICPMS) detection at the Department of Geology and Geophysics, University of Utah. Teeth sections were scanned in a Teledyne 193 nm Excite system equipped with Helex II® cell using trapezoidal patterns (areas) of less than a square millimeters and total scanning time around 30 min. The conditions for laser ablation were as follows: fluence: 2.82 J/cm^2; laser beam section: 20 mm, square shape; firing rate: 25 Hz; scan speed 10 mm/s. Laser fluence was calibrated using an energy sensor (Coherent J-25MUV-193). Laser cell output was directed through a PTFE tube to the plasma of a triple quadrupole ICPMS (Agilent 8900) using argon gas (0.2 L/min in the cup + 0.3 L/min in the cell) for analyses of Ca, Zn, Sr and Ba, using masses 44, 66, 88 and 138 respectively. Nickel cones, S-lenses, and no gas in collision/reaction cell were used. ICPMS tuning conditions were optimized using Standard Reference Material 610 (Trace Elements in Glass, National Institute of Standards and Technology, Gaithersburg, MD, US) prior to each session. Quantification was achieved by using Standard Reference Material MACS-3 (Carbonate Pellet, US Geological Service) as primary quantification standard and Standard Reference Material 612 (Trace Elements in Glass, National Institute of Standards and Technology, Gaithersburg, MD, US) as secondary standard. Typically, three 0.25 mm^2 areas were scanned on MACS-3 at the beginning of a run, and then two 0.25 mm^2 areas were repeated after every area scanned on a tooth. Before any scan area was obtained, background intensities were obtained during 30 s and their respective averages subtracted from the collected for the teeth for each mass. The LA-ICP-MS trace element data were internally standardized using Ca contents in MACS-3 and enamel (39.68% by weight). MACS-3 was also used to evaluate instrument drift and fractionation. Mass spectrometry data were reduced using the Trace Elements Next data reduction scheme within Iolite 4.9.4 (Paton et al. 2011).

NNL identification method 3: Light microscopy. We utilized the full-color .tiff files of the Keyence VHX-7000 photomicrographs produced for method 1 to qualitatively examine features of the dentin and enamel in each specimen. A group of this study's co-authors (TL, KM, ED, HV, CK, JK, KS) described and discussed each photomicrograph in collaboration, in order to assess anatomical features pertinent to locating dental neonatal lines, and to describe general visible features of enamel and dentin.

Methods: Hypothesis 2: We combined the evidence observed in the test of Hypothesis 1 with data culled from the literature, mapping this evidence onto a mammalian phylogeny. The phylogeny was produced using mammalian phylogenetic data from TimeTree 5 (Kumar et al., 2022), life history trait data compiled via PanTHERIA (Jones et al., 2009), and the phylogeny visualization produced in R version 4.3.1 (R Core Team, 2023) with the packages ggtree (Yu et al., 2017) and treeio (Wang et al., 2020). Mammal image silhouettes were added in R using rphylopic (Gearty and Jones 2023), and silhouettes are from PhyloPic (Keesey 2023).

Results

We first report the results of our test of Hypothesis 1, walking through the results for each of the three methodologies we used to assess the presence or absence of NNLs.

For the first methodological approach, the visual histology photomicrographs (Figure 2.2) were compared with graphs of integrated pixel density (Figure 2.3) along the enamel surface (i.e., moving outward from the enamel dentin junction to the outer enamel surface). Grayscale images with labeled transects are also provided (Appendix Fig. 2.2 – Grayscale Images). Each tooth is described individually.

In the *Lynx rufus* specimen (right lower m1 paraconid) we note darker lines and corresponding decreasing graph slopes at roughly 20% from the EDJ, in transects 1, 2, and 4 (Figure 2.3a). Transects 2 and 3 similarly display decreasing graph slopes at roughly 40% from the EDJ. Transects 1, 3, and 4 display a decreasing slope at roughly 70% from the EDJ. When compared to the grayscale image, we note accentuated dark lines at these areas of enamel. However, due to the low angle progression of incremental growth lines from the cervix of the tooth to the outer enamel surface, we do not expect decreasing graph slopes to match up precisely; for example, a dark line or decrease in pixel density in Transect 4, closer to the dental cervix, may be present closer to the EDJ than the same dark line would be in Transect 2, where we would expect the angle to extend the same line outward closer to the OES. Indeed, certain strongly accentuated incremental lines or candidate NNLs vanish from one transect to another if they meet the OES and therefore do not extend further.

In *Canis latrans* (left lower m1 protoconid), we note dark lines and corresponding decreasing graph slopes at 15% EDJ – OES in Transect 1, and roughly 17% in Transect 3 (Figure 2.3b). We also note two sharply negative slope graphs at roughly 20% and 27% EDJ – OES in Transect 2 and 1, respectively. In Transect 2, this decrease in integrated pixel density percentage may correspond to a darker, “Hunter-Schreger band”. While we attempted to avoid these darker bands in our transects, it was not always possible to do so, and our interpretation of pixel density necessitates this cross-check with the photomicrographs. In Transect 1, a dark spot on the transect at roughly 27% may correspond to either a dark feature in the enamel surface, or an imperfection in the slide behind the enamel itself. When we examined this tooth surface we noted a strongly accentuated incremental line beginning in Transect 1, roughly 50-60% of the distance from the EDJ to the OES. We interpret a decreasing slope seen in Transect 1 at roughly 55% as this line, although by the time the same line meets Transect 2, it passes below the 50% mark of the enamel surface.

The specimen of *Lontra canadensis* (left lower m1 protoconid) presents decreasing graph slopes between 0%-25% of the enamel surface in all 4 transects (Figure 2.3c), corresponding to the first darker incremental growth line, just visible at the edge of a broad gray area in the grayscale image that we interpret as optical interference from “Hunter-Schreger bands”. This darker incremental growth line is barely visible optically, however pixel density measurements appear to capture a corresponding dip in pixel density (darker pixels). The pixel densities at Transects 1 and 4 (at approximately 10% of the enamel surface), and Transects 2 and 3 (at approximately 20% of the enamel surface), appear roughly aligned and signal areas of less pixel density. Transects 1 and 4 appear aligned again as areas of decreasing graph slopes at approximately 75% of the enamel surface, closer to the outer enamel surface than the previous measures. A sequence of darker incremental lines, occasionally obscured by the broad gray area interpreted as “Hunter-Schreger bands”, is present at the 75% mark along both transects.

In *Procyon lotor* (left lower m1 protoconid), we note Transects 1, 3, and 4 presenting decreasing slope graphs at roughly 10% along the enamel surface from the enamel dentin junction (Figure 2.3d). However, Transect 2 does not follow this trend, indicating higher density instead. Transect 2 at 10% along the enamel surface corresponds to a lighter gray patch, similar to the optical feature seen in *Lontra canadensis* which we interpret as “Hunter-Schreger bands”. However, in Transects 1, 3, and 4, this feature is less prevalent, allowing a clearer view of the incremental lines of growth. We also do not rule out photographic settings or 16-bit scaling which may contribute to this discrepancy. Transects 1 and 3 are roughly aligned in a dip in pixel density (darker color) at approximately 65% of the enamel surface. Examining the grayscale image, we note there are prominent flame-like projections at these transects which again may correspond to “Hunter-Schreger bands”.

In *Trichosurus vulpecula*, an upper left m1 metacone observed at 500x and 80x magnification, we note decreasing slope graphs which are present in Transects 1 and 2 at roughly 25% along the enamel surface. A notable dip is present in Transect 3 at 75% along the surface (Figure 2.3e). Upon examining the histology specimen, we note very dark areas adjacent to the outer enamel surface, especially near the tooth cervix at Transect 4, which may be attributable to enamel abrasion. When pulling this tooth from its associated skull, both enamel microwear patterns and the fusion of cranial bones indicate this individual was senescent. At roughly 50% along the enamel surface in Transects 1 and 2, a pattern of increasing-decreasing slope is present that may be a result of the darker feature in that region of the enamel. However, we do not identify incremental growth lines or posit that this darker feature is associated with neonatal line or, alternatively, pouch exit. It may simply be an optical feature of the tubular enamel, obscuring further detail deeper within the thin plane of view.

The specimen of *Monodelphis domestica*, a right lower m1 fragment of the metaconid, displays decreasing slope graphs in Transects 2 and 4 at roughly 30% along the enamel surface (Figure 2.3f). Transects 1 and 3 experience a decrease in slope graph offset from these, at roughly 40% along the enamel. There is a dark, broad feature in the enamel image that is present at these regions, though it is not as clearly visible in Transect 4.

The specimen of *Didelphis virginiana* (left lower m1 paraconid) displays decreasing slope graphs in Transects 1, 3, and 4 at roughly 25-35% along the enamel surface (Figure 2.3g). Transect 2 does not share this trend. When comparing with histology we note regions of darker pigmentation closer to the EDJ, and at Transect 2, this darker pigmented area arches away from the EDJ towards the OES. Interestingly, though we did not quantitatively measure pixel density on the occlusal side of the paraconid, we note accentuated incremental growth lines that may warrant further examination of this specimen.

Figure 2.2 – Photomicrographs of the suite of dental histology specimens under non-polarized light and polarized (f-2, g-2) light. A. *Lynx rufus* right lower m1 at 20x magnification, b. *Felis catus* left lower m1 at 20x magnification, c. *Lontra canadensis* left lower m1 at 20x magnification, d. *Procyon lotor* left lower m1 at 20x magnification, e. *Canis latrans* left lower m1 at 20x magnification, f-1. *Microtus ochrogaster* right upper m1 at 150x magnification, non-polarized and f-2. Under polarized light, g-1. *Mus musculus* right upper m1 at 300x magnification, non-polarized and g-2. Under polarized light, h. *Monodelphis domestica* right lower m1 at 100x magnification, i. *Trichosurus vulpecula* upper left m1 at 150x magnification, j. *Didelphis virginiana* lower left m1 at 50x magnification.

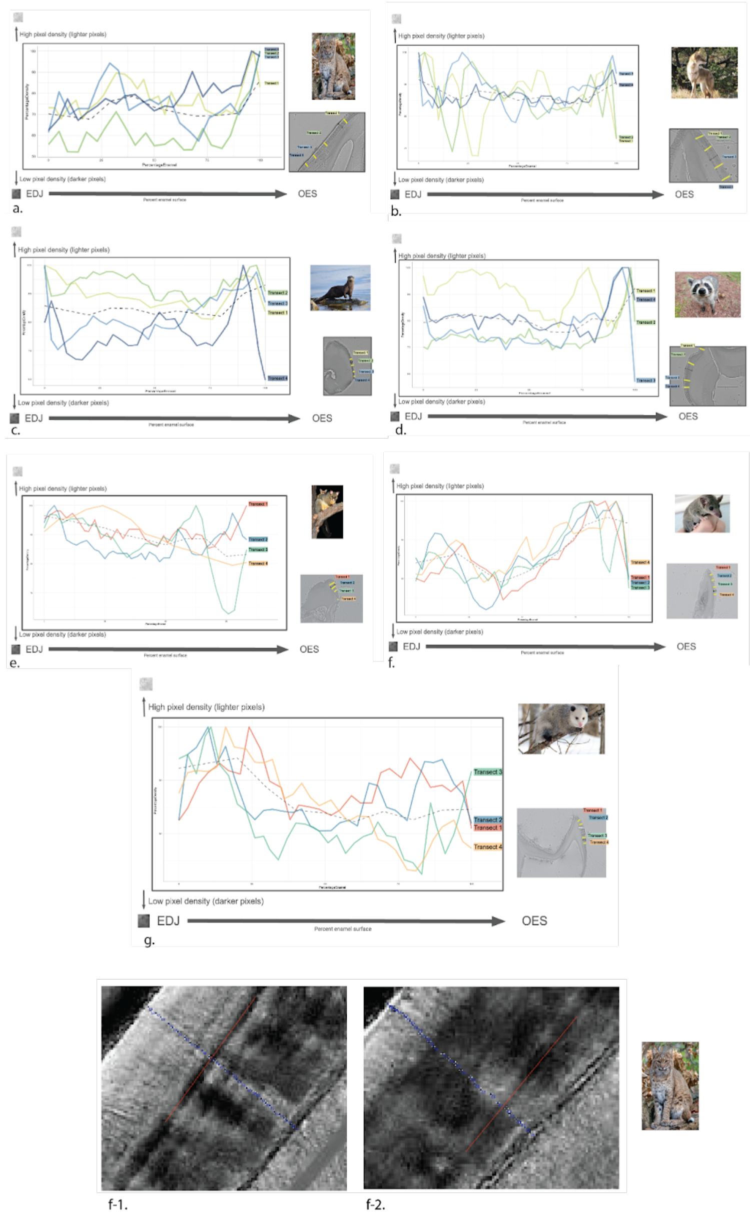
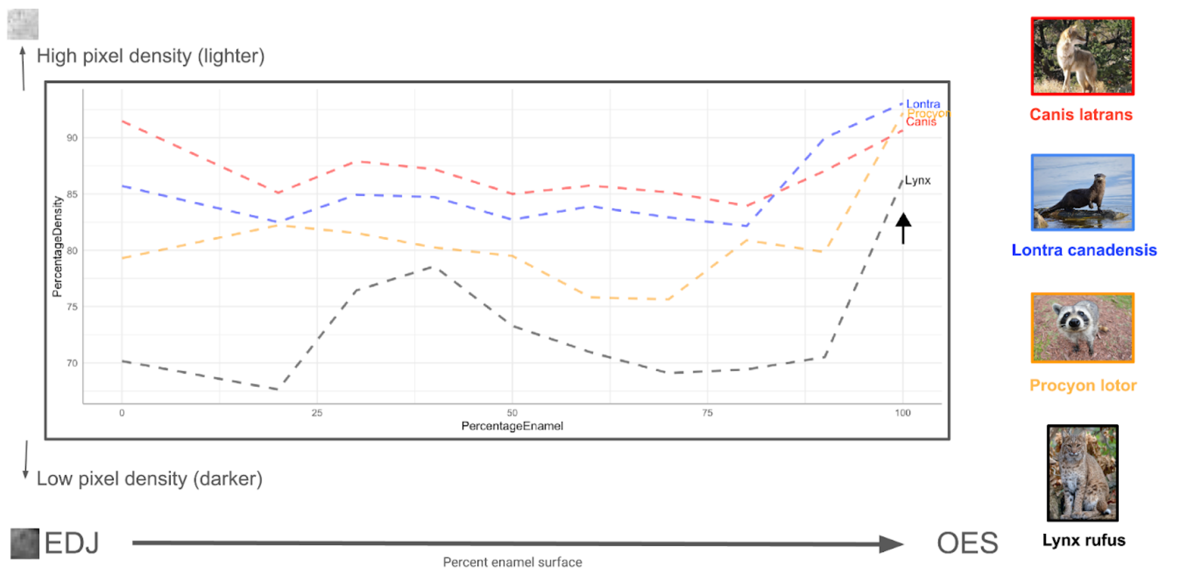


Figure 2.3 – Comparisons of pixel density across four carnivoran taxa (a.-d.) and three marsupial taxa (e.-g.), with yellow lines highlighting transect paths, and black bar indicating enamel-dentin junction (EDJ) and outer enamel surface (OES). Transect labels in the subset grayscale tooth images are closest to the OES. At f-1., a red line at Transect 2 of *Lynx rufus* highlights a promising dark incremental line, which becomes fainter as it is traced to Transect 3 (f-2.). By Transect 4, this line has disappeared. These areas correspond to approximately 60% across the enamel surface from the EDJ to the OES in Transect 2, and approximately 20% in Transect 3. Image of *Lynx rufus*: By Becker1999 on Flickr, CC BY 2.0. Image of *Procyon lotor*: Paxson Woelber, CC BY-SA 3.0 via Wikimedia Commons. Image of *Lontra canadensis*: USFWS Mountain-Prairie via Flickr, CC BY 2.0. Image of *Trichosurus vulpecula*: JJ Harrison, CC BY-SA 2.5. Image of *Monodelphis domestica*: Dawson at English Wikipedia, CC BY-SA 2.5. Image of *Didelphis virginiana*: Cody Pope, CC BY-SA 2.

To probe the carnivore and marsupial results from methodological approach 1 more deeply, we averaged Integrated Density for all four transects across three coders. Each transect had a different number of “clicks” to measure Integrated Density, due to the total width of the enamel surface changing across all transects. These averages were aligned to correspond with the percentage of the enamel surface (0→100%) from EDJ to OES (Figure 2.4).

Averaged pixel density highlighted three distinct areas of low percentage density in *Canis latrans*, *Lontra canadensis*, and *Lynx rufus* at roughly 20% of the enamel surface distance from the EDJ to the OES. Interestingly *Procyon lotor* displayed a corresponding area of higher percentage density at 20% enamel surface. While the marsupial specimens had slightly obscured incremental growth lines, the average transects nonetheless demonstrate a pattern of increasing pixel density in *Monodelphis* and *Didelphis* at roughly 20% along the enamel surface, and decreasing slope graphs at roughly 40% along the enamel surface. *Trichosurus* takes on a different pattern with a decreasing slope graph at roughly 60% along the enamel surface.

a.



b.

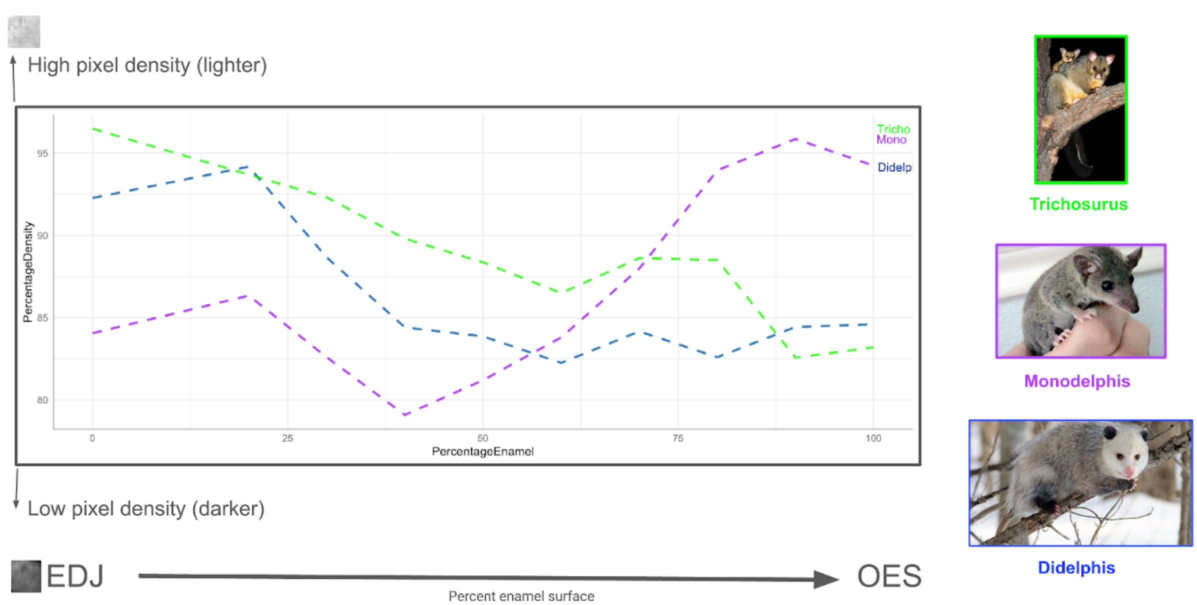


Figure 2.4 – Carnivore versus Marsupial transect pixel densities. a. Averaged Transect Lines (Transects 1-4) for *Canis latrans*, *Lontra canadensis*, *Procyon lotor*, and *Lynx rufus.* Arrow indicates outer enamel surface area which is zinc-enriched in all three taxa. b. Averaged Transect Lines (Transects 1-4) for *Trichosurus vulpecula*, *Monodelphis domestica*, and *Didelphis virginiana.*

The results from our second methodological approach, using laser ablation (LA-ICP-MS) of enamel and dentin, are shown in Figure 2.5.

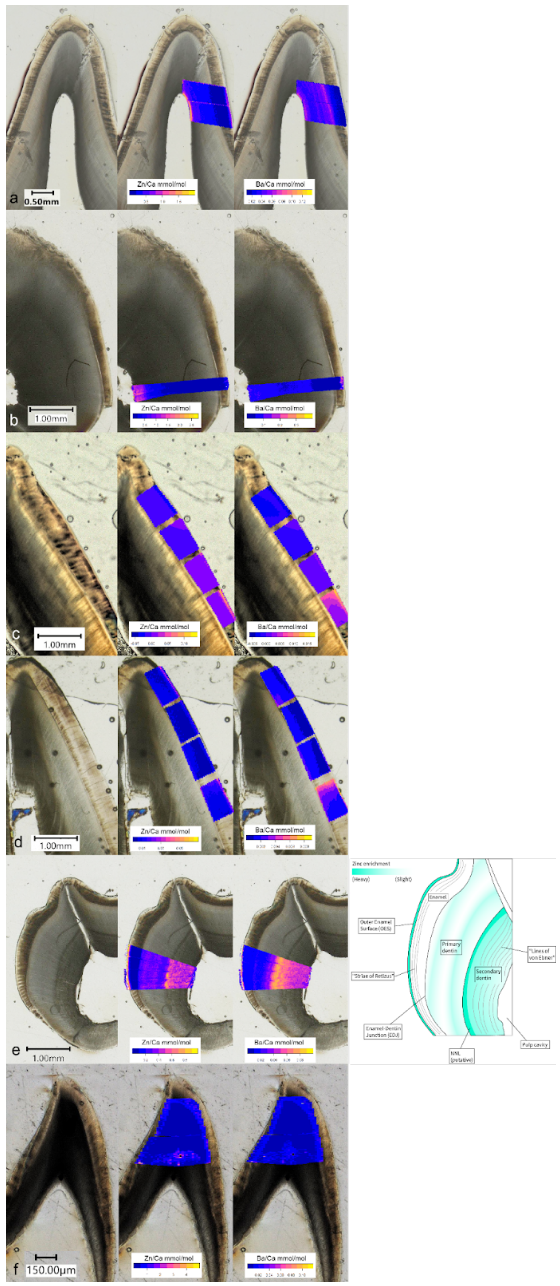


Figure 2.5 - Visualization of LA-ICP-MS results across extant mammal first molars. a. *Lynx rufus,* b. *Lontra canadensis*, c. and d. *Canis latrans*, e. *Procyon lotor*, f. *Didelphis virginiana*. 6e includes an interpretive diagram of potential zinc enrichment as extrapolated across the raccoon molar (*Procyon lotor*).

Of a suite of teeth which underwent laser ablation mass spectrometry analysis, *Procyon lotor* presented the most promising indication of zinc enrichment in dentin, adjacent to a strongly accentuated line in the dentin (Figure 2.5e). Zinc was also strongly enriched at the outer enamel surface (OES) and immediately within the primary dentin adjacent to the EDJ (Figure 2.5e). Other LA-ICP-MS results were less conclusive but nevertheless highlighted areas of zinc enrichment. *Lynx rufus* (Figure 2.5a) displayed an area of high zinc enrichment immediately adjacent to the pulp cavity and in the OES. Barium was enriched adjacent to the pulp cavity, at the enamel-dentin junction (EDJ), and in linear patterns running from the crown towards the cervix in the dentin. These linear patterns do not appear to map along specific dentin visual bands. In the North American river otter, *Lontra canadensis* (Figure 2.5b), a strip of laser ablation did not highlight zinc enrichment at the OES, but did display zinc enrichment immediately adjacent to the pulp cavity. It is unclear whether this zinc enrichment corresponds to a visual band in the dentin due to the close packing of dentin tubules at the pulp and the level of slide polishing. Barium appears to have spots of enrichment adjacent to the pulp surface, though the laser scan transect ran off the enamel surface at the OES, and barium is not present at the OES itself.

Two *Canis latrans* teeth were analyzed, from the same individual (UCMP 297646) - an upper right m1 (Figure 2.5c) and a lower left m1 (Figure 2.5d). Results are inconclusive for zinc and barium across most transects, but the transects closest to the cervix appear to have captured a signal of enriched zinc and barium at the OES. Whether this is a true signal of elemental enrichment is unclear. Finally, zinc and barium analysis was conducted for the marsupial, *Didelphis virginiana* (Figure 2.5f). While barium results are inconclusive, there is a small region of zinc enrichment close to the pulp region and small spots within the enamel itself.

Our third methodological approach is a qualitative description of enamel and dentin features. These are described for each tooth individually in the paragraphs that follow and are shown visually in Figure 2.2.

Structural features of *Lynx rufus* were visualized along the protoconid cusp of the lower right m1 at 80x magnification (Figure 2.2a). In the enamel, histology showed a light band adjacent to the outer enamel surface of the enamel. The EDJ was relatively thicker compared to that of *Canis latrans*. Dark incremental growth lines are visible throughout the enamel, with the darkest line positioned roughly in the center of the enamel (moving from EDJ to OES) and lighter, more faded incremental growth lines closer to the OES. Prominent, dark wavy lines project in a flame-like fashion from the EDJ towards the OES, which we identify as “Hunger-Schreger bands”.

Structural features of *Felis catus* were visualized along the cusp of the lower left m1 at 80x magnification (Figure 2.2b). This specimen was not analyzed via laser ablation mass spectrometry. In enamel and dentin, incremental lines of growth are clearly visible in non-polarized light. On the buccal side of the molar, the EDJ is particularly dark. Incremental lines of growth are more clearly visible on the buccal side enamel as well.

Structural features of *Lontra canadensis* were visualized along the metaconid cusp of the lower left m1 at 80x magnification (Figure 2.2c). The dentin closer to the pulp area is darker relative to the outer dentin, likely from the curvature of the dentin tubules in the captured image. At around 450 micrometers away from the EDJ, within the dentin end there is another dark line that could be a candidate dentin neonatal line. Based on the clarity of the dentin, there are 3 or 4 dark incremental growth lines within the dentin. Darker coloration is present within the enamel at the EDJ. Incremental growth lines are visible within the enamel.

Structural features of *Procyon lotor* were visualized along the protoconid cusp of the lower left m1 at 80x magnification (Figure 2.2d). We note that the outer enamel surface (OES) is brighter than the surface just within the enamel itself. Incremental growth lines are visible within the enamel surface. At first glance the darkest enamel incremental growth line could be assumed to be a neonatal line, however we caution against immediately drawing this conclusion. The distinct EDJ is shown, with the darker colored side representing enamel and the relatively lighter side representing dentin. Moving into dentin, the tissue appears dark near the pulp cavity but is bright toward the enamel. Within the dentin, a dark accentuated line is visible between the primary dentin (toward the enamel) and the secondary dentin (toward the pulp cavity). Within the secondary dentin, “Lines of von Ebner” are visible, growing from the pulp cavity toward the primary dentin, with very clear dentin tubules.

Structural features of *Canis latrans* were visualized along the protoconid cusp of the lower left m1 at 80x magnification (Figure 2.2e). In the enamel, histology indicated softer or translucent incremental growth lines that ran along the protoconid cusp. Incremental growth lines of varying thickness and position occurred within the enamel layer, with thinner and more compact lines present closer to the EDJ, and relatively thicker lines present towards the OES. These thicker lines were more clearly visible as distinct lines. Lines of incremental growth also tapered towards the cervical enamel (i.e., the lines are not parallel to the OES), as expected from ameloblast growth patterns in primates. “Hunter-Schreger bands” were visible extending from the EDJ in the direction of the OES. Additionally, four measurements were taken along the enamel width from EDJ to OES, representing transects from the apex to the cervix, with a mean enamel width of 434.45 μm (min=293.68, max=524.70, SD=103.75).

Structural features of *Microtus ochrogaster* can be seen in the non-polarized (Figure 2.2 f-1) and polarized photos (f-2), the first upper m1 of *Microtus ochrogaster* (magnification 150x) displays an alternating pattern of exterior enamel and internal dentin at the buccal and lingual sides of the tooth. At the center of the tooth and exposed at the occlusal surface is softer, reparative or tertiary dentin. Vole molars are ever-growing (hypselodont) and lack a permanent root, though the root is not visible in the captured image. Under polarized light (f-2), individual lines extend from the EDJ to the OES, which we interpret as individual enamel prisms. These prisms are opaque in non-polarized light (f-1). Polarized light also enhances visibility of the twisted appearance of the reparative dentin. No incremental lines of growth are easily visible in this specimen.

Structural features of *Mus musculus*. In both non-polarized (Figure 2.2 g-1) and polarized photos (g-2), the lighter-colored enamel of *Mus musculus* is situated adjacent to the darker-colored dentin. Additionally, while enamel is primarily composed of minerals such as hydroxyapatite, dentin contains more organic material, which may cause it to appear darker in polarized images. Fine horizontal striations can be observed at the right end of the enamel, which are especially apparent in the polarized image. These may represent paths of individual enamel prisms. Thin, short threads which resemble cracks in the enamel are interpreted as enamel tufts, which represent less mineralized regions of the enamel. In the dentin, numerous dentinal tubules extend from the center pulp region towards the enamel. Overall, the tubules become less dense and the color lightens as they approach closer to the enamel than to the pulp.

Structural features of *Monodelphis domestica* were visualized along a metaconid fragment of the lower right m1 at 100x magnification (Figure 2.2h). There is a dark, broad feature captured in the image which runs through the upper part of the enamel. Incremental growth lines are not easily visible. The coloration of the enamel and dentin are a very distinct lighter brown at the apex of the tooth. Towards the tooth cervix, the coloration starts to become more blurry, making it less obvious where the EDJ is precisely located. Dentin tubules are curved slightly downward throughout most of the tooth, while in the enamel tubules are present, and are curved upward. It is difficult to visually distinguish EDJ, compared to non-marsupial specimens.

Structural features of *Trichosurus vulpecula* dental features were visualized along the metacone of the upper left m1 at 500x and 150x magnification (Figure 2.2i). The tip of the cusp does not show distinctive enamel prisms, which may be out of the plane of focus. The enamel is generally brighter than the dentin, and there is a distinctive darker EDJ. The enamel displays tubules, characteristic of most extant marsupials which possess tubular prismatic enamel (Sasagawa & Ferguson, 1991; Kozawa et al. 1998). Exceptions to this tubular enamel nature in extant marsupials are all teeth of *Vombatus* and anterior teeth of *Tarsipes rostratus* (Gilkeson, 2020). Within the enamel, incremental growth lines if present are obscured. There is a prominent dark feature following along with the shape of the cusp, similar to that visualized in *Monodelphis domestica.* The dentin displays dentinal tubules which curve upwards to meet the EDJ.

Structural features of *Didelphis virginiana*, a left lower m1 protoconid, were examined along the at 100x magnification (Figure 2.2j). Tubular enamel appears as periodic, dark, slightly curved bands running from EDJ towards the outer enamel surface. Multicolored birefringence is visible, likely from packed enamel crystalline structures. Shallow, small grooves are regularly present on the outer surface of enamel, which may be perikymata or alternatively, cracks in the enamel surface due to specimen grinding and polishing. Incremental lines of growth are faintly visible within the enamel with no clear instance of a darker accentuated line. There is a clear boundary at the

EDJ and the corresponding dentin tissue is relatively thin. A network of dentinal tubules runs from the EDJ towards the pulp chamber, slightly curved outwards towards the EDJ. Dentin tubules appear as fine, roughly parallel striations, whereas the clear spaces between tubules may contribute to lower density. Dentin tubules become lighter in color closer to the pulp. There are no visible incremental growth lines in the dentin.

The results from our test of hypothesis 2 are presented in Figure 2.6. Dental neonatal lines have been identified with varying techniques and with variable levels of multimodal evidence. We compare mammal taxa with reported putative neonatal lines, along with our newly explored taxa, on a phylogeny (TimeTree 5, Kumar et al., 2022) alongside log adult mass (g), log neonate mass (g), and litter size where this information is available in the PanTHERIA database (Jones et al., 2009). Because we tentatively ascribe a dental neonatal signal to *Procyon lotor*, but not to *Canis latrans*, *Felis catus*, *Lynx rufus*, *Lontra canadensis*, *Mus musculus*, *Microtus ochrogaster*, or the three marsupials, *Didelphis virginiana*, *Monodelphis domestica*, and *Trichosurus vulpecula*, we have inconclusive data for these latter taxa. Taking this into account, taxa identified as having a dental neonatal line in the literature produce an average of no more than 2 babies per litter, though not all taxa have a relatively large neonate mass to adult body mass. Exceptions to this are *Sus scrofa* and *Procyon lotor*, which produce relatively larger litter sizes, and *Phocoena phocoena* which produces quite heavy babies compared to adult mass in the bright yellow heatmap color. In the warmer orange colors for this ratio, which indicate slightly larger babies compared to adult mass, we note the sika deer *Cervus nippon*, the Mediterranean monk seal *Monachus monachus*, and the primates *Hylobates lar* and *Macaca mulatta*. *Microtus ochrogaster* also appears to produce relatively large neonates compared to adult body size. Fossil taxa are not included in this phylogeny.

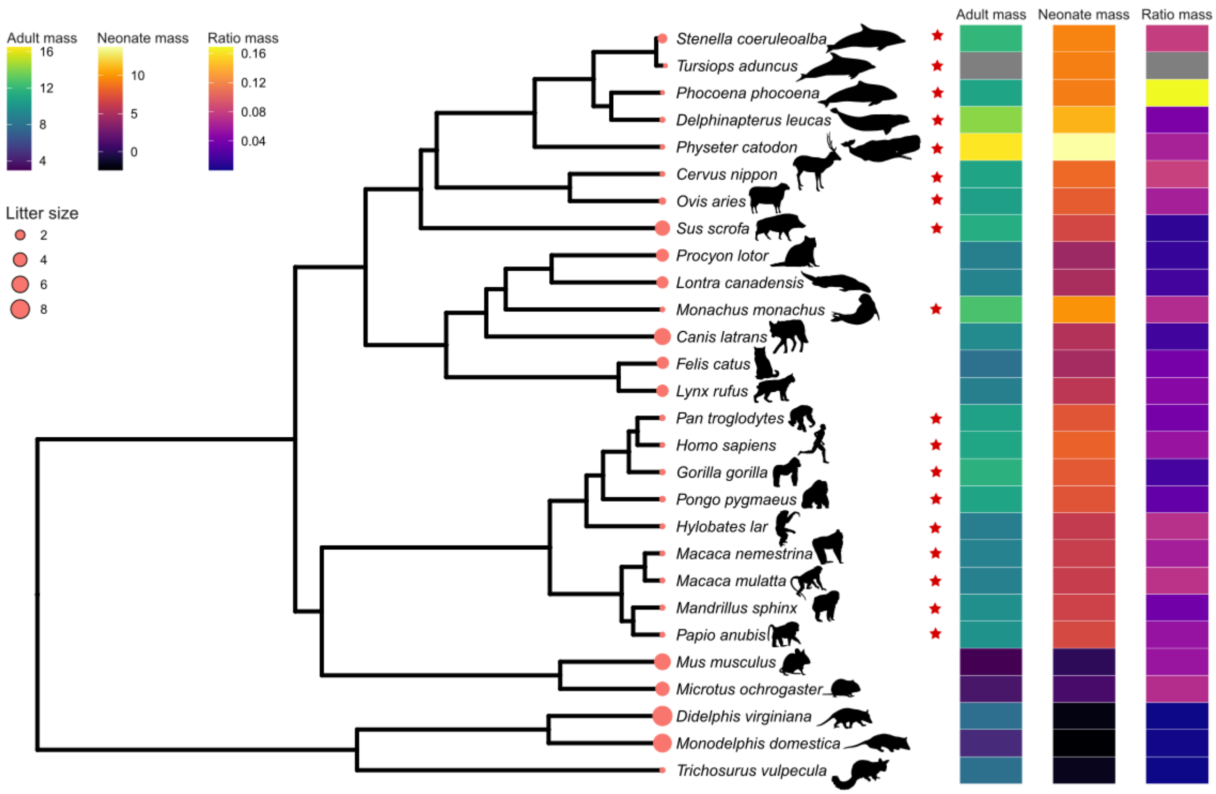


Figure 2.6 **-** Extant mammal phylogeny with sampled taxa, and sample taxa reported as having NNL in literature. See text for details.

Discussion

We investigated the presence of the neonatal line using a mix of dental histology thin-sectioning, pixel density analysis in ImageJ, and laser ablation mass spectrometry to test the hypothesis that the putative NNL is present in representatives of the Carnivora and Rodentia. Our pixel density analysis and qualitative observations returned less certain evidence for the NNL than our zinc enrichment methodology.

We identified patterns in pixel density across specific groups which correspond to various features in the enamel surface, including darker incremental lines of growth that could be candidate NNLs. However, without a known life history of the animal and in the absence of conclusive zinc enrichment associated with these incremental lines of growth, we are cautious to jump to interpretations of NNL presence in all of our carnivoran taxa. Rodent teeth were even less clear, with almost transparent enamel with features visible only via cross-polarized light. Our quantitative approach arose by recognizing a need for novel ways to identify dental neonatal lines in addition to zinc-enrichment, especially in unexplored taxa, recognizing that quantitative patterns may be present where visual, strongly accentuated lines are challenging to interpret. We also desired a more comprehensive understanding of dental neonatal lines across mammalian taxa, and so chose taxa to analyze for which dental neonatal line literature could not be found. Results demonstrate that even where histology images are visually challenging to interpret, patterns of pixel density that indicate potential dental neonatal lines can be captured along enamel transects, but caution must be used to overinterpret accentuated incremental lines of growth as likely candidates for dental neonatal lines. The striking dark band in the *Procyon lotor* molar dentin (Figure 2.2d) was a visual cue that spurred us to focus on elemental analysis in that region of the tooth. Laser ablation analysis identified regions of zinc and barium enrichment which we interpret as corresponding to secondary dentin, marking birth and subsequent milk feeding in the raccoon (*Procyon lotor*); there are also two prominent regions of zinc closer to the EDJ in *Procyon* which appear to correspond with faint dentin incremental growth lines in the primary dentin, and could be indicators of stress *in utero* (Figure 2.5e). We did not identify a corresponding area of zinc enrichment within the enamel surface itself, although the zinc enriched outer enamel surface may obscure finer detailed signatures (Figure 2.5e). Similar dark visual bands are present in the dentin of the lynx (Figure 2.5a) and coyote (Figure 2.5c and d), although laser ablation was only conducted on the enamel of the coyote. In the lynx (Figure 2.5a), we also note higher zinc enrichment adjacent to the pulp cavity, but the curvature of the dentin obscures any potential visual lines that may correspond to this enrichment. The otter tooth (Figure 2.5b) similarly displays an area of zinc enrichment closer to the pulp cavity, and interestingly, there is a dark visual band within the dentin that does not appear to have an enriched zinc signature.

In summary of our zinc enrichment exploration, we observed zinc enrichment in the secondary dentin of *Procyon lotor*, corresponding to, but not limited to a darker accentuated line within the dentin, which we identify as a likely neonatal line. We note zinc enrichment at the outer enamel surface (OES) for lynx, raccoon, and coyote molars, which is expected based on patterns of OES zinc in primates. However, no zinc-enriched NNL can be confidently identified within the enamel or dentin in the lynx, otter, opossum, and coyote. Zinc enrichment is also present close to the pulp-dentin surface in lynx, otter, raccoon, and potentially the opossum. In the literature, neonatal lines have been visually identified in pinnipeds and, in this study, we highlight a likely dentin neonatal line in the raccoon. We paired exploration of zinc-enrichment with visible accentuated lines, aiming to make the best case possible for the presence of putative neonatal lines in unexplored taxa.

We then combined this evidence with the data culled from our literature review to test our second hypothesis, anticipating that zinc-enrichment and strongly accentuated lines of incremental growth would be visible in carnivorans and rodents, but not in marsupials, due to dental development occurring after birth in marsupials. Dental neonatal lines were indeed not identified in marsupials, but contrary to our expectations, we did not identify NNLs in all carnivoran taxa and in no rodent taxa. Based upon the phylogenetic scope of anatomical features identified in the literature as putative dental neonatal lines, we identify dental neonatal lines as a common feature of primates, as well as several reported within Artiodactyla and Odontocetes, suggesting that the dental neonatal line may be a common feature across the Cetartiodactyla. Literature on seal dental growth indicates putative dental NNLs (Murphy et al. 2012, Stewart et al. 1998), which we combine with our raccoon putative NNL to add to the literature of reported carnivoran NNLs, but additional work to compile carnivoran dental NNLs would make a stronger case for this birth marker being a shared trait across Carnivora. Proboscidean fossils have had dental neonatal lines identified (Fisher et al., 2003; Rountrey, 2009), as have extant rhinoceros (Tafforeau et al., 2007), but it is unclear whether dental NNLs are consistently present in Afrotheria or Perissodactyla.

The dental neonatal line has been attributed to birth stress as well as birth gestation, yet the mechanisms of neonatal line presence or absence across mammal phylogeny are unclear. Certain extant mammalian taxa have been reported as having substantially challenging births, or dystocia, which overlaps with several mammals reported to have a dental neonatal line. We briefly discuss the scope of dystocia across taxa within our phylogenetic scope to highlight potential overlap between taxa with putative dental neonatal lines, and those understood to experience substantial incidence of dystocia.

Veterinary and agricultural literature has provided many sources on extant mammal dystocia, where stress and pain are substantial for the maternal parent and/or the neonate, relating to inability of a female mammal to expel a neonate during birth (Martínez-Burns et al., 2021). Causes of such challenging births may be owed to cephalopelvic dimensions as in humans, but also to soft tissue restrictions which are not apparent skeletally. Birth stress may also be attributed to primiparity (first time births), or to lengths of labor that extend beyond average time for a given species (Martínez-Burns et al., 2021). Neonate brain size relative to body size, absolute neonate body mass, and relative neonate body mass, along with pubic symphysis morphology (reviewed in Grunstra et al., 2019) may also play a role in the relative stress of birth. In cattle (*Bos taurus*), an economically important species with high levels of research on birth, dystocia is estimated at 1.5-22.6% of births, and is the leading cause of calf death at birth (Martínez-Burns et al., 2021). Domestic sheep (*Ovis ovis*) additionally have reportedly high mortality prior to weaning, especially within the first three days of birth, with dystocia a cause of between 9% (Refshauge et al., 2015) and 19-67% of lamb deaths (Jacobson et al., 2020); domestic sheep have been reported as possessing a dental neonatal line (Smith et al., 2022). Higher birth weight in domestic pigs (*Sus scrofa*) is identified as a strong indicator for dystocia (reviewed in Martínez-Burns et al., 2021), which also have putative dental neonatal lines (Kierdorf et al., 2019). Sika deer (*Cervus nippon*), another dental neonatal line candidate, have also been reported as suffering from dystocia which is not a “negligible factor of mortality” for parent and offspring, especially under food limitation; factors included malpresentation of neonates, primiparity, and poor maternal parent health (Takahashi et al., 2005). Dystocia has been reported in the spotted hyena (*Crocuta crocuta*), which gives birth through the constricted soft tissue space of the penile clitoris (Frankand and Glickman, 1994). In a fascinating connection to matrix metalloproteinase 20 (MMP-20), the protease that regulates enamel maturation, knockout mice with mmp -/- were noted as having higher incidences of dystocia, with a possible mechanism of extensive fibrosis in the myometrium of the uterus (Kalev-Altman et al., 2023). MMP2 is understood to participate in uterine extracellular matrix remodeling across estrus, and during the cycle of pregnancy, parturition and postpartum (Kalev-Altman et al., 2023).

Dystocia has been studied in the pigtailed macaque (*Macaca nemestrina*), also reported to have a dental neonatal line (Smith et al., 2006), owing to large neonates, malpresentation, or prolonged labor (Stockinger et al., 2011). While to our knowledge no dental neonatal line has yet been identified in squirrel monkeys, these primates are born at a relatively precocial stage with breech presentations 3-4 times as likely as in humans (Bowden et al. 1967); up to 50% of squirrel monkey births in one captive population were stillbirths, likely owing to cephalopelvic proportions (Abee 1989; Trevathan 2015). More work to identify putative neonatal lines in Primates and other mammal taxa through multiple combined methods will provide a framework to better understand how birth and birth stress is recorded in the bodies of mammals.

Zinc enrichment can be a useful tool to identify regions of secondary dentin and potential dental neonatal lines, but certain areas that appear zinc enriched are not necessarily paired with strongly accentuated lines of incremental growth in every taxon, every time. We encourage this integrative methodology pairing zinc enrichment with quantitative and qualitative analysis of dental features to most accurately interpret incremental growth lines, and to utilize multiple serial slices from more than one individual of each taxon, recognizing that this can be time and labor intensive. We note that with LA-ICP-MS, it can be challenging to interpret chemical or elemental signatures within a tooth, given the time and financial constraints of the process. A single tooth run may take several rounds to fine-tune the laser spot size, and other technical issues can occur. When results are produced, we note that it is crucial to compare them to the laser ablation elemental standards. We analyzed only enamel and dentin, and not cementum tissue, which could provide additional information signaling birth. Histological images are challenging to produce; slicing and polishing teeth is tricky and we sometimes erred on the side of visibility and a thicker slide vs polishing whole teeth away. The angle of the tooth slice also greatly impacts the visibility of incremental lines of growth, including dental neonatal lines. Our sample sizes were also quite small, with one or two teeth per taxon, limiting the scope of interpretation. Finally, it is possible that other dental NNLs have been reported in the literature which we did not come across in our literature review.

We consider this work as a step forward in an integrative framework of multiple methods to assess dental neonatal lines, and encourage methodological integration and sampling of multiple teeth per taxon to validate zinc and visual putative neonatal lines. Work comparing life history traits of taxa with birth stress recorded in teeth provides an intriguing backdrop for broader discussion of dystocia, and how stressful birth is recorded in fossil and extant mammal taxa. Propagated phase contrast synchrotron radiation µCT (PPC-SR-µCT) provides a potentially non-destructive method for investigating the internal anatomy of teeth (Newham et al., 2020, Baier-Stegmaier et al., 2023), and work to assess growth and birth signatures through other dental tissue such as cementum (Grue & Jensen, 1979; Baier-Stegmaier et al., 2023) provides additional direction. We look forward to image processing advances such as those brought about by multimodal imaging (Austin et al. 2016), machine learning, or artificial intelligence to streamline this labor-intensive process.

Conclusions

We provide a first known comprehensive review of dental neonatal lines in extant and extinct taxa. Neonatal lines are challenging to pinpoint, and we advise caution in inferring dark accentuated lines as NNLs in taxa without known birth timing or vital labelling. However, combined methodologies can nevertheless allow for hypothesis testing on the phylogenetic scope of this dental feature. Quantitative measuring of integrated pixel density can highlight patterns difficult to discern visually on enamel and dentin, and while it is not necessarily effective as a single methodology, it can be used as a complementary method along with other data such as laser ablation, other chemical analysis, and qualitative description to match chemical and anatomical signatures. Within a phylogenetic framework, additional work is invited to understand the phylogenetic scope of dental neonatal lines in extant and extinct taxa, and whether putative NNLs, when present, are only detectable via different imaging and analytical modalities in different taxa. Our integrative analyses suggest that dental neonatal lines in the enamel and dentin may be a shared feature in Primates, Cetaceans and Artiodactyls, and in some but not all carnivorans, indicating NNLs evolved at least once among boreoeutherian mammals as a marker of placental birth.

Chapter 3 Abstract and Bridging Statement

Abstract

Evolutionary biology courses inherit a long and troubling history of exclusion and othering through problematic evolutionary science communication and debunked concepts of human categorization. As biology educators and education researchers we wish to enact change in our evolutionary biology college classrooms to center our pedagogy in social justice, challenging this history. Specifically, we focused on student awareness of accessibility and disability in science media products, due to the interests and lived experiences of our research group. Our key theoretical framework is Critical Disability Theory. We wished for our students to be practitioners of inclusive education to challenge this history, and we assessed their awareness of accessibility concepts in a science context. We implemented a pedagogical framework centered in Universal Design for Learning (UDL) and tasked undergraduate evolutionary biology students with creating digital science media products throughout our semester-long science communication projects. Student pre-post survey comparisons indicate an increase in ability to define accessibility, consider accessibility in science media, and advocate for access in science. Additionally, post-survey results suggest students experience a greater sense of classroom community, inclusion in science, and awareness of disability as diversity. We encourage future UDL implementation and interrogation of problematic evolutionary biology communication in evolutionary science courses, where future practitioners of science, medicine, engineering, and other fields can feel empowered by this knowledge and community experience.

A modified version of chapter has been submitted for review to the journal CBE: Life Sciences Education (2024); all co-authors are aware of this chapter's inclusion in my dissertation. I thank Leslea J. Hlusko, Z. Jack Tseng, Christopher Schmitt, Oliver Rizk, Laura Armstrong, Tanner Frank, and Anne Baranger for their contributions.

Bridging Statement

This dissertation includes an exploratory research study in evolutionary biology, specific to dental biology and signatures of placental birth as recorded in mammal teeth. As a researcher, I am also strongly interested in questions of equity in evolutionary biology, including in evolutionary biology classrooms and other avenues for education. The following two chapters synthesize the results of this component of my research interests, where I co-developed and implemented a pedagogy project to center equity and inclusive education in evolutionary biology courses. By uniting my interests in paleontology, evolutionary biology, and science education and equity research, I am better positioned for flexible career interests in education and policy, and can aid current and future students to explore interdisciplinary research interests.

Chapter 3: The Tangible Community Benefits of Disability and Accessibility Awareness in Evolutionary Biology College Courses

Introduction

Evolutionary biology has a long history of problematic science communication, which has contributed to systematic othering. Although concepts behind the notion of "survival of the fittest" predate Charles Darwin and his scientific articulation of evolution-by-natural-selection (Malthus in 1798), the publication of On the Origin of Species (1859) provided the illusion of biological validity for harsh philosophical notions of how society could or should operate, based on those who are "fit" or "unfit" (Claeys, 2000). For many influential social leaders, "Darwinian evolution" applied to humans has long provided justification for exclusionary, racist, and ableist practices (Dennis, 1995; Fuentes, 2021), with effects that stretch across a very wide spectrum, from bias in STEM disciplines to the Nazi justification for genocide during World War II (O'Mathúna, 2006; Bergman, 2014, p.13). The social concept of Darwinian evolution includes scientifically debunked but incredibly pervasive notions of human racial categorization (Morning, 2008; Yudwell, 2014). The eugenics movement (Allen, 2011) also relies on many of these same concepts to justify the marginalization, sterilization, and oppression of people deemed non-white and aberrant from the so-called normal (Dyett & Thomas, 2019; Cronin et al. 2021). In particular to our work, disabled and neurodivergent people have also been historically cast off and othered by evolutionary science (Vaahtera, 2016; Branch et al., 2022).

The ways in which evolutionary biology has been communicated within the scientific community still contains echoes of this history, which has broad implications for the general public's understanding of societal diversity and fitness or normality. For example, some of the terms and narratives traditionally used in evolutionary science are laced with ableist meaning and undertones, such as "we could swim before we could walk" – assuming all can walk – and terms such as "wild type" and "mutant" which subtly emphasize a spectrum of normality in nature (Vaahtera, 2016; Branch et al., 2022; Packer & Lambert, 2022). Academic systems continue to be rife with oppressive practices (Patton, 2004; Settles et al., 2021; Bhopal, 2022), and simultaneously, efforts to counter exclusion of minoritized groups have been made (Draffan et al., 2017; Lafferty et al., 2023). As science educators and evolutionary biology researchers, it is essential that we take a hard look at this history and current practice of exclusion, and here, we focus on disabled equity based upon our experiences as disabled researchers and allies. One way to begin to reckon with this history is to implement tangible pedagogical changes which give instructors and students alike the tools to communicate science in an equitable fashion, acknowledging this troubling history and teaching our students that there is a more equitable path forward for all who wish to learn about and contribute to science.

Background

Evolutionary Biology as a Forum for Science Communication

The way that science is communicated to our students, and how students approach their own science communication, clearly matters. Evolutionary biology courses provide an opportunity to create a structural change in the education and perspectives of scientists. Courses centered in evolution are required in a majority of biology fields and thus, we have an opportunity to introduce concepts of equity to most people who work in this field.

As graduate student teaching assistants and faculty lead instructors, we wish to create evolutionary biology courses with a social justice mindset that expects our students to become practitioners of equity-centered science communication. We are particularly interested in awareness of concepts such as accessibility and disability, based on the lived experiences of the lead author and other broad experiences of our research group. Inclusive science education is one way in which this awareness can be realized, through reflexivity and intentionally inclusive practices, as has been recognized by dedicated efforts in inclusive science communication (Canfield & Menezes, 2020). It is important to investigate the tangible benefits of disabled equity awareness in evolutionary biology courses on our university students – whether self-identified as disabled or non-disabled - and to teach students what to do with this awareness. In this way, we can develop best practices for teaching students to recognize and produce inclusive science. Evidence of the effectiveness of equity-centered science communication will inform continued practice of inclusive science education pedagogy in college science classrooms, uniting subject-matter pedagogy with inclusive pedagogy for the benefit of all (Stinken-Rösner et al., 2020). Further, as discipline-based education researchers, we share our instructional best practices to recognize the cultural and organizational norms of our departments and institutions, and “address those norms that pose barriers to change in teaching practice” (National Research Council, 2012, p. 195), especially in the context of disability perception.

Study Pedagogical Framework

We developed a pedagogical framework of lesson plans which allowed our students to share the science concepts they had learned in our courses, and to implement components of disabled accessibility in their final projects, over a span of approximately six weeks. Our goal was to investigate the benefits or drawbacks on student conceptualization of access and disability resulting from this pedagogical approach. We grounded our student semester projects in inclusive design, more specifically, Universal Design for Learning (UDL) (Rose, 2000; Hall et al., 2012). We implemented our UDL-centered project in four evolutionary biology courses at three separate U.S. universities, where students learned methods of Universal Design for Learning as a vehicle for equitable science communication.

This study shares the results of pre-post surveys and student interviews that assessed student experiences with the project and their perceptions on accessibility and disability in science communication media. There are several studies which analyze the impact of UDL on student learning (Lee et al., 2015; Almumen, 2020) and classroom equity (Price et al., 2012; Basham & Marino, 2013; Finnegan & Dieker, 2019), but to our knowledge there are none that look at the impact of university students as practitioners of UDL themselves, especially on their perceptions of accessibility and disability. While instructor and administrator understanding of UDL is important, we wish to add to the literature by including the perspectives of students themselves as UDL practitioners. By emphasizing UDL and disabled equity in evolutionary biology courses across multiple universities, this study not only addresses historical shortcomings in our field, but also emphasizes the ability of such pedagogical approaches to foster a sense of community and social responsibility among future science, engineering, technology, and math (STEM) practitioners. Science communication can be a powerful medium through which students can practice this social responsibility in science courses.

Definitions

Universal Design for Learning and Science Education

Universal Design for Learning (UDL) has evolved as an inclusive pedagogical framework with significant implications for science education. Initially rooted in the field of architecture to promote accessible design (Mace, 1985), UDL has extended accessibility best practices into educational settings (Hall et al., 2012). The concept of UDL gained traction in response to the need for inclusive practices which accommodate diverse learners in an inherently inequitable academic environment, and which address various learning modalities, abilities, and backgrounds. Within the context of science education, UDL has been highlighted as a method for equitable science, technology, engineering, and math (STEM) K-16 teaching (Price et al., 2012; Basham & Marino, 2013; Finnegan & Dieker, 2019); studied for its effect on science learning globally (Lee et al., 2015; Almumen, 2020); and has been supported within subject-specific endeavors such as introductory biology (Orndorf et al., 2022), evolutionary biology (Harris et al., 2020; Hasley et al., 2024), anatomy (Balta et al., 2021; Dempsey et al., 2023), undergraduate health science (Kumar & Wideman, 2014), nursing school courses (Celestini et al., 2021; Celestini, 2022), and computer science (Israel et al., 2020), among others. The COVID-19 pandemic has also led to a refreshed look at UDL as a potential pathway to equitable and inclusive digital learning (Montgomery & Bridget, 2023). One of our four study courses was run entirely online during the COVID-19 lockdowns, and two others had a hybrid online component. The ongoing impact of inclusive digital learning during this span of time will likely be a subject of interest for inclusive education researchers.

Defining accessibility

Accessibility, most generally, is a term which can be used to encompass equitable societal access for all people, to the greatest extent possible. Accessibility is defined (Merriam-Webster, 2024) as a capability of being reached, understood, used, appreciated, or influenced; in standard use, accessibility can be understood as the ability of a *person* to be capable of these things, as well as a state of certain *resources* such as goods, services, or knowledge. The fifth definition on the Merriam-Webster list, as of this writing, pertains to disability, where accessibility is defined as ease of use or ease of access for disabled people, or an adaptation for use by disabled people.

These definitions both influence, and are influenced by, societal understandings of disability as related to ease or adaptation. The definitions strikingly omit mention of equity or equality. Therefore, we provide an additional definition of accessibility, specifically related to disability equality and disabled experience. The U.S. Department of Justice and U.S. Department of Education (2010), along with the National Center on Accessible Educational Materials (2023), define accessibility as below. It is the same definition which CAST, the developer of the current UDL resource website, utilizes in its development of UDL materials:

> Accessibility means that an individual with a disability can acquire the same information, engage in the same interactions, and enjoy the same services as an individual without a disability, in an equally integrated and equally effective manner, with substantially equivalent ease of use.

We present both definitions of accessibility to underscore how the meaning of access can change depending upon the context in which it is used, its intended audience, and an understanding of its use as a disability-centered term. Ease of use is present in multiple definitions, and equity is omitted from both, while equality is implied in the CAST and U.S. Department of Education definition.

Defining disability

The Americans with Disabilities Act (ADA) (1990) defines an individual with a disability as:

> A person who has a physical or mental impairment that substantially limits one or more major life activities, a person who has a history or record of such an impairment, or a person who is perceived by others as having such an impairment.

Disability can also be defined in ways that critique the idea of impairment as strictly negative, and which acknowledge the social and political nature of disabled status. Impairment can also be viewed as a difference or divergence that is respected in a diverse society. For example, another definition of disability to which we prescribe is that shared by Cameron (2010; 2011, p. 20; 2014, p. 6) in their reframing of disability and impairment:

> Disability: a personal and social role which simultaneously invalidates the lived experiences of people with impairments, and validates the lived experiences of those considered normal
>
> Impairment: a physical, sensory, emotional, and cognitive difference, divergent from culturally valued norms of embodiment, to be expected and respected on its own terms in a diverse society

As we document the narratives of student understanding of both accessibility and disability, it is crucial that we recognize the lived experiences and identities that have shaped our understanding of these terms, as researchers. We acknowledge the shifting cultural meanings of these terms. We use “disability” and “disabled” to reflect the use of these concepts within higher education. Some have suggested the visual disruption of the terms, as (dis)ability (Schalk, 2017), dis/ability, and dis/abled, to trouble the idea that disability is fixed and factual. Dis/ability is a way to interrogate an “inability to perform culturally-defined, expected tasks (such as learning or walking) that come to define the individual as primarily and generally ‘unable’ to navigate society” (Annamma et al. 2013, p. 24). We present these visual disruptions specifically to assert that being disabled does *not* represent a lack of ability. We also wish to acknowledge that we use the terms “disabled people” rather than “persons with disabilities”, and thus center disability as core identity through identity-first language and the social model of disability. Other readers may be more familiar with or prefer the use of person-first language.

<u>Ableism and anti-ableism</u>

Increasing accessibility in our academic systems through techniques which utilize universal design may allow students and educators to lessen the impact of many forms of othering, including ableism. Leah Smith (n.d.) of the U.S. Center for Disability Rights defines ableism as follows:

> Ableism: a set of beliefs or practices that devalue and discriminate against people with physical, intellectual, or psychiatric disabilities, which often rests on the assumption that disabled people need to be ‘fixed’ in one form or another

Ableism is further intermingled with different forms of systemic othering. Talila “TL” Lewis (n.d.), in community with Disabled Black and other minoritized people, including Dustin Gibson, defines ableism as:

> Ableism: a system that places value on people’s bodies and minds, based on societally constructed ideas of normality, intelligence, excellence, desirability, and productivity. These constructed ideas are deeply rooted in anti-Blackness, eugenics, misogyny, colonialism, imperialism, and capitalism. This form of systemic oppression leads to people and society determining who is valuable

and worthy based on a person's language, appearance, religion, and/or their ability to satisfactorily [re]produce, excel, and 'behave'. You do not have to be disabled to experience ableism.

These two definitions of ableism highlight our belief that ableism is inextricably linked to a multitude of oppressive systems, and that in interrogating one such as ableism, we can simultaneously interrogate others such as racism, sexism, and Eurocentric hegemony.

Positionality and Theoretical Framework

Authors' positionality

As researchers, we recognize we are not values-neutral. In an attempt to highlight our values and add to our study's reflexivity and accountability, we provide reflexive accounts of our positionality below.

The lead author (TJL) is an insider researcher as a disabled person, yet occupies only small slices of the full diversity of disability, rendering the insider status as situational and conditional. She is autistic/ADHD and has had shifting low vision issues throughout her life, having been born extremely premature. She is a PhD candidate in paleontology and science education research at a major research university, 40+, white, queer, non-binary and femme, from a suburban middle-class upbringing with strong cultural roots and practices, including Sicilian and Scottish earth-based folk culture. She became Jewish as an adult and is a first-generation researcher.

LJH is a full professor of biology at a major research university, and now a research scientist at a national research center in Spain. She has been in academia for more than twenty years with strong ties to the discipline of biological anthropology, is 50+, heteronormative, from a rural upper middle class upbringing in Appalachia with Christian cultural roots.

LBA is an assessment professional for a health education program at a major research university. She originally was a chemistry graduate student before obtaining her PhD in science education. She is 35+, white, heteronormative, and was the first in her family to obtain a doctorate degree. She grew up in a mid-sized town with a working class family.

TMF is a PhD candidate studying paleobiology at a major research university. He is 25+, heteronormative, and was raised in a suburban middle class household in the New York metropolitan area with Ashkenazi Jewish cultural roots.

CAS is an associate professor of anthropology, biology, and women's gender and sexuality studies at a research-intensive private university. He has been a member of the biological anthropology community for over 20 years, is 40+, white, gay/queer, non-binary man married to another man, raised without religion in working class households with housing/financial insecurity in a predominantly Black urban context in the Midwestern US.

OR is a middle-class Mexican-American man originally from Los Angeles, and now working at a community college in Los Angeles County.

ZJT is an associate professor at a research-intensive public university. He has been a member of the vertebrate paleontology community for nearly twenty years, is 40+, heteronormative, and a first generation immigrant and academic in the US with cultural roots in Taiwan and mainland China.

AMB is a full professor of chemistry and a member of a graduate group in science education at a major research university. She has been in academia for more than twenty-five years, is 50+, heteronormative, from an upper middle class upbringing in urban settings. Her work has focussed on student learning and experiences for 13 years.

Theoretical Framework

Our central guiding theories are Critical Disability Studies (Vehmas & Watson, 2014; Schalk, 2017; Goodley et al., 2019) and social justice education (Liasidou, 2013). Critical Disability Studies can be viewed as a subject-oriented area of study, studying disabled people; or as a methodology (Schalk, 2017). When taken as methodology, it involves “scrutinizing not bodily or mental impairments but the social norms that define particular attributes as impairments, as well as the social conditions that concentrate stigmatized attributes in particular populations” (Minich, 2016). Minich (2016) further emphasizes the importance of Critical Disability Studies as methodology in the context of teaching, where disabled students in university systems are subjected to the medical model of disability and instructors are strained in properly implementing disabled access. Sami Schalk (2017) also concurs on the importance of teaching Critical Disability Studies as a methodology to help shift students’ able-bodied views of the world. We utilize Critical Disability Studies as methodology in a pedagogical context, to assess awareness of disability and accessibility in our science classes, among our largely non-disabled or non-neurodivergent (as of yet) student bodies.

Social justice is a concept that is understood and manifested in many ways. Here we define it as a way of challenging systems which privilege one group over others (Choules, 2007), leading to a reflexive, conscious process intended to enhance equity and boost social action (Carlisle et al., 2006). Universal Design for Learning cannot achieve these goals in isolation or in a few university courses alone; we emphasize social justice education as a framework and mindset for helping students grapple with multiple forms of social disadvantage and oppression, while engaging in small components of transformative pedagogical action (Liasidou, 2013).

Research Questions

Through the critical disability and social justice pedagogical frameworks, we seek to answer the following questions:

Question #1: How does implementing inclusive design in a science communication project impact student perception of accessibility and disability? This may include self-assessed perception of the definitions, awareness of disability and accessibility, sense of access and advocacy in science media, and perception of disability as diversity.

Question #2: What are the community benefits of implementing inclusive design in a science communication project? This may include students' sense of classroom cohesion and community, as well as students' sense of connection to others.

Methods

Here we outline the course learning concepts, study design, survey reliability and validity. We created a new survey instrument to test these research questions, and focused specifically on three of the fixed response questions, comparing pre-project to post-project survey responses. We also analyzed a set of post-survey Likert-scale questions. Fixed responses were analyzed using either post-test descriptive statistical analysis (Likert questions) or paired pre-post t-tests (Guttman Questions 1, 3, and 5). We conducted post-course semi-structured interviews with students and faculty who agreed to participate, selecting four quotes from a total of 9 students interviewed in fall 2020 (HumanBio), and one quote from one student interviewed in spring 2022 (Dinosaurs). Only students from HumanBio and Dinosaurs agreed to be interviewed. Two of the four instructors were also interviewed, and sample responses are included.

<u>Learning concepts relevant to students' projects</u>

Student projects spanned a range of evolutionary biology content and concepts, but all courses were centered in some aspect of evolutionary biology and offered within a biology or anthropology department (Table 3.1). We include objectives and the scope for the science communication project (Table 3.2).

Course Designation (University Type and Location) - Short Name	**Course Subject (Course Listings)**	**Enrollment**	**Course Semester**
Pilot Course at University #1 (Public 4-Year, West Coast U.S.) - "HumanBio"	Human Biological Variation (Biology, General Education, American Cultures*)	675	Fall 2020
University #1 (Public 4-Year, West Coast U.S.) - "Dinosaurs"	Life During the Age of Dinosaurs (Biology, General Education)	100	Spring 2022
University #2 (Private 4-Year, Northeast Coast U.S.) - "EvoBio"	Evolutionary Biology of Human Variation (Anthropology, General Education, Women and Gender Studies)	50	Spring 2022
University #3 (Private 4-Year, West Coast U.S.) - "Evolution"	Evolution (Biology)	60	Spring 2022

Table 3.1 - Courses included in this study
*American Cultures at University #1 is a suite of courses that fulfill a requirement for all undergraduate students to have taken a course that engages with race and ethnicity in the U.S.

Project Objectives	**Example**
Scientific accuracy	Students received direct instruction on how to identify reliable scientific sources of information
A frame for understanding the science that does not rely on the scientifically incorrect idea of there being human races; practice talking about human variation in a way that explicitly rejects the framework of racial variation. This will keep your science communication scientifically accurate, and consequently, antiracist.*	Students whose projects specifically addressed human skin pigmentation and the social construct of race practiced more prevalent examples of antiracist science communication through group discussion
Consideration of your target audience throughout the project framing process	All student groups considered an imagined target audience for their digital product (demographics, location, etc.)
Choosing a media-type that is appropriate for your target audience and the message you are conveying	All student groups chose or were directed to produce a media type appropriate for their audience and message; examples included podcasts, videos, social media mock-up posts, children's books, traditional poster presentations+
Considering audience accessibility and inclusion of those with sensory access needs	Access needs were essential to each student project and included closed captioning, audio narration, colorblind palettes, alt text, signed language, etc.
Learn how to effectively communicate science, as well as the difficulties in doing so effectively; gain a critical eye for science presentations, in particular those on the topic of a chosen academic paper centered in an evolutionary biology concept	Each week of the project guided students with examples and challenges of effective science communication, including comparing different examples of science communication; considering audience, accessibility, and narrative; storyboarding; peer reviewing drafts of digital products; building teamwork skills; and presenting final edited products.

Table 3.2 - Project Objectives
*Fall 2020 and University #2 2022; these courses involved specific student exploration of scientific articles on human skin pigmentation and deconstructing any biological schema for the social construct of race
+University #1 in 2022 produced solely poster presentations, each with an aspect of universal design and accessibility such as signed languages, colorblind-friendly palettes, audio narration, etc.

Study Design and Course Scope

This study focused on survey results from the fall 2020 semester of human biological variation (Pilot Course at University #1 taught by LJH), which we title "HumanBio", at a major public university in the U.S., the subsequent spring 2022 semester of life during the age of dinosaurs at the same university (University #1), which we title "Dinosaurs", and two additional evolution-based courses at private universities external to the first university (Universities #2 and #3), which we title "EvoBio" and "Evolution" for ease of reference, respectively.

Science Communication Project Overview

In each course, the science communication project (CP) led students through the process of choosing, reading, and synthesizing an academic research paper, understanding processes of ethical science communication, and implementing a component of disability accessibility through inclusive design methodologies.

Over the course of several weeks, student groups created final course projects such as videos, podcasts, or social media infographics and infused their pieces of science communication with aspects of UDL. We tailored our lessons to teach students about disabled equity and accessibility, and about practical techniques for implementing accessible options within their final project presentations. Providing examples of disabled voices was key to this process, and our pedagogy team was led and assisted by disabled and/or neurodivergent contributors throughout the process - maintaining a critical sense of "nothing about us without us" (Sarju, 2021). Before and after the student projects, we asked the students to reflect on their understanding of accessibility – a concept that is central to disabled equity – and how strongly they may notice or consider accessibility when interacting specifically with science media products (documentary videos, podcasts, social media posts, etc.) as a form of science communication. The CP was initially designed by LJH through her participation in the university's Creative Discovery Fellows Program, formerly known as the Adobe Fellows Program. The fall 2020 HumanBio version of the CP was further developed to include aspects of disability accessibility and additional science communication instruction in collaboration with LJH and the graduate instructor team. This version of the project was again implemented in spring 2022 with minor changes to accommodate course curricular timing.

Fall 2020 Implementation

In fall 2020, HumanBio student enrollment was 665, and the course was implemented entirely online during the COVID-19 lockdowns. The lecture was taught by one of the authors (LJH), with discussion sections taught by TL and a team of fellow graduate student instructors. The weekly lectures supplemented the discussion sections through discussion of human biology, while the CP was conducted over 6 in-class discussion sections. Students were given a choice of target audience and final project medium, and selected a topic of interest from three academic papers chosen by the teaching team. Each paper focused on refuting the trope of race through biological evidence.

Spring 2022 Implementation

The Spring 2022 dinosaur course at University #1 was newly revised and offered in spring 2022 after an "age of dinosaurs" course hiatus of several years. The flexibility of the Dinosaurs course revision allowed the CP to be implemented as a key component of the student experience. The spring 2022 course at University #1 was implemented in-person, with weekly synchronous lecture components. The lecture was taught by one of the authors (ZJT), with guest lectures and sections taught by the graduate student instructor and co-author (TF). The weekly lectures allowed 30-90 minutes of discussion time, with the CP conducted over a period of 8 in-class work weeks. The Dinosaurs course had an approximate enrollment of 100 students. Students were given a fixed audience of peers, and students selected a topic of interest for independent research through primary literature. Projects were presented as digital posters with an accompanying accessibility component.

The two external spring 2022 courses were evolutionary biology of human variation at University #2, taught by one of the authors (CAS); and evolution at University #3, taught by one of the authors (OR).

The course at University #2, EvoBio, was implemented in-person, with weekly synchronous lectures taught by one of the authors (CAS), and a weekly synchronous discussion component taught by a graduate teaching fellow. The weekly discussion allowed up to 50 minutes of discussion time, with the CP conducted over a period of 5 in-class work weeks. The course had an approximate enrollment of 50 students. Students were given a choice of target audience and final project medium, and selected a topic of interest from several primary literature sources provided by the instructor.

The course at University #3, Evolution, was implemented in-person, with weekly synchronous lecture and lab discussion components, both taught by the lead instructor, and an asynchronous Zoom lecture was captured as well. The weekly labs allowed up to 2 hours of discussion time, with the CP conducted over a period of 6 in-class work weeks. The course had an approximate enrollment of 60 students. Students were given a choice of target audience and final project medium, and were guided by the instructor to find a primary literature source which informed their communication project to a target audience.

<u>Research Survey Instrument</u>

Students completed an online Qualtrics survey at the beginning two weeks and the final week of the semester, before and after their CP intervention. All surveys were conducted under the home university's Committee for the Protection of Human Subjects (CPHS) Institutional Review Board (IRB) Protocol #2019-10-12589 for fall 2020, and amendment Protocol #2022-07-15503 to add the spring 2022 semester courses. We offered up to 5 extra credit points for survey completion, and students had an optional alternate assignment of 500 words centered in accessible design, if they did not wish to complete the survey. Survey participation was entirely voluntary.

The survey comprised a series of paired fixed-response and open-response questions, divided into broad categories which sought to elicit student responses on accessibility and science communication, as well as general perceptions of diversity. Instructionary text prompted students to reflect on their experiences with accessibility and science communication, and student respondents could not move back to change a previous answer. This was important as we first asked students about their confidence in defining accessibility, whereas later questions provided our definition of accessibility.

We implemented the full survey in each of the four evolutionary biology courses, from which the subset of fixed-response questions were selected. This subset was chosen for analysis to focus the research around perception of accessibility and disability.

The following Guttman-style questions (Table 3.3) are addressed within this study. The Guttman-style questions were paired in pre-post surveys to assess the impact of the CP, while a separate set of Likert scale questions (Table 3.4) were provided only in the post-surveys.

Survey Items
Pre-Post Guttman - Question 1 “How well can you define accessibility?” Scale 0 [I cannot define accessibility] Scale 1 [I can define accessibility in broad terms, but I cannot provide specific explanations or examples] Scale 2 [I can define accessibility and provide a few (1-2) explanations or examples] Scale 3 [I can define accessibility and provide many (3 or more) explanations or examples]
Pre-Post Guttman - Question 3 *Definition of accessibility provided after this point; students could not return to previous questions to edit answers “Accessibility is a concept that results in accommodating a resource or physical place so that it is equitably reached, entered, or utilized by people with disabilities. Imagine you are watching, reading, listening to, or engaging with a piece of science media. How would you respond to the following statement? When interacting with a piece of science media, such as a news article, video, podcast, website, social media post, or infographic about science: Scale 0 [I would never think about the accessibility of that medium for disabled persons] Scale 1[I would sometimes…] Scale 2 [I would always…]
Pre-Post Guttman - Question 5 Accessibility is a concept that results in accommodating a resource or physical place so that it is equitably reached, entered, or utilized by people with disabilities. How would you respond to the following statement? Accessibility is important to consider when science communicators craft science media. Scale 0 [I believe accessibility is always important to consider when crafting science media] Scale 1 [I believe accessibility is sometimes important to consider when crafting science media] Scale 2 [I do not believe accessibility is important to consider when crafting science media]

Table 3.3 - Guttman Survey Items

Theme	Likert Scale Questions
Disability Awareness and Advocacy	I have grown in my awareness of disability accessibility and accommodation I am more motivated to advocate for disability accommodation in the future I now consider disability to be a part of human diversity more than before this project or course
Community Connection	I have a greater connection to other human beings as a part of the human race As a student, I feel more included in science because of this course or project I built a greater connection with my peers and instructors as a classroom community I have made new friends throughout this learning experience

Table 3.4 - Likert Scale Survey Items

Survey Reliability and Validity

The goal of the survey was to assess student confidence in defining, thinking about, and valuing the inclusion of accessibility in science media. The question sub-sets were chosen to reflect this focus on disability and accessibility, whereas the larger survey contained questions related to diversity more broadly. We assessed survey item reliability and validity through a number of correlated methods (Cobern & Adams, 2020), which are described here. Initial survey items and response choices were drafted in Qualtrics by the lead author in consultation with several experts in science education research and disability studies within the College of Chemistry, School of Education, Department of Integrative Biology, and Department of Anthropology at University #1. An expert writer and editor also completed a sample of the survey instrument and provided feedback as an external reviewer. Undergraduate student volunteers unassociated with the study provided think-aloud feedback on individual questions. Any confusing or jargon-based wording in the item questions or response choices was edited for clarity following this process of review. In addition, the initial round of pre-surveys at University #1 (HumanBio) underwent testing through Item Response Theory (IRT), which allowed further clarification within future versions of the survey.

Item Response Theory (IRT) protocol (Wilson, 2023) was conducted under the guidance of Prof. Mark Wilson and a team of graduate student peer-reviewers familiar with IRT at the University of California Berkeley School of Education. Any unclear or internally inconsistent question response stems were removed accordingly. Specific changes included removing unclear or double-barreled question choices (e.g., [pilot survey] I always think about the accessibility of that medium, and I always or almost always communicate my thoughts to others = [new survey] I always think about the accessibility of that medium). From Pilot University #1 pre-survey to post-survey, double-barreled question responses were analyzed so that the highest construct map levels (always and almost always) were combined; no significant difference was found when examining the results with or without combining. Both the pilot survey in HumanBio and the new spring 2022 version of the survey in Dinosaurs, EvoBio, and Evolution maintained the same open response questions, which are the subject of additional forthcoming work. With regard to the Likert scale questions, we conducted exploratory factor analysis to assess question groupings into themes of disability awareness and advocacy, and community connection (Table 3.4). The two resulting two factors had scree plot and eigenvalues greater than 1 and those two factor sets resulted in factor loading of 0.5 or greater (Appendix Figure 3.1).

Response Rate

We report the following response rates (Table 3.5) for the total course responses, as well as consented responses.

Survey Instrument	Timeline	Total Responses	Total Enrollment	Total Response Rate (%)	Consented Responses	Consented Response Rate (%)
Pilot Course University #1 (HumanBio) Pre-Survey	Fall 2020	597	665	89.77	382	57.44
Pilot Course University #1 (HumanBio) Post-Survey	Fall 2020	560	665	84.21	462	69.47
University #1 (Dinosaurs) Pre-Survey	Spring 2022	83	107	77.57	79	73.83
University #1 (Dinosaurs) Post-Survey	Spring 2022	89	107	83.18	73	68.22
University #2 (EvoBio) Pre-Survey	Spring 2022	35	50	70.00	23	46.00
University #2 (EvoBio) Post-Survey	Spring 2022	30	50	60.00	25	50.00
University #3 (Evolution) Pre-Survey	Spring 2022	49	60	81.67	37	61.67
University #3 (Evolution) Post-Survey	Spring 2022	36	60	60.00	29	48.33

Table 3.5 - Survey Response Rates
*Only consented responses are included in the study, with a matching pre-and-post survey.

Demographics

These demographics (Table 3.6) represent the Pilot Course in Fall 2020, as well as the combined Spring 2022 courses. Spring 2022 courses are combined due to relatively small sample sizes in each individual course. We report self-reflections of gender identity, ethnicity/race, and sexual orientation. In addition, we combined responses reflecting neurodiversity, disability identity, and for spring 2022 we report those who shared that they receive disability services on their campuses. In the spring 2022 courses, 34% of the student total (N=61) identified as non-heterosexual, and 18% identified as disabled, whereas in fall 2020, 19% of the student total (N=203) identified as non-heterosexual, and 7% identified as disabled.

Category	Fall 2020	Spring 2022
Gender Identity*	Female: 110 Male: 88 NB: 1 Prefer not to say: 7	Female: 33 Male: 28 NB: 0 Prefer not to say: 1
Ethnicity/Race**	American Indian/Alaska Native: 1 Black or African American: 1 East Asian: 94 South Asian: 46 Southeast Asian: 15 Hispanic/Latinx: 15 Pacific Islander: 1 Middle Eastern/Southwest Asian: 2 White: 22 Prefer not to say: 7	American Indian/Alaska Native: 0 Black or African American: 5 East Asian: 20 South Asian: 9 Southeast Asian: 3 Hispanic/Latinx: 10 Pacific Islander: 0 Middle Eastern/Southwest Asian: 4 White: 8 Prefer not to say: 2
Sexual Orientation+	Heterosexual: 164 Bi/Ace/Queer/Other: 39	Heterosexual: 38 Bi/Ace/Queer/Other: 20
Disabled/Neurodivergent	Yes: 14 No: 177 Unsure: 8 Prefer not to say: 7	Yes: 11 No: 49 Unsure: 0 Prefer not to say: 1 -Disabled: 3 -Neurodivergent: 11 -DSP Services?: 2

Table 3.6 - Demographics *Students were given the choice of male, female, non-binary (NB)/third-gender. In the spring 2022 survey, students were also asked whether they identified as transgender in a separate question, though none responded yes.
**Tabulated from pre-responses (N=204 fall 2020; N=61 spring 2022); each respondent was given multiple examples of countries and regions potentially corresponding to these categories.
+Tabulated from pre-responses (N=203 fall 2020; N=58 spring 2022); non-heterosexual categories are combined

Results

Taken in sum, we share statistical analyses from the pre-post paired surveys and the post-survey Likert responses. We also provide sample quotes from the semi-structured student and instructor interviews to highlight participant experiences in their own words.

Statistical Analysis

We compare inferential statistics and pre-post t-tests for the fall 2020 (HumanBio) (Table 3.7) and spring 2022 (Dinosaurs, EvoBio, and Evolution) (Table 3.8) survey cohorts. In addition, there is no statistical significance shown when comparing subsets of STEM major students versus non-STEM major students within the cohorts (Table 3.9).

Inferential Statistics - Pre-Treatment and Post-Treatment, Fall 2020 HumanBio, p = 0.05

*Scale 0 - 3 +Scale 0 - 2						
Question	Mean Pre	Mean Post	SD Pre	SD Post	Effect Size	*p*
Q1*: "How well can you define accessibility?"	1.92	2.45	0.68	0.67	0.72	0.000
Q3*: "I always/sometimes/never think about accessibility in science media"	0.91	1.77	0.75	0.95	0.87	0.000
Q5+: "I always/sometimes/do not believe accessibility is important to consider when crafting science media"	1.75	1.86	0.46	0.37	0.23	0.001

Table 3.7 - Inferential Statistics for Fall 2020

N-size, degrees of freedom

Q1 N = 199 (df=198)

Q3 N = 205 (df=204)

Q5 N = 204 (df=203)

Inferential Statistics - Pre-Treatment and Post-Treatment, Spring 2022 Courses, p = 0.05

*Scale 0 - 3 +Scale 0 - 2						
Question	Mean Pre	Mean Post	SD Pre	SD Post	Effect Size	*p*
Q1*: "How well can you define accessibility?"	1.83	2.08	0.65	0.75	0.37	0.006
Q3*: "I always/sometimes/never think about accessibility in science media"	0.82	1.10	0.59	0.50	0.47	0.000
Q5+: "I always/sometimes/do not believe accessibility is important to consider when crafting science media"	1.87	1.84	0.34	0.41	0.07	0.568

Table 3.8 - Inferential Statistics for Spring 2022

N-size, degrees of freedom
Q1 N = 59 (df=58)
Q3 N = 62 (df=61)
Q5 N = 62 (df=61)

STEM Majors vs. Non-STEM Majors - Fall 2020 HumanBio					
	MANOVA			**Linear Regression**	
Question	STEM Major (N)	Non-STEM Major (N)	*p*	R^2	*p*
Q1*: "How well can you define accessibility?"	168	38	0.7526	0.0005	0.7641
Q3*: "I always/sometimes/never think about accessibility in science media"	168	38	0.3071	0.0051	0.3319
Q5+: "I always/sometimes/do not believe accessibility is important to consider when crafting science media"	168	38	0.7928	0.0003	0.7347

STEM Majors vs. Non-STEM Majors - Spring 2022 Dinosaurs, EvoBio, and Evolution					
	MANOVA			**Linear Regression**	
Question	STEM Major (N)	Non-STEM Major (N)	*p*	R^2	*p*
Q1*: "How well can you define accessibility?"	38	23	0.4081	0.0123	0.3850
Q3*: "I always/sometimes/never think about accessibility in science media"	38	23	0.5261	0.0068	0.5296

Table 3.9 - STEM vs. Non-STEM Majors - Comparison Groups

Survey Questions 1 and 3 - Accessibility Definitions, and Thinking About Accessibility in Science Media

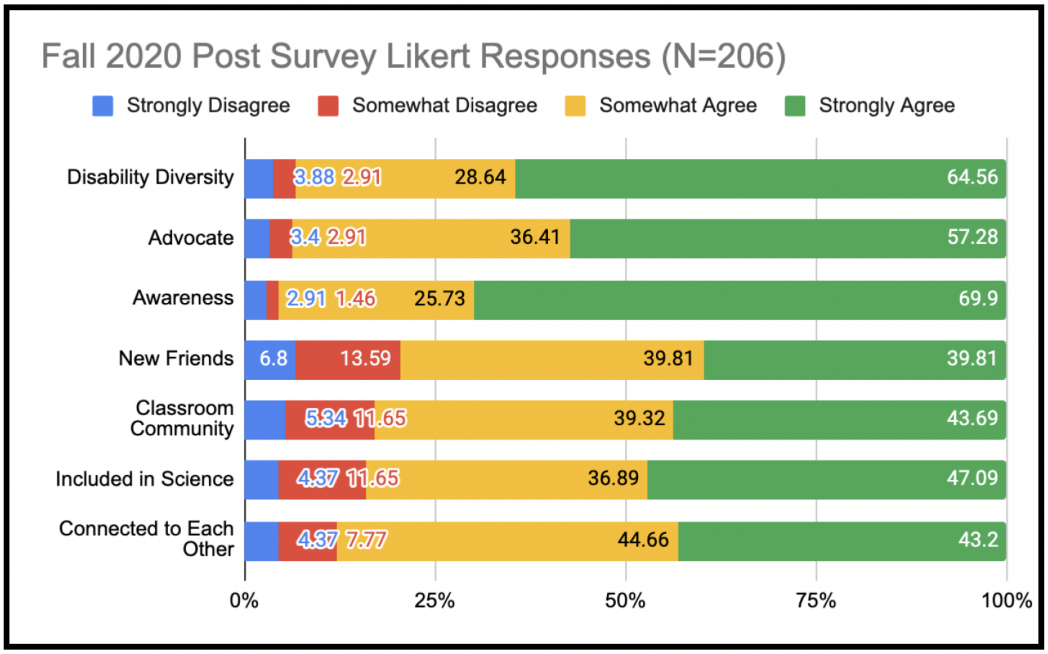
When asked how well they could define accessibility (Question 1), student responses shifted from a mean of 1.92 to 2.45 (Fall 2020) and from 1.83 to 2.08 (Spring 2022 combined). The effect size in Fall 2020 was high enough to indicate a likely effect, at 0.72, however the effect size in Spring 2022 was much smaller at 0.37. When asked how much they think about accessibility in science media (Question 3), student responses shifted from a mean of 0.91 to 1.77 (fall 2020) and from 0.82 to 1.11 (spring 2022 combined). *P*-values were <0.01 for fall and spring in questions 1 and 3.

Survey Question 5 - Accessibility's Importance in Science Media

When asked whether they agreed that accessibility was important to include in science media, student responses shifted from a mean of 1.75 (pre) to 1.86 (post) in fall 2020. In the spring 2022 courses, the shift was slight from "always" to "sometimes" thinking accessibility is important in science media, from 1.87 (pre) to 1.84 (post); this result was not statistically significant, with very low effect size (0.07).

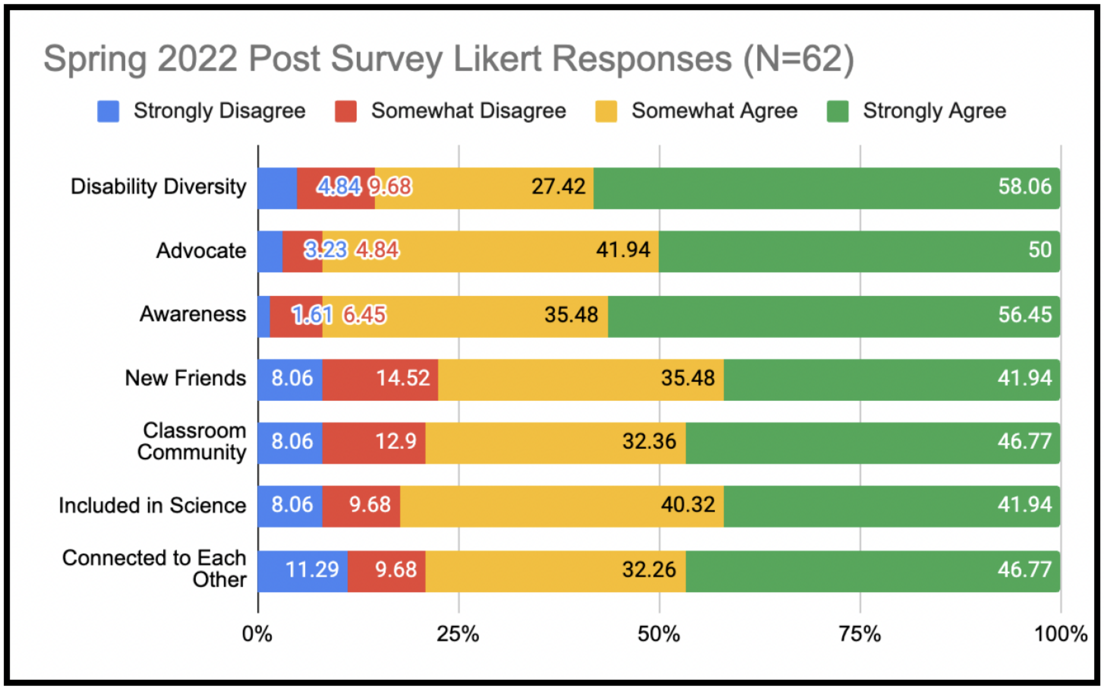
<u>Post-Survey Likert Responses</u>

The Likert results were generated from fall 2020 post-survey responses (N=206) (Figure 3.1) and the spring 2022 post-survey responses (N=62) (Figure 3.2). Bar charts show abbreviations of the survey question, with fixed-response ordinal choices ranging from Strongly Disagree to Strongly Agree. Neutral / No Response was not a respondent option. Aggregate inferential statistics are provided here, indicating the majority of students "agreed" or "strongly agreed" across each question.



Disabled Diversity: “I now consider disability to be a part of human diversity more than before this project or course”
Advocate: “I am more motivated to advocate for disability accommodation in the future”
Awareness: “I have grown in my awareness of disability accessibility and accommodation”
New Friends: “I have made new friends throughout this learning experience”
Classroom Community: “I built a greater connection with my peers and instructors as a classroom community”
Included in Science: “As a student, I feel more included in science because of this course or project”
Connected to Each Other: “I have a greater connection to other human beings as a part of the human race”

Figure 3.1 - Fall 2020 Post-Survey Likert Scale Responses (N=206)



Disabled Diversity: "I now consider disability to be a part of human diversity more than before this project or course"
Advocate: "I am more motivated to advocate for disability accommodation in the future"
Awareness: "I have grown in my awareness of disability accessibility and accommodation"
New Friends: "I have made new friends throughout this learning experience"
Classroom Community: "I built a greater connection with my peers and instructors as a classroom community"
Included in Science: "As a student, I feel more included in science because of this course or project"
Connected to Each Other: "I have a greater connection to other human beings as a part of the human race"

Figure 3.2 - Spring 2022 Post-Survey Likert Scale Responses (N=62)

Sample Quotes

To better understand the context of the science communication project and its impact on our classroom communities, we conducted semi-structured post-course interviews (Appendix Table 3.1) with students and faculty who had agreed to participate. The selected quotes highlight student thinking around accessibility as a focus of the course project, as well as accessibility as a term that incorporates disability. Respondents also reflected more generally on the project experience. The quotes were selected to synthesize a representative sample of student thinking around these concepts.

When asked by the interviewer, *How did you feel about the accessibility focus of the project and why?,* students responded with thoughts about the social and content learning aspects of the project.

One student [F2020-7, F/South Asian] from the HumanBio course reflected on the social implications of including accessibility, such as building a more inclusive university environment:

"I actually thought it was really cool, I feel like a lot of classes I'm in don't really make time to make accessibility a factor in the course. I also like how it went along with the material and showed the social implications of the material. I wish more courses would do it because I feel it would help make the school a more inclusive environment."

Another student [S2022-1, F/Latinx-white] from the Dinosaurs course discussed broad accessibility during COVID and the helpfulness of the project in self-assessing learning:

"There was a big focus on trying to figure out how to make the project accessible in the class. I felt like the class was pretty accessible to people who didn't want to come in because of COVID. Um, so, yeah there was a lot of talk about accessibility and that was really helpful. … I felt like I got a good grasp of what we were learning about."

During the semi-structured interview, one student was also asked, *When you think of the word "accessibility", are there definitions that come to mind? Did your definition change, thinking about accessibility as a disability-centered term?* The respondent, the same student from the Dinosaurs course [S2022-1, F/Latinx-White] shared their broadened understanding of disability and accessibility:

"Um, yeah, I definitely changed my definition over time. So first it was really simple, I just thought of um, like, people who don't have certain abilities, like Deaf uh non-hearing or blind people, and trying to make things accessible to [people categorized within] different races or socioeconomic statuses, but then, there are a lot of things I didn't, like I didn't think about colorblind people, like how certain graphs may be really difficult for them to see. So it really broadened my understanding of like, oh yeah, we need to make things accessible to all these different groups."

The interviewees were also asked a final question, *Do you have any other thoughts about the project?* Because the largest sample of interviewees by far was from HumanBio, all three sample quotes are from this interview cohort:

[F2020-2, F/South Asian] - "Personally I don't like biology, but I thoroughly enjoyed this class, how considerate everybody was, it's much more than the sciences, it's reaching out and saying there's a place for all of you in this science world."

[F2020-9, M/East Asian] - "I actually learned quite a lot from the project and I guess for me it strengthened some of the thoughts I had about diversity and accessibility."

[F2020-6, F/East Asian] "I have a deeper impression of the skills to help those with [a] disability. And it's also motivate [*sic*] me to do those in the future."

The instructor of the Evolution course shared thoughts on the project implementation:

“Despite this being a tough semester with Zoom and the pandemic, I thought this was the best version of this kind of science communication project that I’ve had.

Thinking about the science and learning about the science is important - but also the other side of it, thinking much more sensitively about how [the students] are communicating about it.” - Spring 2022 University #3 Professor (Evolution)

Finally, the instructor of the EvoBio course shared reflections on how they perceived a benefit to students by completing the project:

“It’s a new way of thinking about the science that is really kind of beneficial for [the students]; it forces them not to just memorize the information, but process it in a way that helps them think about themselves as part of a community, and communicate to a community.” - Spring 2022 University #2 Professor (EvoBio)

Discussion

In our pedagogical framework, we are curious about the tangible benefits of greater accessibility and disability awareness in evolutionary biology courses. We highlight quantitative and qualitative evidence in the form of Guttman-style pre-post survey questions, Likert scale post-survey questions, and semi-structured interview responses, each providing new information on student perceptions of accessibility and disability, particularly in an evolutionary biology and science setting. Returning to our research questions, we aimed to better understand how implementing an inclusive design project, hard-wired with disability and accessibility content knowledge, would impact student perception of these concepts. We also asked whether there are broader community benefits to such an implementation within our evolutionary biology classrooms.

Research Question #1: How can implementing inclusive design in a science communication project impact student perception of accessibility and disability?

We share our interpretation of results from Guttman-style questions in a pre-post comparison t-test, from Likert scale questions, and from select interview quotes from students and instructors. Respondents considered aspects of accessibility’s definition, their awareness of accessibility, their sense of advocacy in science media, community aspects of an accessible course project, and their sense of disability as diversity. In the pre-post comparison, survey questions 1 and 3 sought to understand how students define accessibility, and their readiness to think about accessibility when engaging with science media.

<u>Guttman Questions (pre-post comparison)</u>

Survey Questions 1 and 3 - Accessibility Definitions, and Thinking About Accessibility in Science Media

In both Fall 2020 (Pilot, University #1, HumanBio) and Spring 2022 (Universities #1, #2, #3 - Dinosaurs, EvoBio, and Evolution), students agreed that they could define accessibility more confidently, with more examples or explanations of what accessibility means, compared with before the project. This is an interesting measure, which we find important as a baseline for students to reflect on their own knowledge of access. A reflexive qualitative analysis of some of the student written responses 3can further help us understand when students had a wide range of actual definitions of accessibility, including general access to goods and services rather than disability-specific access; in addition, some of the student respondents relied on the internet to answer their definition of accessibility, and the definitions generally reflect a sense of ease of access rather than equity for disabled people.

We note these written responses may not always reflect disabled accessibility, which provides insight into student understanding of the word as used in standard conversation; this also ties to the Merriam-Webster dictionary usage of accessibility as "a capability of being reached, understood, used, appreciated, or influenced". Students reflected on their definition of accessibility before the course and answered accordingly, based upon what they believed to be accurate. Given our direct instruction on accessibility as a disability equity term, and the increase in students' self-reflection of more holistically defining accessibility following the project, we interpret a positive shift in students' conceptualization of accessibility to incorporate more awareness of disabled accessibility. The shift from a mean of 1.92 to 2.45 (Fall 2020) and from 1.83 to 2.08 (Spring 2022 combined) indicates that students came in to the project with a fairly high confidence in their ability to define accessibility, and both cohorts saw increases, while the shift towards more confidence (closer to 3) was greater in Fall 2020. The effect size of 0.72 in Fall 2020 indicates a likely effect of the treatment, however the effect size in Spring 2022 was much smaller at 0.37. This could be due to numerous factors, including the smaller sample size in Spring 2022, mixed student population samples across three courses, and the slight changes in treatment between courses in Spring 2022, as well as the many other variables at play when considering the magnitude of a treatment's effect. *P*-values were <0.01 for fall and spring in questions 1 and 3, indicating a statistically significant shift in both cohorts of students.

Students in both semesters expressed that they think about accessibility in science media more readily after the project. This result indicates the effectiveness of our pedagogical goals to help students build awareness of target audiences that include disabled people and others who have specific access needs. We centered this question on accessibility in science media specifically to prompt students to consider their experiences engaging with science communication products in their day-to-day lives and during their learning experiences at their university. The prompt included text-based description of examples of what we consider to be science media, such as science podcasts, documentaries, and social media posts. If students then create their own equitable science media products, it appears that the needle is shifted towards more awareness of accessibility in the science communication media that they consume. The shift from a mean of 0.91 to 1.77 (fall 2020) and from 0.82 to 1.11 (spring 2022 combined) indicates that students increased their self-reflected awareness of accessibility in science media, with a greater shift towards always thinking about accessibility (closer to 2) in Fall 2020.

To further delineate student experiences regarding accessibility definitions or accessibility in science media, we revisit sample quotes shared by students in the post-survey interviews. Student F2020-9 shared about their increased awareness of diversity and accessibility, while Student F2020-6 shared that they now had a greater sense of the skills needed to "help those with [a] disability", and felt motivated to do more in the future. We note that the sense of helping disabled people may be founded in ableist ideas of disability as a limitation, although it is encouraging to see students sharing their sense of skill building in disabled access and awareness. Student S2022-1 further reflected on their increased understanding of different disabled identities such as colorblindness, and their increased awareness of a wider variety of disabled access needs. These narratives are important to document as these students will potentially stay motivated to bring their awareness of disabled equity and accessibility to future endeavors. Critical Disability Studies as methodology invites us to shift non-disabled students' ableist views of the world (Schalk, 2017), and as educators, we take on this role to help expose evolutionary biology's ableist and troubled history of exclusion.

Survey Question 5 - Accessibility's Importance in Science Media

There was a significant increase in believing accessibility is always important to consider when crafting science media, from 1.75 to 1.86 in fall 2020. This may have been due to a strong belief coming into the course that accessibility is always important in science media. In spring 2022 there was a very slight decrease from "always" to "sometimes" thinking accessibility is important in science media, from 1.87 (pre) to 1.84 (post); this result was not statistically significant, with very low effect size (0.07). Taken together, we emphasize the difference between students acknowledging the importance of accessibility when asked about it in the pre-survey, and continued belief in its importance after having actively engaged with UDL. Student interviews provided occasional reflections on accessibility's importance, though reflections specific to science media were less common. Student S2022-1 reflected in the post-survey on the course's increased accessibility during COVID lockdown, and as well as the importance of accessibility in the course project at large. With an increasing trend towards digital learning, utilizing UDL as a method of inclusive design may continue to benefit students in multiple classroom settings, particularly post-COVID-19 (Montgomery & Bridget, 2023).

<u>Likert Questions</u>

Regarding disabled awareness and advocacy, >91% of students agreed they had increased their sense of disability awareness and sense of disability advocacy across all courses. When asked about their sense of disability as a part of human diversity, >85% of students agreed they considered disability as part of human diversity more than before the course. Although singular implementations aren't enough to change the perception of disability and wholly promote ongoing disabled advocacy, these results are encouraging and signal the potential for more disability and accessibility awareness if projects such as these are implemented in science courses.

Research Question #2: What are the community benefits of implementing inclusive design in a science communication project?

Past studies have recognized that students benefit from inclusive community building (Elliott et al., 2016; Walker et al., 2024) and collaborative learning (Cabrera et al., 2001), with pedagogical implementations that include group work with clear goals, knowing one another's names, and genuine dialogue (Gordon, 2011) that encourages openness and safety. Our inclusive instructional practices and direct teaching about Universal Design for Learning encouraged all of these aspects of community building, and we sought to understand student narratives around their sense of community, friendship, and inclusion. When considering Likert scale questions centered on classroom community, building friendships, a sense of inclusion in science, and student sense of connections to one another, our respondents substantially agreed that these aspects of connection increased as a result of the project or course. These findings underscore the broad community benefits of implementing inclusive design, especially in a science communication project, and within an evolutionary biology course.

Classroom community and sense of inclusion or connection were also documented through selected student and instructor interview quotes. Student S2020-7 reflected upon the inclusive quality of the science course, and how more courses could implement accessibility as part of a pedagogical framework. In addition, Student F2020-2 shared that they do not like biology, but enjoyed the course and the "considerate" nature of the course community. This student shared how crucial it was to reach out and make a place for all in science, which ties to our questions surrounding a sense of inclusion in science and connections to one another in a classroom community setting.

Instructors also shared their sense of a tough semester with online teaching and the COVID pandemic, while simultaneously feeling enthusiastic about implementing a science project that emphasizes inclusive pedagogy. Student-to-instructor informal reflections included not just thinking about science and learning science, but thinking more sensitively about communicating science, especially while considering themselves as part of a community. With a growing literature of inclusive pedagogy implementation in evolutionary biology college courses (Harris et al., 2020; Hasley et al., 2024), we add to this ongoing conversation on science communication best practices through social justice in our evolution-based classrooms.

In general, we were interested in the ideas that students and, to a lesser extent, faculty have about accessibility. We find that student respondents are more readily reflecting on sensory disabilities or more noticeable disabilities, such as wheelchair ramps, signed languages, braille, and closed captioning. These access needs are also tied to our pedagogy, as student projects most often implemented accessible techniques such as closed captioning, audio narration, alt text, and/or colorblind palettes. Building on this enhanced awareness, we also encourage future work on invisible or non-apparent disabilities, such as mental health and learning disabilities, anxiety and depression, vertigo, fatigue, chronic pain or autoimmune disabilities, and so on. As advocates for disabled and neurodivergent awareness, we know that more work is needed to underscore student awareness and co-creation of community that is welcoming and inclusive for all learners. Future studies on the implementation of UDL-based course projects and modules should take into account these additional dimensions of disability.

Limitations

Our survey instrument was not a replicate of a statistically or internally validated instrument, though we conducted intensive validation through the expert reviews, think-alouds, and IRT. Our Likert scale questions were limited in the nature of data collection without paired open responses. We recognize that these courses were based in highly selective research universities in the United States, which limits the global generalizability of the results. However, we also share results from multiple universities and student populations within a single country.

Certain courses may have primed students in different ways; for example, the Fall 2020 pilot course had both a biology and humanities designation. Students may have enrolled expecting to be made aware of societal disparities, and therefore may have come into the project experience with greater knowledge of accessibility and disability as multifaceted. Similarly, the EvoBio course was co-listed within anthropology and women's/gender/sexuality studies, which may have attracted students with greater knowledge or understanding of disabled equity due to the subject matter often covered in these types of courses and the perception that these disciplines may be more welcoming to minoritized identities (Forbes, 2020; Friedensen et al., 2021). The lived experiences of our students likely influenced the ways in which students responded, and we note that during the first two years of the COVID-19 pandemic from late 2019 to 2022, students may have grown in their own awareness of self-identifying factors such as queerness and/or disability. In addition to personal awareness of disability, COVID-19 has been identified as a mass disabling event (Roberts et al., 2022) with persistent long-term symptoms occurring (Del Rio et al., 2020). While we did not ask students about their COVID-19 experiences or symptoms, these factors are important to consider for future work.

Social Justice and Undergraduate Equity

In order to create more equitable educational environments, we believe that it’s essential to build awareness within our undergraduate student populations of the educational disparities that exist around them. This includes awareness of disparities that exist within the disabled and/or neurodivergent communities. We highly encourage weaving social justice concepts and practice into science courses in general, and evolutionary biology courses in particular. Evolutionary biologists have a particularly salient obligation to counter the prejudices which our discipline attempted to justify in American and global society. By reflecting on the limitations and unique qualities of their own individual experiences, our students may become more aware of their biases, which in turn may help improve classroom climate for *all* students. Engaging in this type of social justice learning can help students start to consider matters of justice in their daily lives (Leonardo, 2010; Waitoller and Artiles, 2013). Faculty perceptions of equity have been shown in some cases to range from confusion with equality, or devoid of concepts of justice, which can lead to ineffective pedagogy practices and potentially maintain rather than deconstruct educational barriers (Russo-Tait, 2023). Providing opportunities for faculty to practice equity and confront their biases alongside their students, using methods such as UDL, may help foster classroom equity. In case studies, faculty have indicated that exposure to UDL practices has increased their confidence in implementing inclusive pedagogy (Izzo et al., 2008). Disabled students have themselves advocated for more faculty awareness of inclusive design principles and general knowledge of disabled experience (Black et al., 2015). In addition, effective course design should make the purposes behind our pedagogical decisions clear to our students, which universal design insists on doing. Disabled and neurodivergent people are experts on their own experiences in STEM and other fields (Kingsbury et al., 2020), and in sharing reflections of majority non-disabled students, our findings highlight equitable community-building efforts that can support, rather than supplant, the perspectives and experiences of these medicalized and marginalized disabled and/or neurodivergent groups. This is important because majority non-disabled students can have very different perceptions of accessibility and disability from those of disabled students, which can influence overall perspectives on disabled community at large.

Conclusion

Universal Design for Learning (UDL) is an effective method of implementing flexible pedagogy, with the goal of building a more inclusive classroom environment. We share evidence from pre-post survey comparisons that indicate projects that implement UDL make a difference in student sense of defining and advocating for accessibility in science, through direct practice learning about accessibility, engaging with disabled voices, and crafting accessible science media. Student and instructor quotes provide context for the fixed response analysis, which also indicate a statistically significant shift in accessibility definition and advocating for accessibility. Likert questions demonstrate broad agreement on an increase in various community and personal benefits for students, such as a sense of inclusion in science community as well as disabled advocacy. Despite its demonstrated effectiveness, UDL is not a fix-all method for classroom inequities, and a larger culture shift in how we assess our students with rigid summative exams may be part of this equation. However, providing students with the tools and awareness of accessibility and disability in science, through flexible methods such as UDL, can create a classroom environment that instills inclusive teaching and learning and a social justice mindset. Moreover, non-disabled students and instructors can become more conscientious about accessibility when teaching and conducting their science across formats beyond the classroom, such as conference talks, designing figures, and so on. Evolutionary biology still has a long way to go in order to create welcoming spaces, given its extremely fraught history of upholding and supporting bias.

We advocate for greater awareness and appreciation of disabled voices in evolutionary biology and other science courses, and in doing so, we aspire to help students and instructors co-create class environments where all students feel they are represented, listened to, and can thrive. In future work, we aspire to continue building inclusive education into our pedagogical frameworks in evolutionary biology and related science fields, interrogating the inequitable academic systems in which we operate and to which science has contributed, through tangible and evidence-based action in our teaching and empowerment of our students.

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Chapter 4 Abstract and Bridging Statement

Abstract

Inclusive educational environments are crucial to building equitable and inclusive academic communities. We implemented an undergraduate student science communication project centered in Universal Design for Learning (UDL), with the goal of increasing student awareness of inclusive educational tools and practices. We surveyed students on their conceptualisation of accessibility, and accessibility of various media used for science communication, in four evolutionary biology courses. We conducted data familiarisation and interpretation through reflexive thematic analysis to craft our themes and narrative. We utilised a non-positivist qualitative research mindset and a critical disability theory framework. Students reflected on concepts of accessibility, disability, and meaning-making around knowledge and privilege of access. It is important for science, technology, engineering, and mathematics (STEM) courses in general, and evolutionary biology courses in particular, to embrace qualitative analysis of teaching methods and a social justice mindset to assess and build inclusive classrooms for disabled and non-disabled students alike.

A modified version of chapter has been submitted for review to the International Journal of Inclusive Education (2024); all co-authors are aware of this chapter's inclusion in my dissertation. I thank Leslea J. Hlusko, Jenny Lu, and Renee Starowicz for their contributions.

Keywords tied to the United Nations Sustainable Development Goals (SDG), as required by the journal to which I submit this work: International Journal of Inclusive Education

SDG 4: Quality education
SDG 10: Reduced inequalities
SDG 16: Peace, justice and strong institutions

Bridging Statement

The final chapter utilizes a qualitative research methodology, in a reflexive thematic analysis framework, with a theoretical underpinning centered in Critical Disability Studies. I synthesize the written survey responses from the courses where I co-developed and implemented a pedagogy project to center equity and inclusive education. This chapter allowed me to build a suite of qualitative research skills which I hope to take forward into my research career as an evolutionary biologist and science education researcher.

Chapter 4: Student Perception of Accessibility and Disability in College Evolutionary Biology Courses Centered in Universal Design for Learning (UDL): A Qualitative Study

Introduction

A severe lack of equity in science and higher education has prevented full support and involvement of marginalized people in science fields (Huang, 2000; Bensimon, 2005; Glass and Minnotte, 2010; Chang et al. 2014; National Academies of Sciences, Engineering, and Medicine, 2016; O'Connor, 2020; Denaro et al. 2022). Disabled and neurodivergent people are among those further marginalized by this inequitable system. The U.S. Department of Education (2012) reports that disabled students enter college with the intent to enroll in science and engineering majors at roughly the same rate as their non-disabled peers, yet in 2021, 65% of the disabled STEM workforce report having less than an undergraduate degree (National Center for Science and Engineering Statistics, 2023). In addition, disabled people earned just 11% of U.S. doctoral science and engineering (S&E) degrees in 2021, along with only 13% of doctoral degrees in non-S&E fields (National Center for Science and Engineering Statistics, 2023) despite making up as much as 27% of the U.S. population (CDC, 2023). Broadly, disabled adults in the U.S. are half as likely than their non-disabled peers (16.7% versus 34.9%) to earn an undergraduate degree (Ingram, 2017). Disabled college students in comparative international interviews have expressed that inaccessible learning environments, medical eligibility, and variable instructor understanding of accessibility and disability have created barriers for truly equitable education (Berggren et al., 2016).

Diversity, equity, and inclusion (DEI) initiatives at colleges and universities have promoted inclusive education as a necessary path forward to achieving a more welcoming academic environment for marginalized groups, including disabled and neurodivergent learners (Draffan et al. 2017; Leišytė et al., 2021; Wilkens et al. 2021; Addy et al. 2022; Goering et al., 2022; Charania and Patel, 2022). One method for enacting inclusive education is universal design (Mace, 1985), coupled with the schema of Universal Design for Learning (UDL). While applicable to all learners, universal design and UDL were first conceptualized through discourse about disability social justice and equity (Mace, 1985; Meyer et al., 2014). The field of universal design seeks to eliminate barriers, a central focus of its philosophy, and it takes on this challenge as a matter of civil rights (Steinfeld & Maisel 2012, p. 15). UDL can be an effective counterweight to elitism, but this requires transformative action, rather than simple inclusion alone (Liasidou, 2014; Fine, 2019). Universal design has already made its way into science-based college classroom practices as a vehicle for inclusive education (e.g., Super et al. 2021), but we believe a much broader implementation of drastic change should be realized. These educational and design praxes hold promise for breaking down systemic barriers in higher education (Treviranus, 2018), and for paving the way for both science and academia at large to reflect the diversity of global society.

We are a group of evolutionary biologists and education researchers, working to become more inclusive educators by recognizing the oppressive systems in which we operate and seeking to disrupt them. The lead author (TL) and another author (RS) are also disabled, and we have all been impacted by the inequities of academia in different ways. Our college courses and labs focus on teaching evolutionary biology, understanding science accurately, and practicing equitable science communication as a tool for social good. In this work, we specifically present examples of U.S. college students' understanding of accessibility and disability. We performed our study implementation in two separate courses at a public 4-year West Coast university; one course at a private 4-year West Coast university; and one course at a private 4-year East Coast university. When our students learn about inclusive education and practice Universal Design for Learning to communicate a piece of science, we wanted to know how they reflect their understanding of accessibility, and the accessibility of science. In addition, we wanted to analyze how disability is interwoven into these understandings.

We believe that in order to foster a more equitable educational environment, we need to build awareness within our undergraduate student populations of the educational disparities that exist around them. This includes awareness of disparities that exist for disabled and neurodivergent students. We encourage weaving issues of disability justice into science course content. Our students should reflect on the limitations of their own individual experiences and understand one another's lived experiences, which may help build an overall sense of inclusion, and ultimately improve classroom climate for all students. When students engage in this type of social justice learning, they may begin to consider matters of justice in their daily lives (Leonardo, 2010; Waitoller and Artiles, 2013). In addition, part of good course design is making the purposes behind our pedagogical decisions clear to our students, which universal design insists upon. Furthermore, concepts of evolutionary biology are charged with able-bodiedness (Vaahtera, 2016) and evolutionary biology courses inherit a long history of eugenic harm against disabled people, perceived as unnatural or deviant from the 'norm' (Branch et al., 2022). This echoes McRuer's (2006) description of compulsory able-bodiedness, defined as an assumption of able-bodiedness being the 'natural order of things'. It is essential that we interrogate these assumptions within evolutionary biology. We recognize that these small steps towards inclusive and equitable pedagogy in evolutionary biology courses will not undo this history and present status of ableist harm, and in some ways, research to uncover this harm can inadvertently perpetuate it.

Universal Design for Learning is also not a perfect methodology, and has been critiqued as ignorant of the global South (Song, 2017), ambiguous in its pluralism (Rao et al., 2014; Smith et al., 2019; Baglieri, 2020), and beneficial only for those students who already operate with significant racial and socioeconomic capital (Song, 2017). Nor is it the only model of accessible or inclusive education (Seale, 2017a; Seale et al., 2022). But it is a micro-level method (Seale, 2017a) that aims to break down barriers to education by creating safer and more welcoming environments for students to learn in flexible and accessible ways, anchored in this embedding of justice.

Becoming effective practitioners of universal design and UDL requires an understanding of its growth from disability equity and social justice, and how society shapes the definitions of access and disability. Accessibility and disability are terms that are defined differently within a wide array of social contexts. For example, what is readily accessible to one person in one part of the world may be inaccessible to someone in a different part of the world. Disability is socially mediated based on the social and political control of bodies that are deemed not 'normal' (Davis, 1995). A disability may be perceived as neutral, a detriment, or a benefit depending upon individual and social construction of what it means to be disabled. Therefore, we underscore key perspectives on accessibility and disability to center our work in the social construction of these concepts.

Key Perspectives on Accessibility and Disability

Giving our students the tools to practice universal design allows us to create more equitable spaces in our classrooms, because it challenges students to present information flexibly, and promotes equitable access to education. If we increase accessibility in our academic systems through universal design, we may be able to lessen the impact of many forms of othering, including ableism. Leah Smith (n.d.) of the U.S. Center for Disability Rights defines ableism as follows:

> Ableism: a set of beliefs or practices that devalue and discriminate against people with physical, intellectual, or psychiatric disabilities, which often rests on the assumption that disabled people need to be 'fixed' in one form or another.

Ableism defies a single definition of disability discrimination, and is further intertwined with different forms of othering. Talila "TL" Lewis (n.d.), in community with Disabled Black and other negatively racialized people, including Dustin Gibson, defines ableism as:

> Ableism: a system that places value on people's bodies and minds, based on societally constructed ideas of normality, intelligence, excellence, desirability, and productivity. These constructed ideas are deeply rooted in anti-Blackness, eugenics, misogyny, colonialism, imperialism, and capitalism. This form of systemic oppression leads to people and society determining who is valuable and worthy based on a person's language, appearance, religion, and/or their ability to satisfactorily [re]produce, excel, and 'behave'. You do not have to be disabled to experience ableism.

We provide these two definitions of ableism to the reader in order to highlight our belief that ableism is inextricably linked to a multitude of oppressive systems.

In order to provide baseline definitions for our students and in our teaching practice, we provide the following definitions of the key terms relevant to this work:

> Accessibility: a term used to encompass equitable societal access for all people, to the greatest extent possible, frequently used in disability studies as a disability-specific term; yet, there is a broader definition of accessibility as simple access to information, goods, and services

Accessibility has been described as a concept that depends upon a person-environment relationship, juxtaposing what is possible for an individual with what is possible in the individual's environment (Iwarsson and Ståhl, 2003).

In the affirmative model of disability, which critiques the idea of disability as a tragedy, disability and impairment are defined following Cameron's (2010; 2011, p. 20; 2014, p. 6) reframing of these two terms:

> Disability: a personal and social role which simultaneously invalidates the lived experiences (subject position) of people with impairments, and validates the lived experiences (subject position) of those considered normal
>
> Impairment: a physical, sensory, emotional, and cognitive difference, divergent from culturally valued norms of embodiment, to be expected and respected on its own terms in a diverse society

We know that words hold power, and shifting individual meanings of these terms should be acknowledged. We use "disability" and "disabled" to reflect these concepts within the institution of higher education, but also recognize the use of dis/ability and dis/abled as a visual disruption of disability and ability as fixed and factual. Dis/ability is a way to interrogate an "inability to perform culturally-defined, expected tasks (such as learning or walking) that come to define the individual as primarily and generally 'unable' to navigate society" (Annamma et al. 2013, p. 24). Dis/ability highlights that this identity marker is not individual, but rather a combined product of economic, cultural, and political practices (Davis, 1995; Waitoller & King Thorius, 2016). Further, we use the phrase "disabled people" rather than "persons with disabilities", centering disability as core identity through the use of identity-first language and the social model of disability. We recognize that others may be more familiar with or prefer the use of person-first language.

Inclusive Education in Colleges and Universities

With these terms in mind, we briefly review the literature on views of inclusive education in higher education systems. Previous research has examined faculty (Houck et al., 1992; Marquéz and Melero-Aguilar 2022, Sánchez Díaz and Morgado, 2023) and staff (Lopez-Gavira et al. 2019) perspectives of inclusive education, as well as disabled students' first-hand perspectives of inclusive education (Lopez-Gavira et al. 2021, Griful-Freixenet et al. 2017), barriers to higher education institutional support (Vickerman and Blundell, 2010; García-González et al., 2021; Hamilton et al. 2023), and their perceptions of accessibility through digital teaching methods (Wilkens et al. 2021). Several studies have emphasized the ableist experiences of disabled students outside of the United States (Shevlin et al., 2004; Fuller et al. 2004; Gibson, 2015; Seale, 2017b; Grimes et al. 2019; Yusof et al., 2020; Woolf and Bie, 2022). Some work has examined non-disabled university students' perceptions of disabled students (Ash et al., 1997). Disabled college or university students have long faced barriers to equitable education and in turn, their voices have been silenced rather than privileged (Seale, 2017b). In addition, disabled students risk rehashing harm while disclosing their experiences for the sake of research, which Eve Tuck (2009) refers to as damage-centered research. The COVID-19 pandemic has further exposed ableist norms within the United States, as reflected by Mia Ocean's (2021) call for institutional activism surrounding our disability perceptions. A substantial focus has been placed on the 'challenges' faculty face in implementing inclusive education for disabled students, such as funding, knowledge, and resources (Hernández-Quirama, A., & Oviedo-Cáceres, 2019; Zaki and Ismail 2021). University faculty and teaching assistants have ranked training in inclusive education such as UDL as highly desired, and have reported greater comfort in implementing inclusive education practices following multi-modal professional development and training (Izzo et al. 2008).

Faculty awareness of inclusive education principles is crucial, since many are instructors and research mentors. However, little is known about how non-disabled or as-yet-unidentified-as-disabled college students understand the concepts of accessibility and inclusive education. Students play just as important a role as faculty and staff in prompting a future where inclusive education is commonplace, as they move forward to build and engage with their own communities. Publishing papers with simple steps towards inclusive classrooms, anti-racist and anti-ableist academic environments (Arif et al., 2021; Ali et al. 2021), and indeed publishing papers on inclusive pedagogy such as our study, will not carve out this imagined future by themselves. These works call attention to the urgency with which this radical change must be generated. We need consistent, systemic, and multi-level efforts. We believe that equipping our students, those who pay tuition and generate income for colleges and universities, with an inclusive education mindset and an understanding of accessibility practices holds promise as our academic circles continue to deconstruct the hard-wired, ableist, systemic barriers to equity.

Background on Disability as Identity

A major driving force behind this study was the lead author (TL)'s lived experiences as a disabled person, both day-to-day and in their education experiences. The lead author's disabilities are largely non-apparent or invisible, which can skew or erase outsider perception of disability in an individual. Further, disability can be internalized as a deficit, especially in educational systems. Perception of disability as deficit can lead to stigma, shame, and internalized ableism. As educators dedicated to a social justice mindset, it is imperative that we undertake a disability-as-identity centered view in order to better understand ourselves and to provide care and mentorship to all of our students in a way that does not place ourselves or our students at a deficit. Yet, the academic systems we operate within are still centered largely in the medical model of disability. This model inherently equates disability with deficit rather than with identity (Linton, 1998, p. 11).

For these reasons we are particularly curious about student perception of accessibility and of disability in general. We intend this work to be part of the larger discussion on perception of disability as identity or deficit, ableism in STEM fields, as well as perception of science accessibility.

Exploring societal understanding of accessibility and access to science media can allow us to outline how these concepts are tied to disability and disability advocacy. By studying student written reflections, we can build a clearer picture of student perception of accessibility and of disability as diversity, and develop evidence-based, effective science pedagogy that merges core subject matter with social justice education. In addition, by discussing accessibility and disability in a positive light in college courses, we can champion disability awareness and advocacy in college student populations.

Theoretical Framework

The central guiding theory of this work is Critical Disability Studies (Vehmas & Watson, 2014; Schalk, 2017; Goodley et al., 2019). We are also informed by a number of related theories. We draw from Dis/ability Critical Race Studies (DisCrit), which underscores the intersections of race and ethnicity within and between disability identity in the construction of Whiteness and ability as privileged positions (Annamma et al. 2013). Anti-deficit thinking serves to shift the blame of academic failure away from individual students or their environments, and towards the oppressive nature of institutions; one example of this oppressive nature is high-stakes testing, which focuses on student deficiencies rather than the larger social inequities involved (Valencia and Guardarrama, 1996). The anti-deficit model (Davis & Museus, 2019) also ties into Critical Race Theory by recognizing that minority students are experts on their own experiences, rather than relying on deficit-laden reinforcements of student underachievement so commonly reported in education and social science literature (Harper, 2010; Lambert, 2018). These deficit perspectives claim the superiority of so-called formal knowledge, and create narratives that position students as solely responsible for their own underachievement (Adiredja, 2019), especially racialized students (Menchaca, 2012). Fears of “dumbing down” science media contradict (Haggis, 2006) what we know about the necessary supports required to scaffold new learners (Greenstein et al., 2015) into domain specific knowledge.

Concepts of pro-sociality entered our analytical space while we read repeated student reflections of accessibility as hard to notice, unless it impacted individual students themselves. An individual’s dependence or interdependence rests on interpersonal relationships that may increase motivation to act altruistically, rather than from self-interest (Agnew & Le, 2015). Perceptions of what is accessible or inaccessible have been studied quantitatively, with comparison between individualist and non-individualist cultures demonstrating greater willingness to assist disabled people in inaccessible situations in the non-individualist culture (Miyahara et al. 2018). In our work, student reflections did echo an individualist framing of accessibility, especially in science media. And if disabled people aren’t afforded social capital and capacity to participate in community, pro-social interaction can't be realistically achieved or shifted (White et al. 2010).

The social model of disability (Oliver 1983, 1990, 2013) centers disability as identity, and allows us to rebuke the medical or curative models of disability (Brisenden, 1986; Marks, 1997) that emphasize the fault of the individual rather than the societal structure as a disabling force. Taken together, these perspectives attempt to disrupt underlying social narratives on disability as a drawback or limitation, which ought to be interrogated.

Research Questions and Methodology

Our research is driven by three major questions:

1. What are U.S. undergraduate student conceptualizations of accessibility and disability? We're curious about how students reflect on their understanding of the broad concepts of accessibility and disability, before and after practicing UDL pedagogy methods first-hand. As stated in the introduction, we define accessibility as a term used to encompass equitable societal access for all people, with an understanding that accessibility can also take on a disability-centered meaning in disability theory and in societal practice.

2. How do students conceptualize accessibility and disability when interacting with science media? We are curious to see how students conceptualize accessibility in science media, including how they may notice or respond to the presence or absence of accessibility features while engaging with science videos, podcasts, or social media posts. Because accessibility and disability are terms that can be interpreted and internalized in many different ways dependent upon social and personal context, applying the lens of critical disability theory will allow us to dig deeper into student conceptions - and misconceptions - of disability in general.

3. Does Universal Design for Learning (UDL) make a difference in the way students reflect on their understanding of accessibility and disability? UDL is one method for creating more inclusive educational environments. Providing students with the tools to implement UDL allows us to share their narratives of the impact of this experience.

We aimed to teach our students how to be inclusive science communicators. This study assesses their conceptualization of several concepts surrounding accessibility and access in science media, by interpreting their written reflections of these concepts. To do this, we provided students with a short video to watch asynchronously and two short readings to introduce them to the basic concepts and tools for Universal Design for Learning, followed by a brief activity to critique a piece of science communication of their choice through the lens of UDL. We then tasked them to communicate key points of an academic peer-reviewed science article in a creative and accessible manner, with options such as a short video, a podcast, infographic, poster, or mock-up draft of a social media post. Using reflexive thematic analysis (Braun and Clarke 2006, 2013, 2020), we analyzed how students reflected on their definitions of accessibility and conceptualized accessibility in science media before and after this process. Science media here is defined as scientific journal articles, popular documentaries, podcasts, and social media posts. We place specific emphasis on the importance of inclusive education methods and full accessibility as foundational to the project rather than a hasty add-on; in other words, “accessibility by design” (Hamraie, 2018). Developing and integrating instructional strategies such as UDL, which address the many barriers disabled students face, has been urgently called for within geoscience (Carabajal et al., 2017), adjacent to our own evolutionary biology classrooms.

We chose short, open-ended online survey responses to gather feedback from as many people as possible in our convenience sample of enrolled students, including disabled and non-disabled students, and to offer the survey as an extra credit incentive to all students in the study courses. In addition, the online aspect allowed data collection during the COVID-19 pandemic lockdowns and across geographic distances. Access to technological resources at their respective universities may also have boosted participation of student respondents. While ours was a fully mixed survey (Terry and Braun 2017) of qualitative and quantitative questions, we focus on two selected qualitative questions here, as the qualitative interests of the lead author grew out of the survey development process. In this sense, we consider the subset of survey questions that we analyze here to be fully qualitative, prioritizing Big Q qualitative research values and techniques (Braun et al. 2020, Braun and Clarke, 2022c). As this study relates to the perception of marginalized disabled identities, and is relatively unexplored in academic literature, we deemed qualitative methodologies to be appropriate.

Area and Criteria	**Implementation**
1. Learner Variability and Environment	Students were provided with multiple means of accessing course content knowledge in each project unit, including podcasts, text, and video. When implementing UDL in their projects, student groups chose from an array of project presentation media, anchored to an imagined target audience.
a) Participant information	Majority non-disabled and non-neurodivergent, majority intention to enroll in a science, technology, engineering, or math (STEM) major, roughly 50/50 female-male with minority gender non-conforming or non-binary
b) Setting	Instruction was conducted online or in-person dependent upon semester, university, and COVID-19 restrictions. Flexible methods for instruction included online drop-in instructor hours for project guidance, website modules with text- and video-based project guidance, and synchronous/asynchronous options for direct instruction.
2. Proactive and Intentional Design	Students created science communication media that reflected an academic science paper or other science topic of their choosing, with guidance from instructors.
a) Addressing Barriers and/or Increasing Access	Students engaged with UDL practice such as implementation of closed captions, colorblind palettes, audio narration, or alt text to reduce or eliminate barriers for disabled, d/Deaf or Hard of Hearing, and/or neurodivergent people in their science media products.
b) Designing to Address Variability	During weekly planning sessions, instructors met to discuss design and implementation. Variability and choice in student media, topic, and target audience was interwoven in the students' UDL hands-on experience from the beginning to end of the project.
c) Application of UDL Guidelines and Checkpoints	Students engaged directly with the following UDL guidelines: ● Providing their science communication audience with multiple means of representation

	Options for Perception ○ 1.2 - Offering alternatives for auditory information ○ 1.3 - Offering alternatives for visual information Options for Language and Symbols ○ 2.4 - Offering multiple languages in their science communication projects, including non-English spoken and signed languages Options for Comprehension ○ 3.1 - Students practiced examples of basic narrative structure to engage their science communication audience and to activate or supply audience background knowledge ● Providing their science communication audience with multiple means of action and expression Options for Physical Action ○ 4.2 Optimize access to tools and assistive technologies for their science audience Options for Expression and Communication ○ 5.1 - Multiple media for communication, in both access of content knowledge and choice of science communication media (podcast, video, etc.) Options for Executive Function ○ 6.1 - Students had direct instruction on project goals, but student groups were in charge of appropriate goal setting with low-to-no stakes check-points with instructors, and increasing goal autonomy throughout the course of the project (from guided instruction to student peer-review of one another's projects) ● Providing their science communication audience with multiple means of engagement Options for Recruiting Interest ○ 7.1 - Students were encouraged to practice individual choice and autonomy in the selection of their project topic and media; and, in their science

	communication media products, students were encouraged to engage their audience
3. Implementation and Outcomes	Each course implemented the following UDL-centered independent work prior to beginning the project: Each course implemented the following independent work: A. To engage with and reflect on two inclusive design videos from the Microsoft Inclusive Design website (https://www.microsoft.com/design/inclusive/), specifically Haben Girma's video on community education and accessibility and the short film titled Inclusive; B. To read and reflect on the blog post The Evolution of Universal Design: A Win-Win Concept for All (Simmons, 2020), C. To read and reflect on the Seven Principles of Universal Design (Center for Universal Design, 1997); D. A pre-project assignment asking students to respond in writing with a one benefit and one drawback of four types of science communication, of the instructors' topic choice - including an infographic, a podcast, a popular newspaper or magazine article, and a short video. Students were then guided through the iterative steps of their science communication project over the span of 6-8 weeks. See description of implementation and practice above. Full outcomes and implications are described in the paper text.

Table 4.1 - UDL Implementation

Orientation and Epistemological Underpinnings

These research questions are underpinned by a critical orientation, meaning that we are analyzing how students reflect on concepts of accessibility and disability through the language they use and the meaning they've made surrounding these concepts. However, individual student responses may also reflect lived experiences and perspectives (experiential orientation) (Braun & Clarke 2022b, p. 10). Our team shared a critical realist epistemological stance, noting that experiences of reality are mediated by culture and social conditions (Fletcher 2017). This was underpinned by social constructionism and the making of collective social meaning - in this case, perspective of accessibility and disability through a social lens.

Study Context

Students were given the opportunity to complete an online Qualtrics survey at the beginning (a two week span prior to direct project instruction) and end (final week) of the semester, before and after their science communication project intervention. All surveys were conducted under the home university's Committee for the Protection of Human Subjects (CPHS) Institutional Review Board (IRB) Protocol #2019-10-12589 for fall 2020, and amendment Protocol #2022-07-15503 to add the spring 2022 semester courses. Up to five bonus points incentivized students to complete the pre- and post-surveys, and students were given an alternate assignment of 500 words, based in an accessibility design process, if they did not wish to complete the survey. Survey participation was entirely voluntary. Written responses to open-ended questions 2 and 4 were selected from within these paired pre-post fixed response data sets on the basis of completion of, at minimum, the pre-survey written prompts. All responses were assigned a pseudonym and an alphanumeric identifier to protect anonymity.

Administration of the Science Communication Project

To assess the perception of disability and accessibility, we used student-led science communication course projects as a vehicle for disability-centered pedagogy. These projects followed a flexible component of direct instruction and independent work reflecting on inclusive design and Universal Design for Learning. An outline of project administration and UDL reporting criteria (Rao et al., 2018) is provided (Table 4.1). While we acknowledge that there is no one-size-fits-all approach to accessibility and inclusive or universal design, our goal was to encourage students to practice at least one component of accessibility and inclusive methods, and to engage with inclusive thinking as a process hardwired into their project design.

Survey Questions and Implementation

This study focused on survey results from the fall 2020 semester of human biological variation (Course at University #1) at a major public university in the U.S., the subsequent spring 2022 semester of life during the age of dinosaurs at the same university (University #1), and two additional paleobiology and evolution-based courses at private universities external to the first university (Universities #2 and #3) in spring 2022 (Table 4.2). We selected two written response questions from within a larger survey dataset.

Course Designation (University Type and Location)	**Course Subject (Course Listings)**	**Enrollment**	**Course Semester**
Course at University #1 (Public 4-Year, West Coast U.S.)	Human Biological Variation (Biology, General Education, American Cultures*)	675	Fall 2020
University #1 (Public 4-Year, West Coast U.S.)	Life in the Age of Dinosaurs (Biology, General Education)	100	Spring 2022
University #2 (Private 4-Year, Northeast Coast U.S.)	Evolutionary Biology of Human Variation (Anthropology, General Education, Women and Gender Studies)	50	Spring 2022
University #3 (Private 4-Year, West Coast U.S.)	Evolution (Biology)	60	Spring 2022

Table 4.2 - Courses included in this study.
*American Cultures at University #1 is a suite of courses that fulfill a requirement for all undergraduate students to have taken a course that engages with race and ethnicity in the U.S.

The two survey questions read as follows:

Question 2
"In your own words, define accessibility. Please provide specific examples of what accessibility means or looks like to you."

Question 4
"Accessibility is a concept that results in accommodating a resource or physical place so that it is equitably reached, entered, or utilized by people with disabilities.

Imagine you are watching, reading, listening to, or engaging with a piece of science media.

Definitions of science media: a news article, video, podcast, website, social media post, or infographic about science.

Please explain and provide specific examples of what this interaction with science media accessibility might look like to you."

Participants

The demographics reported in Table 4.3 represent the total consented respondents of the Course post-surveys in Fall 2020, as well as the combined Spring 2022 courses' post-surveys. Category totals differ due to student differential responses to each category. The demographics have been aggregated in this fashion to reflect our qualitative research values, to protect student anonymity (Morse and Coulehan, 2015), and to highlight the relatively small number of gender non-conforming minorities and disabled students. We also share our respondents' reported intent to major in a science, technology, engineering, or math (STEM) subject, because the focus of their project was inclusive science communication, which is relevant to STEM fields.

Fall 2020 Post-Survey	Category	N	N %	Spring 2022 Post-Surveys	Category	N	N %
Age	18-21	292	94.8%	Age	18-21	91	87.5%
	22-25	14	4.5%		22-25	11	10.6%
	25-28	1	0.3%		25-28	1	1.0%
	28-35	1	0.3%		28-35	1	1.0%
Gender Identity	Male	147	46.8%	Gender Identity	Male	47	44.8%
	Female	154	49.0%		Female	54	51.4%
	Non-binary / third gender	2	0.6%		Non-binary / third gender	1	1.0%
	Prefer not to say	10	3.2%		Prefer not to say	3	2.9%
	Other	1	0.3%		Other	0	0.0%
Identify as disabled and/or receiving campus disability services	Yes	15	4.8%	Identify as disabled and/or receiving campus disability services	Yes	5	4.8%
	No	277	88.2%		No	96	92.3%
	Unsure	14	4.5%		Unsure	0	0.0%
	Prefer not to say	8	2.5%		Prefer not to say	3	2.9%
Intent to enroll in a STEM major	Yes	254	80.4%	Intent to enroll in a STEM major	Yes	59	56.7%
	No	48	15.2%		No	41	39.4%
	Unsure	14	4.4%		Unsure	4	3.8%

Table 4.3 - Post-Survey Demographics

Authors' Positionality

As researchers, we recognize we are not values-neutral, and provide reflexive accounts of our positionality as part of our accountability.

The lead author (TJL) is an insider researcher as a disabled person, yet occupies only small slices of the full diversity of disability, rendering the insider status as situational and conditional. It took the lead author many years to break down internalized conceptualizations of disability, especially positioned in a family with other more apparently disabled family members. She is a PhD candidate at a major research university, 35+, White, queer, non-binary and femme, from a suburban middle-class upbringing with strong cultural roots and practices.

JL is a first generation undergraduate student in her third year of study at a large university studying biology and creative writing. She is very much still learning about disability conceptions and how it is intertwined within science. She is Asian American from an immigrant and refugee multilingual family, 20+, heteronormative, from a suburban middle class upbringing in California.

RS is a social scientist working in a data lab at a major research university. She identifies as a disabled person who is passionate about supporting disability culture and arts. She has worked with other disabled folks in their homes, schools and community programs before pursuing further education to continue advocating for self-determination and multimodal communication.

LJH is a full professor of biology at a major research university, and now a research scientist at a national research center in Spain. She has been in academia for more than twenty years with strong ties to the discipline of biological anthropology, is 50+, heteronormative, from a rural upper middle class upbringing in Appalachia with Christian cultural roots.

We acknowledge that qualitative researchers are not neutral and that qualitative data does not seek a single truth, reflective of a non-positivist approach (Braun and Clarke 2013). We chose reflective thematic analysis because of the relative lack of information published on our research interests, for which qualitative methods can be useful as an exploratory device; and because we believe equipping more trained natural scientists with excellent qualitative research skills is worthwhile. Acknowledging researcher positionality as a strength rather than a limitation is also a part of this qualitative method. Further, it was enjoyable to learn new ways of interpreting how students discuss their lived experiences with accessibility and disability.

Reflexivity

We modeled personal reflexivity through the two main coders (TJL and JL), who both kept a reflexivity journal throughout the coding process. This process allowed us to continuously reflect upon and acknowledge our own positionality and subjectivity central to generating the research. Memos and merge notes in MaxQDA also kept track of the shifting process of crafting themes. As disability identity is very personal and can be ever-evolving, we reflect upon our own internal sense of identity as far as we are currently aware. For example, the lead author's positionality as an invisibly disabled person. While most survey respondents were not made explicitly aware of the authors' disability identity while answering each question, notices which were sent out to students with the survey link included information on the lead author's positionality as a disabled person. The two main coders on this study encouraged one another to develop and refine our thinking throughout the coding process through regular meetings and discussions, to "optimize the rigor and quality of the analytical process" of reflexive TA (Rance et al. 2017).

Analysis

We engaged in the six steps of the reflexive thematic analysis process (Braun and Clarke 2006, 2013, 2022a, 2022b) and recognized the iterative, recursive nature of this process. Following familiarization with the student response excerpts, our initial stage of analysis involved one of the authors (JL) coding all dataset responses and crafting these codes inductively, taking what participants wrote and described and assigning codes in the 'bottom-up' or data-driven fashion (Braun & Clarke 2006). Codes were crafted with the assumption that what participants wrote reflected what they thought to be real; themes were developed using a mixture of latent and semantic coding, taking into account the face-value meaning of student's words (latent) as well as the occasional societally-influenced meaning (semantic).

As themes were crafted from initial codes, analysis moved into a more theory-based approach, specifically Critical Disability Studies. Another author (TJL) coded the entire dataset separately, reviewing the initial codes and adding several more. JL and TJL met frequently to discuss this iterative process, collapsing and expanding codes as analysis progressed. The two coders then developed themes and sub-themes recursively, using MaxQDA software memos to organize themes around a central organizing concept that was unique and did not overlap with other themes. This combined process allowed us to take what respondents wrote at face value (inductively, via critical realism), while also recognizing that meaning-making around disability, accessibility, and disabled identity is largely a social and internalized product (social constructionism).

As ours was a non-positivist qualitative methodological view, centered in critical realism, we did not undertake data saturation or triangulation, because these methods are typically realist and can assume a finite interpretation (Braun and Clarke 2019); and we did not perform interrater reliability or intercoder agreement, because these methods are positivist (Guba and Lincoln 1989, Smith and McGannon 2018). Our study focused on a broad, exploratory aim with a large data set composed of relatively thin data snippets that were generated by each participant. Following the concepts of information power (Malterud et al. 2016), we crafted and refined codes while using our interpretive judgment (Sim et al. 2018) to determine a subjective analytical end-point.

Findings and Discussion

We collected both pre-and-post survey reflections. We will provide a brief overview of the pre-survey findings in order to highlight student thinking before they completed their science communication project. We focus in depth on the post-survey responses, which we understand as evidence of meaning-making following the completion of student projects. The four themes crafted from the sum total of survey responses are: Theme #1 “Accessibility: Individual and Interdependent”, Theme #2 “Access Takes a Little More Effort to Notice”, Theme #3 “Disability Perception - What Does Disability Mean?” and Theme #4 “Who Has Access to Knowledge?” (Table 4.4). These four main themes are supported by sub-themes, which we further describe in the post-survey section. The four themes are also visually represented in terms of the proximity of their core concepts for both pre-and post-survey themes, together (Figure 4.1). The two coders crafted and utilized this conceptual map to share our conceptualization of the relatedness, or proximity, of the major themes (Trombeta & Cox, 2022).

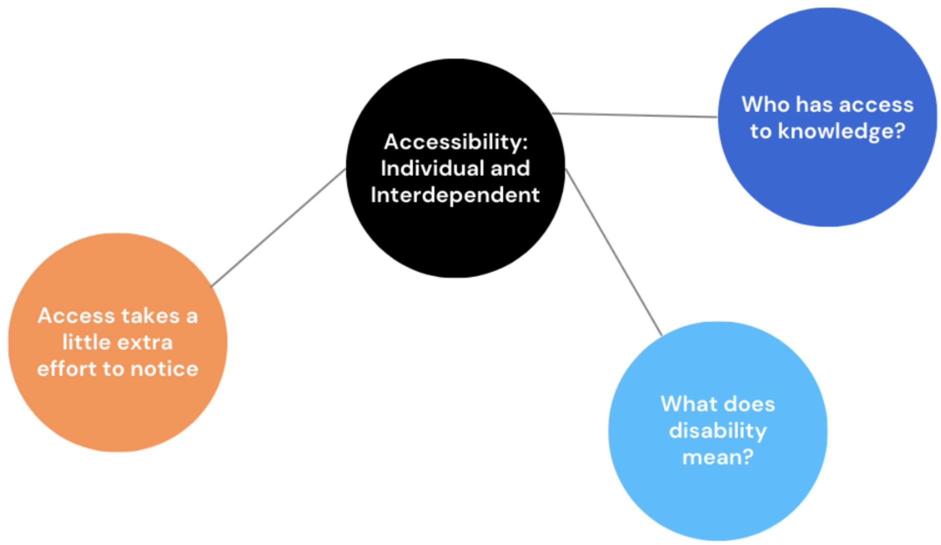

Figure 4.1 - Thematic map demonstrating relative closeness and positioning of the thematic concepts.

Overarching Idea	Theme	Sub-Themes at End-of-Analysis	Initial Codes
Access	*Accessibility: Individual and Interdependent*	Accessibility: Easy, Available, and Possible Accessibility: Equal Access for All Access to Basic Needs	Is it possible for me? Financial barriers Financial freedom Basic needs
	Access takes a little extra effort to notice	Accessibility Crosses My Mind Accessibility Doesn't Impact Me Couldn't Define or Describe	Design awareness Do not interact regularly with this concept I never think about it I don't understand it
Disability	*What does disability mean?*	Disability Visibility Disability is a Limitation	Disability-specific barriers Physical disability: Mobility Vision Hearing Learning and mental health disabilities

Knowledge and Learning	*Who has access to knowledge?*	Science Research is Hard to Understand Learning is a Privilege	Science research is for the educated Science media costs too much Access is challenging Science jargon Written language and non-English languages

Table 4.4 - Thematic Narrative

Overall Pre-Survey Theme Reflections

In the pre-survey, students framed accessibility as ease of access, and frequently conceptualized disability as an individual limitation or deficit. They also linked the word accessibility to opportunity, especially in a social or racial context. Further, students described access to basic needs and other necessities. Some students claimed they wouldn't notice accessibility barriers unless they were personally impacted by the barrier.

Student responses framed disability largely in terms that were visible or apparent, such as mobility or sensory disabilities, and reflected upon invisible or non-apparent (e.g. mental health) disabilities with much less frequency. Students framed disability as a limitation or a problem to be solved, and expressed lack of understanding of some access tools such as screen readers.

Finally, students expressed that science media in particular is challenging to understand, and that financial or educational barriers can limit or privilege access to science knowledge.

As with our post-survey themes, we categorize our pre-survey narrative into three overarching ideas: Access, Disability, and Knowledge and Learning (Table 4.4). Within these overarching ideas, both the pre- and post-survey reflections are categorized into the same four themes, each with sub-themes. Students defined accessibility in their own words in the pre-survey responses (question 2), and reflected upon accessibility in science media (question 4). The themes displayed here match those in our post-survey narrative, although the sub-theme Accessibility Crosses My Mind was not captured within the pre-responses.

Post-Survey Themes

The post-survey results are categorized into four main themes (Table 4.4), each with corresponding sub-themes. The themes are broadly organized around perception of accessibility as individual or interdependent; the challenge of noticing access needs when they are not applicable to students' daily lives; disability as a visible attribute or a limitation; and the privilege of access to knowledge, especially science knowledge. We also provide sample quotes corresponding to each theme (Table 4.5). These results show that students have varying perceptions of accessibility, disability, and access to science information, which can be parsed into key overarching ideas and themes. We emphasize the importance of capturing student perceptions of accessibility and disability in science, as evolutionary biology courses are uniquely primed to help students examine their own biases about the naturalness of the body-mind.

Theme Name	Code	Example Quote	Pseudonym	Survey
Accessibility: Individual and Interdependent	Accessibility: Easy, Available, and Possible	Accessibility is the ability of someone to access a certain form of information or service. This extends particularly to individuals who have disabilities, and how they are able to access these in spite of their disabilities.	Lashawn	University #1 Pilot Post Q2
		Accessibility is the ability to connect or view certain information with a certain degree of ease. A[n] example is an infographic, where the information presented and written in a simple language can be accessible to students and adults.	Campbell	University #1 Pilot Post Q2
		Accessibility is the level of which an individual can obtain or access a certain piece of information or convenience.	Sina	University #1 Pilot Post Q2
		Accessibility is having a wide range of people having the ability to use something easily. A ramp is an example because those who require a wheelchair are also able to go up a ramp easily.	Ricki	University #1 Pilot Post Q2
	Accessibility: Equal Access for All	Accessibility is the ability for all to access and be able to consume media or services. When I think of accessibility I think of closed captions, sign language interpreters, and having that without having to go through hoops to get them.	Rande	University #2 Pre Q2
	Access to Basic Needs	I consider accessibility to be how well things are easily made available to groups of people. For example, I would say healthcare has limited accessibility, as prices of it can be very unaffordable to low income and middle class families.	Chai	University #2 Pre Q2

Access takes a little extra effort to notice	Accessibility Crosses My Mind	When I interact with examples of science media, the Creative Discovery Project has given me a new lens through which to question how people are able to receive the information. In the past I experienced how sometimes some pieces of science media were difficult to understand, and now I can appreciate how many times people with disabilities are left with another layer of complexity.	Shay	University #1 Pilot Post Q4
		I think this really just comes in the form of being mindful of it. For the creative discovery project, I had initially thought of the obvious groups to reach out to for accessibility: deaf, blind, etc. At the same time, I never gave any thought to things like dyslexia or colorblindness.	Nicky	University #1 Pilot Post Q4
	Accessibility Doesn't Impact Me	I never consider the accessibility of science media. When reading a news article I always think that news is such a common thing that anyone who wants to access it can access it. The same goes for social media posts. For example I don't think I will ever look at an Instagram post about science and think about how it is not accessible enough.	Corie	University #1 Pilot Pre Q4
		Since I am not affected by a disability, I find it hard to think about the accessibility of science media.	Lennie	University #1 Pilot Post Q4
	Couldn't Define or Describe	I'm not sure what this would like to me, as I actually don't regularly interact with science media.	Jessy	University #1 Pilot Pre Q4
What does disability mean?	Disability Visibility	Now, when it comes to science media I think more about how the color scheme would affect an audience that is color blind, or very sensitive to bright colors. I would also consider blind audiences that cannot see the visual images of a piece of science media, but could listen to an audio description of the media and visuals.	Halen	University #1 Post Q4

		Accessibility is when everyone has equal access to resources. This means providing extra resources to those who have disabilities to ensure they have equal access. For example, hearing aids during conferences or tours, wheelchair ramps etc.	Lasean	University #1 Pre Q2
		I would think about the accessibility of that medium if it in some way was difficult for me to process. I would consider how other individuals with different learning disabilities might be affected by the medium of the content.	Indiana	University #3 Pre Q4
	Disability is a Limitation	Accessibility is considering the quality of life of all types of people in the world and inventing enhanced techniques to improve the lives of specifically those who are mentally or physically challenged and the overall public as well.	Sheridan	University #1 Pilot Post Q2
Who has access to knowledge?	Science Research is Hard to Understand	Accessible interactions with science media include being able to be understood and accessed by all people, not just those who have extensive scientific background. This could come in the form of using less scientific wording so that those not well versed in the subject could better understand the science media. This could also come in the form of using images to better illustrate the study, as well as using text descriptions to describe the photos for those with lowered vision.	Chayse	University #1 Post Q4
	Learning is a Privilege	Much scientific media is available to read only for money, or through a university or institution. Only people with these resources have access to this kind of media, which seems wrong; all people should have access to scientific information.	Riley	University #1 Pilot Pre Q4

Table 4.5 - Example Themes & Quotes

Theme #1: Accessibility: Individual and Interdependent

Students reflected on accessibility in the post-survey through conceptualization of access as individual and interdependent. These sub-themes were centered within the question #2 prompt, “In your own words, define accessibility. Please provide examples or explanations of what accessibility means or looks like to you.” The students were not provided with a definition prior to this. However, after completing this open-ended question, they were given a definition of accessibility to utilize when responding to other questions regarding science media. Student respondents could not backtrack to edit their previous responses. Therefore, post-survey respondents developed their definition of accessibility from their understanding of the course and outside course experiences. In crafting the overarching theme, we noted that respondents largely reflected on the term accessibility as simple access to goods and services, while occasionally reflecting on disability. In addition, students noted that accessibility has multiple meanings, and shared conceptualizations of accessibility as either someone’s individual ability to access a service, or a societal process that allows access to a service.

<u>Accessibility: Easy, Available, and Possible</u>

Is accessibility an individual person’s ability? Or is it the status of a designed environment, product, or learning tool? Students answered the post-survey questions several weeks after direct course instruction on accessibility, and largely reflected individualism in their responses. Often, but not always, these definitions included reflections on disability.

For example, Lashawn stated: “Accessibility is the ability of someone to access a certain form of information or service. This extends particularly to individuals who have disabilities, and how they are able to access these in spite of their disabilities.”

Campbell shared in the post-survey: “Accessibility is the ability to connect or view certain information with a certain degree of ease. A[n] example is an infographic, where the information presented and written in a simple language can be accessible to students and adults.”

Ricki shared in the post-survey: “Accessibility is having a wide range of people having the ability to use something easily. A ramp is an example because those who require a wheelchair are also able to go up a ramp easily.”

These reflections highlight how students conceptualize the idea of accessibility as someone’s individual ability to access something they might need. While we understand that disability is not individual (Waitoller and King Thorius, 2016), students reflect an individualistic view of access. Lashawn’s use of the phrasing of access “in spite of” disabilities gives the strong impression that disabilities are a limitation (see Disability is a Limitation), as either a form of resistance to the disability, or conceptualizing the disabled status as a barrier to that access. Reflections such as these echo the medical or curative model (Marks, 1997).

When Campbell shares that accessibility means connecting with information easily, using simple language, the phrasing here is charged with meaning-making around accessibility equalling ease, rather than accessibility equalling possibility to be accessed (Haggis, 2006).

Ricki's conceptualization of accessibility reflects that a disability accessibility feature, indeed a universal design feature, such as a wheelchair ramp will boost ease rather than possibility to be accessed at all. We did not expect this reflection of ease to be such a strong part of our analytical narrative, but it is interesting to consider the way ease of access may be underlain by conceptualization of disability accommodations as making things easier for disabled people. Disabled students in other studies have reported a sense that their peers consider their accommodations as making things "easy" (Timmerman & Mulvihill, 2015; Fleming et al. 2017). Unpacking this sense of ease is important because of institutional preconceptions of access needs as so-called reasonable accommodations, which strikes a paternalistic ease-of-access chord with the word "accommodation", rather than making something possible to be accessed. Others have called out the harm that this rhetoric can cause (Krebs, 2019). In other words, the phrasing our institutions use to describe accessibility are characterized by a sense that a class of people must be "accommodated" to easily fit into the larger system that is not designed for them.

<u>Accessibility: Equal Access for All</u>

Stevie shared, "Accessibility is receiving certain necessities or needs or products that are indiscriminately available to all types of people. Examples are internet access or computer use at a public library, captions on a video, and materials and textbooks given to children in school to aid them in studying."

Many reflections conceptualized accessibility as some form of equal access for all people. This was encouraging to see, even with a wide range of expression of access to what in particular? Some students did include specific mention of disabled access. Stevie's quote here shares a concept of accessibility that encompasses necessities rather than ease of access, and that these necessities are "indiscriminately" available. The examples provided further in the quote also overlap with the code for access to basic needs, however, the major component of the quote was categorized under equal access because the quote does emphasize this important concept. Student responses that denote accessibility as equal access for all are in line with our pedagogical intentions, the definition of accessibility students had learned (Center for Universal Design, 1997), and pro-social attitudes that might increase altruism (Agnew & Le, 2015).

Access to Basic Needs

Chayse shared, “Accessibility is the ability to provide equal means for all, in all senses. This could be seen through equal access to education, home necessities, etc. In class, we saw accessibility through using captions on Zoom, or providing text descriptions of images for those with low-visibility.”

This conceptualization of access highlights the multifaceted use of the word beyond disability accessibility. We did not take a positive or negative stance towards these reflections, and observed them as common to students’ vernacular, even while we taught our students about disability-specific accessibility. In fact, students in the post-survey frequently reflected access to basic needs in the same paragraph as access to aspects of disability accessibility, as Chayse reflects in the given quote. Because accessibility has many interdependent and interpersonal meanings for our students, we are reminded of how a lack of access can impact many people on an intersectional basis.

Theme #2: Access Takes a Little Extra Effort to Notice

Centered within the question 4 prompt, students reflected on whether and how accessibility is noticeable when they interact with science media, including journal articles, videos, podcasts, and social media posts which share pieces of science communication. These three sub-themes can be perceived as access taking a little extra effort to notice, with the ‘noticing’ on a rough scale between more noticeable (“Crosses My Mind”) and completely unnoticeable or unimportant (“Doesn’t Impact Me” and “Couldn’t Define or Describe”).

Accessibility Crosses My Mind

Shay reflected in the post-survey, “When I interact with examples of science media, the [science communication project] has given me a new lens through which to question how people are able to receive the information. In the past I experienced how sometimes some pieces of science media were difficult to understand, and now I can appreciate how many times people with disabilities are left with another layer of complexity.”

Nicky shared in the post-survey, “I think this really just comes in the form of being mindful of [accessibility]. For the [science communication project], I had initially thought of the obvious groups to reach out to for accessibility: deaf, blind, etc. At the same time, I never gave any thought to things like dyslexia or colorblindness.”

It is encouraging here to see that some students have recognized the idea that accessibility for disabled people can assist with broader accessibility for all, especially when considering science jargon. It is important to juxtapose the sense of accessibility as ease with the sense that science jargon is not perceived as easy. We share this juxtaposition because efforts to equitize science pedagogy are sometimes met with resistance to presumably making science content too easy. The Principles of Universal Design themselves emphasize simplicity or ease of use (Center for Universal Design, 1997). Faculty and teaching assistants have shared challenges to full implementation of inclusive pedagogy (Hernández-Quirama, A., & Oviedo-Cáceres, 2019; Zaki and Ismail 2021), which reduces the chances that inclusive pedagogy will be implemented at all. Further, this reflection of ease may tie to the sense of "complexity" students reflect and have come to expect in their perception of a quality education.

<u>Accessibility Doesn't Impact Me</u>

When accessibility becomes an inconvenience for the individual learner, then broader thinking about access may be part of the thought process. This was categorized under the extra effort to notice theme within the sub-theme that expressed a sense of apathy to accessibility - that is, accessibility doesn't impact me.

To provide one student reflection, Lanie shared from the post-survey, "Since I am not affected by a disability, I find it hard to think about the accessibility of science media."

Here we share a student quote from the pre-survey that falls within this category, and the same student's quote in the post-survey, for comparison. Corie shared in the pre-survey: "I never consider the accessibility of science media. When reading a news article I always think that news is such a common thing that anyone who wants to access it can access it. The same goes for social media posts. For example I don't think I will ever look at an Instagram post about science and think about how it is not accessible enough."

Corie later expressed that accessibility did cross their mind, and shared in the post-survey, "After completing the [project] when I see science media I think about the different kinds of people who might want to access it. For example, if there are no features to help a blind person understand graphs or images I might bring that up to the creator so they can improve on that. I learned how to do this by critiquing other [student projects]."

This reflection provides a singular example of pro-sociality being boosted as a result of the science communication project. It may also have given students the chance to interrogate their own sense of elitism and begin to enact their own version of transformative change (e.g. Liasidou, 2014).

Couldn't Define or Describe

This sub-theme was not highlighted within the post-survey responses.

Theme #3: Disability Perception - What Does Disability Mean?

This theme highlights those reflections that specifically describe disabilities. These include direct mention of mobility, vision, hearing, learning, and/or mental health disabilities, whether based upon lived experience or reflecting upon disability access in general. An interesting theme was crafted around disability as a limitation, and was determined through repeated reflections of disability as some form of disadvantage or abnormality, or a sense of gratitude for being non-disabled.

While related to the theme, “Accessibility crosses my mind”, the themes below parse out specific meaning-making around what disability means to students. For example, the Disability Visibility theme, named in honor of disability advocate Alice Wong’s edited collection of disability essays and corresponding podcast, categorized student reflections of specific types of disability. It is interesting to note that these disability “types” fell into code categories such as mobility, vision, hearing, and a combination of learning and mental health. This theme evolved from a topic summary on disability “types” which simply collected these codes, into a more cohesive narrative of how students notice disability.

Disability Visibility

Student respondents reflected on disability through conceptualizations of what is visible or apparent, with Disability Visibility corresponding to nearly 30% of the 1234 coded segments (N=359). The codes here were largely student descriptions of visual and mobility disabilities as well as the d/Deaf and Hard of Hearing communities. However, only 21 of these 359 Disability Visibility codes reflected learning or mental health disabilities, which is important to note due to the relative invisibility of these aspects of disabled community. We report quantitative data here solely to reflect on the invisibility of certain disabilities.

Wyn shared, “Now when I look at different mediums, I am more inclined to think about who is most likely to benefit from each medium. For instance, when I see a science podcast, I now think of how beneficial they are for folks with ADHD who might need to do something while consuming this media.”

Sky’s response is one of very few where students disclosed their own lived experiences with disability and/or neurodivergence, and specifically call out accessibility as a feature of a service or environment: “Accessibility is the features of [sic] thing that allows users to utilize it, regardless of personal circumstances. I have Sensory Processing Disorder and I learn a lot through touch, it's almost like my brain can't fully comprehend that something is there unless I can rub it's texture, so accessibility for me can look like hands-on exhibits in museums. For other people, it can look like apps that have screen readers for the blind, or the replacement of stairs on a building with ramps so that people in wheelchairs don't potentially feel othered by having to use a separate entrance-way.”

Seng shared, in response to question 4, “I do consider how accessible the product is to audiences with disabilities now that I’ve learned about the importance of science communication. I sometimes share with others if I find a medium weak or stronger based on how accessible it is, because better-developed media should be accessible to a wider audience. I typically consider deaf and blind people, as well as if the word choice is logical and understandable for those with neurological disorders.”

The quotes within this theme show that some students are thinking about barriers that disabled people might face when interacting with various resources. Students also reflected the ways in which disability was visible or apparent to them, by explaining how they consider their audience when crafting science communication. While this allows for some forward movement towards a deeper understanding of disability access needs, it highlights the limited knowledge that students have related to the non-physical needs of disabled people. Workers have shown that college students express a relative ignorance of the needs of disabled students, along with the loss of independence that comes with perceived disability (Ash et al., 2017).

<u>Disability is a Limitation</u>

Disability as limitation was crafted from reflections of non-normativity, disability as challenge, and improvement of disabled people’s lives, underscoring student reflections of disability as a lesser quality of life.

Sully answered the question 4 prompt, “Disabled people sometimes could be the center for the science discussed in the media, like which kind of technology is beneficial for disabled people. So these kinds of science media could easily get exposed to disabled people. But since disabled people suffer a lot in daily life, they could ignore anything other than themselves, not to say science media.”

Zhan described their interaction with science media as follows: “I usually never see science presentations take into account the disabled or those who are not ‘normal’.”

Sheridan shared, “Accessibility is considering the quality of life of all types of people in the world and inventing enhanced techniques to improve the lives of specifically those who are mentally or physically challenged and the overall public as well.”

It is not without some irony that we reflect upon Sully’s description of disabled people as “suffering”, and ignoring “anything other than themselves”, a belief that disabled people are somehow less prosocial. Phrasing such as “the disabled” and “not ‘normal’” (quote emphasis is the student’s) also highlight a lack of clarity on how to use anti-ableist language. The use of the phrase “to improve the lives”, the word “challenged”, and the concept of disabled people as somehow separate from the “overall public”, are ableist ideas that set certain people aside to be ‘fixed’ in some way (Leah Smith, n.d.) and centered in societally mediated ideas of ‘normality’ (Talila “TL” Lewis, n.d.) as well as evolutionary biology concepts of normality (Vaahtera, 2016). Erevelles (2011, p.72) calls out ghettoization of marginalized and disabled students in a dichotomy of normality, where "'we' therefore, try really hard not to be like "them'." This is potent in our student reflections that separate disabled people from those perceived as non-disabled. Recording student responses such as these can help us better understand the ableist misconceptions students in evolutionary biology courses have about disabled people, and to foster accountability in our educational spaces.

Theme #4: Who has access to knowledge?

These sub-themes center around both science and education, because written reflections demonstrate a sense of science research being hard to understand, which science education and communication can attempt to alleviate. In addition, reflections underscored a sub-theme of learning as a type of privilege, whether through difficulties accessing higher education, or the exclusive nature of learning resources at certain universities. Education is not the great equalizer some propose it to be, and the concept of learning privilege and exclusivity is not lost on some of our students.

<u>Science Research is Hard to Understand</u>

Chayse shared, "Accessible interactions with science media include being able to be understood and accessed by all people, not just those who have extensive scientific background. This could come in the form of using less scientific wording so that those not well versed in the subject could better understand the science media. This could also come in the form of using images to better illustrate the study, as well as using text descriptions to describe the photos for those with lowered vision."

This quote exemplifies student conceptions of who has the privilege of understanding science, and also incorporates a mix of disabled access along with general science accessibility. Students used language such as "extensive scientific background", "scientific wording", "those not well versed in the subject", and "individuals who are not of high enough scientific caliber" to describe ways in which science is inaccessible. This language evokes a certain scientific or academic elitism and the privilege of having access to science knowledge. UDL can be an effective counter to elitism (Liasidou, 2014), but a single encounter with inclusive education in a science space will not deconstruct elitist preconceptions for every student.

<u>Learning is a Privilege</u>

When reflecting on accessibility in science media in Reve shared, "I would avoid using complex science jargon that someone who is not trained in science could understand."

Chaney reflected, "Especially at a prestigious institution like [my university], I sometimes recognise the privilege of the fact that I get to learn much of this information because of the fact that I am at this institution. My academic databases and teacher knowledge are not available to the majority of the human population."

In a similar fashion to Science Research is Hard to Understand, the Learning is a Privilege sub-theme underscores student conceptions of who has access to learning, the prestige of access in higher education, and the privilege of learning science concepts and terms. It differs slightly from the above sub-theme in its broader application of the privilege of learning, beyond science knowledge.

Tying It All Together: UDL, Science Media, and Student Perceptions of Accessibility and Disability

Our students conceptualize their responses to the survey questions in three main overarching ideas: Access, Disability, and Knowledge & Learning. These overarching ideas are further expanded into themes that were created from student narratives, either defining accessibility or considering accessibility for disabled people in science media. We have especially focused on the post-survey responses as we believe they capture aspects of student understanding of these concepts after engaging with elements of UDL as practitioners. Here we tie together our analysis of student responses with our three main research questions.

Research Question #1: What are U.S. undergraduate student conceptualizations of accessibility and disability?

Disability and accessibility are socially mediated concepts, and our students reflected pieces of this social mediation in their responses. Clearly accessibility is multifaceted, yet the many meanings of accessibility are not infinite. Our respondents shared that accessibility does connect with disability access and equity, and there are definitions of accessibility that branch out to ease of access or possibility of access to goods, information, and services. The dichotomy between ease of access and possibility of access in the narrative tells us that accessibility is reflected by students as something that provides ease as well as the chance of access in the first place. This is important to understand because disability in higher education is predicated by so-called accommodations which create access, but can be perceived as creating ease (Fleming et al., 2017) . Faculty conceptualizations of accessibility accommodations as challenging (Zaki and Ismail 2021) further complicate the ways in which higher education defines and supports accessibility.

Some students reflected disability as a limitation, a problem to be solved, or a challenge that deviates from the ‘norm’. This sits uncomfortably with student reflections of accessibility as an individual responsibility, or accessibility as ease of use. Students do generally reflect that accessibility can mean equal access for all people, which is encouraging at face-value. However, the deficit-charged language many students used to describe disability speaks to a larger cultural understanding of disability as a limitation or detriment. While our respondents were majority non-disabled, we emphasized and centered disabled voices and perspectives throughout our UDL pedagogy in these courses, in an attempt to strongly challenge deficit thinking in an institutional and systemic setting (Davis & Museus, 2019).

Research Question #2: How are these conceptualizations reflected when considering science media?

Prompting students to consider access within science media led to reflections that centered on the privilege of knowledge access, along with the challenges of understanding science. Our students noted that because they are college students, they have the benefit of access to both general scientific resources as well as a science education. Creating equitable access to science education was reflected as avoiding complexity, and the importance of using science media to create different ways of accessing science knowledge. Some students reflected that access to science media doesn't matter to them, or that they wouldn't think about it or notice the absence of accessibility if they were not personally impacted. Other students shared personal experiences of access or lack thereof, including some sparse disabled student reflections.

Students also shared that, in general, science is perceived as hard to understand. When sharing their own science media products as part of their courses, students were instructed to consider a key target audience, and could tailor the information towards that imagined audience's needs. This includes disabled and/or neurodivergent people within said audience. Equipping students with the tools to share their science knowledge with others forces students to confront the systemic challenges inherent to implementing equitable science communication, such as added effort, time, or skills.

The science communication project and the corresponding science media products that students created allows instructors to directly impact the existing trajectory of science media and access in science. There is a general lack of integration of disability awareness in STEM fields, and evolutionary biology courses are no exception, even utilizing terms that are outright ableist (Branch et al., 2022). Evolutionary biologists have historically played a role in the eradication of disabled people through eugenics and institutionalization (Vaahtera, 2016; Snyder and Mitchell, 2019), and these courses within the academy are especially crucial forums in which to boost disability awareness and social justice. Multiple avenues of disability awareness and consistent implementation of inclusive education methodologies such as UDL are necessary to enact slow but steady change within our science college courses. We envision a near future where ableist conceptions of disability and accessibility are far less commonplace in our science classes, and equipping our majority non-disabled students with ways to challenge their own conceptions is one path forward to enable this future.

Research Question #3: What difference does practicing Universal Design for Learning make, if any?

Universal Design for Learning is one method for introducing flexible learning into classrooms. It is particularly useful because it can serve as a pedagogical aspect of universal design, and as a method for students to understand how to assess access and disability more broadly. This study focuses on its use as a method that undergraduate students can engage with as they practice science communication. This study offers new insights about student perspectives in evolutionary biology that can help us to further our student understandings of UDL, but we again emphasize that a single implementation is not enough. Systemic, consistent anti-ableist change is sorely needed. We also add student perspectives regarding the importance of these anti-ableist UDL resources, aligned with faculty perspectives (Hernández-Quirama, A., & Oviedo-Cáceres, 2019; Zaki and Ismail 2021), which may continue to influence faculty feelings of encouragement and competency (Izzo et al. 2008) with UDL implementation.

We recognize that a single implementation isn't going to change every students' preconceptions about learning, disability, and accessibility. But it is a start. This approach offers integrated application of UDL in evolutionary biology courses, allowing students to set up an initial foundation and build comprehension regarding accessibility and disability. It was our goal to infuse evolutionary biology content with a social justice and anti-ableist framing, which students can recall and engage with in the future. Some of our students did reflect on how their awareness of disability accessibility had changed following the science communication project, and others reflected that they had begun to think about science media with this accessibility lens.

As we strive to create more equitable educational environments, it is important to understand student baseline definitions of accessibility, since inaccessible environments are inherently inequitable and not inclusive. Student understandings of disability are equally important to record and decipher, because there is a great deal of ableist misconception in our non-disabled student populations. When students reflected on disability in their conceptualization of accessibility, the language often centered the responses in a tragic or medical sense of disability. While not entirely surprising, these reflections echo the larger university systems of ableism, capitalism, and colonialism from which they're formed.

Our findings demonstrate that student conceptualization of accessibility, disability, and science access is multifaceted, and that training in UDL concepts takes practice to really sink in. UDL is not a perfect methodology, rather it is one method to help students practice and experience inclusive education in an inequitable academic system. We encourage students and faculty alike to engage with UDL as a means to interrogate the ableist systems in which we operate.

Strengths and Limitations

This study is strengthened by our students, who have been open to participating in these projects and the associated surveys. We especially acknowledge those few students who identified as disabled and/or neurodivergent. As researchers, we bring our reflexivity and positionality into the research process with honesty and integrity. Another strength of our work is that it aims to open dialogue between science classrooms and disability studies, with the qualitative methods of reflexive thematic analysis and our social justice theoretical frameworks at the core. Limitations include the study setting operating only within the United States, with a particular set of selective universities that attract highly motivated students.

Conclusions

This work offers a template for how to develop an undergraduate course project regarding science media that interrogates access through Universal Design for Learning perspective. While acknowledging the limitations and critique of UDL from the disability studies field (Baglieri, 2020; Rao et al., 2014; ; Song, 2017; Smith et al., 2019), we point towards its potential as an entry point to conversation in STEM coursework. We view this as a micro-level (Seale, 2017a) intervention that can be used alongside work at the structural and policy levels to create more inclusive and equitable higher education. In this study, the process of asking students to generate their own understanding of accessibility initially allowed for a baseline understanding of how students conceptualized access, in their own words. Following this baseline with disability-centered curricular activities allowed us to implement direct instruction about what accessibility means in science communication, and students could practice its implementation within their own pieces of science media. Student responses offered key insights regarding their current understandings, stances and foundational knowledge about accessibility and disability, especially within science media and communication.

We recognize the limitations of this short-term course activity as one element in a larger constellation of Disability justice work that is happening on these campuses and beyond. This pedagogical implementation allowed for the integration and dialog of disability social justice into evolutionary biology spaces that have not historically engaged with this work (see Vaahtera, 2016; Snyder and Mitchell, 2019; Branch et al., 2022). We look forward to the development of future social justice initiatives in evolutionary biology and science communication through relationship building across campus departments and policy organizations. The increased resourcing of higher education disability justice work and relationship building across stakeholders will improve our opportunity to radically center disabled voices, and interrogate ableism in Higher Education.

Chapter 5: Conclusions

In this dissertation I present independent research on the extent and visualization of the dental neonatal line in modern mammals, tying to the evolution of mammal birth and how life histories are recorded in teeth. This work is relevant to the paleontological, mammalogy, and dental communities as a study centered on the anatomy and phylogeny of dental metabolic records, which can be used to better understand how mammal birth is recorded, and ultimately, how it evolved. I also present independent research on a science communication pedagogy project that is infused with Universal Design for Learning (UDL) and utilized both qualitative and quantitative research methods with a critical disability studies framework. This work is relevant to the paleontological and evolutionary biology communities as well as to educators and disability studies scholars as it highlights the need for more inclusive education in our fields, and the need to acknowledge and support people from all backgrounds in our classrooms. As a disabled and neurodivergent person and scientist, this dissertation weaves together both my identity as a paleontologist and science researcher, and my identity as a science education and disability researcher, but foremost, it ties into the things I’m passionate about: upholding values of equity and inclusion in my professional and personal spaces.

The work that we do as scientists, while bringing our whole selves into our science, matters. It is important to teach the next generations of scientists and policy makers that science is not the cold Ivory Tower endeavor that it is made out to be. However, the systems of academic science are not extremely friendly to those who do not conform to a particular set of molds. While academia espouses to open its doors to campuses, communities, and conferences as welcoming and inclusive spaces, the reality is that the human beings who operate within these communities have not yet realized true equity for the people that academia has marginalized.

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Appendices

Note: No appendix materials for Chapters 1 or 4.

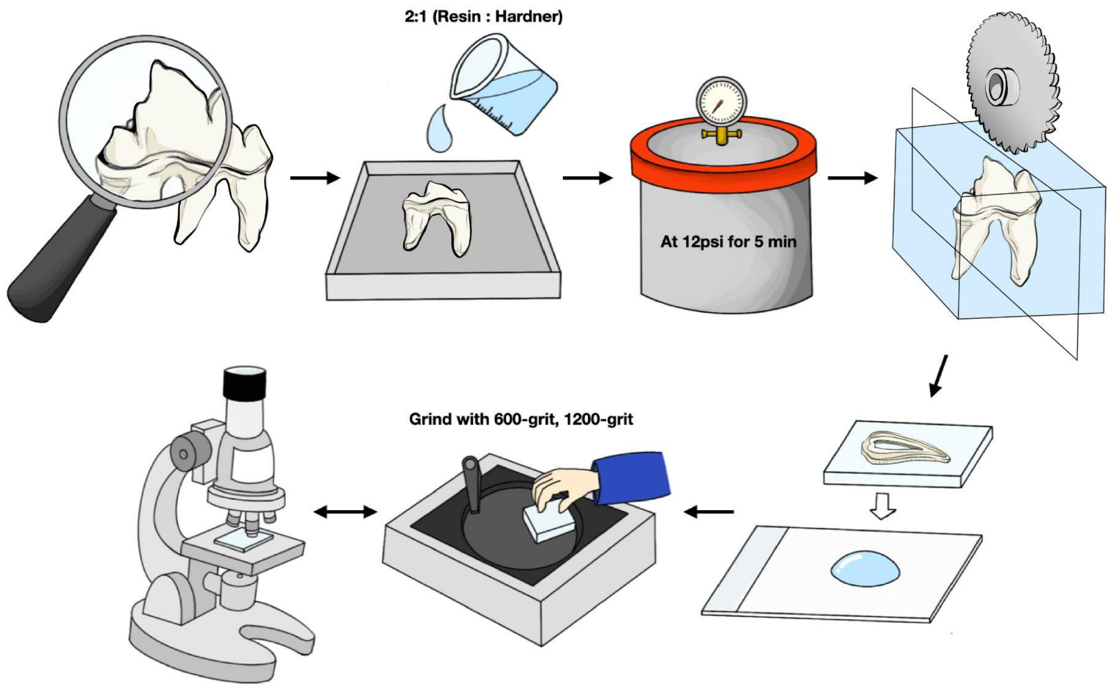
Appendix - Chapter 2

Mammalian Evolution Event	**Time Bracket**	**Methodology**	**Reference**
Sauropsid-Synapsid split	340?Myr	Fossil analysis	Kemp 2005
Crown Mammalia common ancestor	~170Myr	Fossil analysis	Flynn et al. 1999 Beninda-Emonds et al. 2007 Luo 2007 Benton et al. 2009
Earliest eutherian mammals	125Myr	Fossil analysis – discovery of new fossil	Kemp 2005 Ji et al. 2002
Earliest metatherian mammals	160Myr	Discovery of new fossil (*Juramaia sinensis*) and molecular clock analysis	Williamson et al. 2014
Earliest monotremes	126Myr	Oldest known monotreme (*Teinolophos trusleri*)	Flannery et. al 2022
Milk evolution	310-200Myr	Comparative genomics of casein	Brawand et al. 2008
	160Myr	Comparative genomics of milk protein genes (casein and alpha-lactalbumin)	Lemay et al. 2009
	?	Hypothesis based on antimicrobial and structural similarities of lysozymes and	Vorbach et al. 2006 Urashima et al. 2012

		alpha-lactalbumin	
	?	Hypothesis connecting lactation to fossil diphyodonty	Oftedal 2002 Oftedal 2012 Oftedal 2020
	?	Hypothesis based on lactose digestive evolution	Power & Schulkin 2016
	Posited expression of proto-milk in Cynodontia or Mammaliaformes	Review of bovine lactation evolution	Capuco & Akers 2009
Hair evolution	165-164Myr	Fossil analysis and description	Zhou et al. 2013
	164Myr	Fossil analysis and description	Ji et al. 2006
	125Myr	Fossil analysis and description	Ji et al. 2002
	?	Comparative genomics of cysteine-rich type I and II alpha-keratins, indicating divergence after sauropsid-synapsid split	Eckhart et al. 2008
Yolk genes	70-30Myr	Comparative genomics, inactivation in eutherians and metatherians (VIT3, VIT1)	Brawand et al. 2008 Ross and Boroviak 2020
Evolution of mammalian middle ear	125 Myr	Fossil analysis and comparative anatomy	Chen et al. 2007 Meng et al. 2011
Parasagittal gait	125 Myr	Fossil analysis and description (*Eomaia scansoria*)	Kielan-Jaworowska & Hurum 2006

Fibrolamellar bone	Late Carboniferous - Early Permian	Fossil analysis (*Ophiacodon*)	Shelton & Sander 2017
Large relative brain size	Mid-Jurassic	Comparative fossil analysis	Smaers et al. 2021
Milk weaning	?	Milk evolution analysis	Brawand et al. 2008
Placentation	Mid-Jurassic	Milk evolution analysis	Brawand et al. 2008
Isotopic evidence of thermometabolism	~252-259Myr	Comparative fossil analysis	Rey et al. 2017
Putative parental care of neonates	260Myr	Varanopid synapsid with 5 neonates; parental care?	Botha-Brink & Modesto 2007
	160Myr	Fossil *Kayentatherium* with several neonates	Hoffmann & Rowe 2018
Diphyodonty evidence	~160Myr	Fossil evidence in morganucodontids e.g. *Wareolestes rex*	Panciroli et al. 2018
Dental neonatal line	? Oldest to date is ~55Myr	Fossil evidence in *Pantolambda bathmodon*	Funston et al. 2022

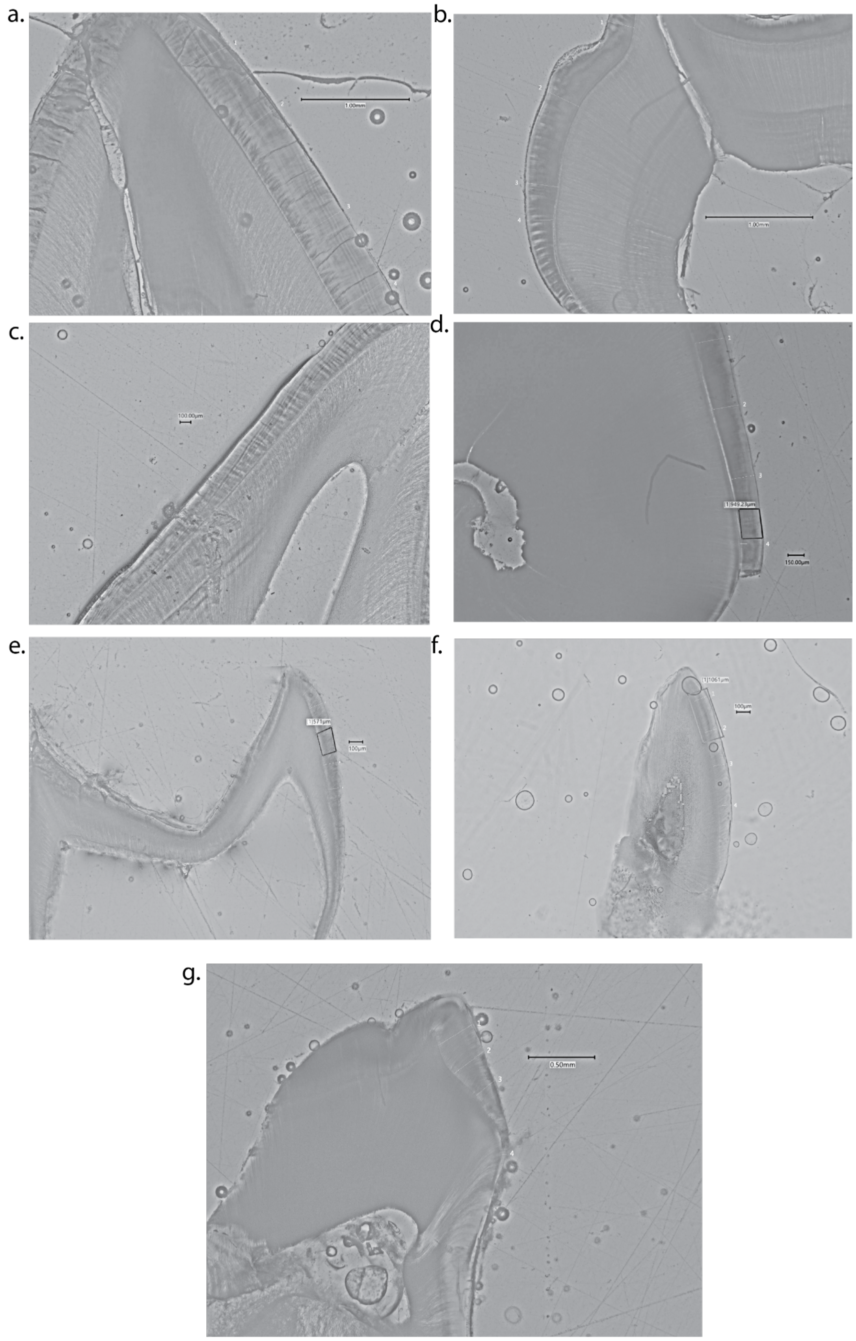
Appendix Table 2.1 - Mammal Trait Evolution Table



Appendix Figure 2.1 - Detailed Methods

Histology Methods. Teeth were documented via photography or CT scanning, embedded in epoxy resin, sliced on a diamond wafer blade into thin sections, and glued to microscope slides via 2-ton epoxy. These slides were then polished to a thickness of roughly 100 microns or until subjective optical clarity. Methodology figure by Jiho Kim and Rhea Ewing.

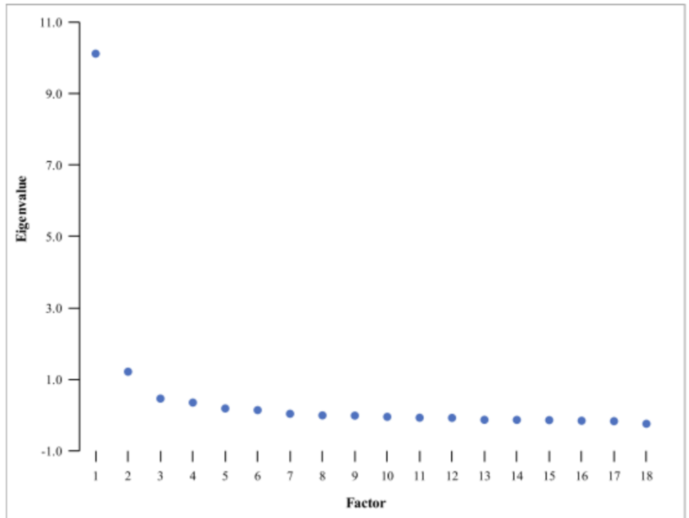
Scientific Illustration and Imaging:
Our team of scientific illustrators created anatomical illustrations of teeth and labeled them with directions such as mesial, distal, lingual, and buccal, along with indications of cusps. In these illustrations, we specify which area of the tooth was sliced. Illustrators utilized both 3D and 2D illustrating tools, such as Adobe Photoshop, Adobe Illustrator, and Inkscape. They utilized specific plugins such as the 3D Revolve tool in Illustrator and the Path effects in Inkscape to facilitate the rendering of complex tooth geometries. For instance, illustrators captured images of the sampled teeth from various angles and uploaded them to Adobe Illustrator. They then used the image trace function to outline the tooth forms, and subsequently, these traced images were combined into 3D representations using specialized 3D illustrating tools. In addition, scaling consistency was maintained by setting specific ratios in the software, corresponding to the actual dimensions measured from the physical samples, ensuring that the digital models accurately represented the original specimens. Discrepancies were addressed by revisiting the original images and making necessary adjustments to the illustrations. The finalized illustrations are intended to aid the visual documentation of research focusing on dental neonatal lines and tooth development in mammal tooth.



Appendix Figure 2.2 - Grayscale Teeth Images

Appendix - Chapter 3

Factor	Eigenvalue	Difference	Proportion	Cumulative
1	10.12	8.90	0.89	0.89
2	1.22	0.75	0.11	1.00
3	0.46	0.11	0.04	1.04
4	0.35	0.16	0.03	1.07
5	0.19	0.05	0.02	1.09
6	0.14	0.10	0.01	1.10
7	0.04	0.04	0.00	1.10
8	-0.01	0.01	0.00	1.10
9	-0.01	0.03	0.00	1.10
10	-0.05	0.02	0.00	1.10
11	-0.07	0.00	-0.01	1.09
12	-0.08	0.05	-0.01	1.09
13	-0.13	0.00	-0.01	1.07
14	-0.13	0.01	-0.01	1.06
15	-0.14	0.02	-0.01	1.05
16	-0.16	0.01	-0.01	1.04
17	-0.17	0.07	-0.01	1.02
18	-0.24	.	-0.02	1.00



Appendix Figure 3.1 - Eigenvalues and Factor Loading for Likert Scale Questions

Semi-Structured Interview Questions for Students:

1. How have you felt about the accessibility focus of this class so far? Why?
    a. Follow-Up: When you think of the word “accessibility”, are there definitions that come to mind?
    b. Follow-Up: Did your definition change, thinking about accessibility as a disability-centered term?

2. What would make it easier to make your communication project more accessible to sensory-needs audiences?

3. What sort of resources would you like or have liked?

4. Is there anything else you would like us to know about your experience with the project so far?
    a. Alternative: Do you have any other thoughts about the project?

Semi-Structured Interview Questions for Faculty:

1. How have you felt about the accessibility focus of this class? Why?
    a. Follow-Up: Did students reflect about their own experiences with disability?

2. What would make it easier to make your creative discovery project more accessible to sensory-needs audiences?
    a. Follow-Up: What sort of resources would you like or have liked?

3. Is there anything else you would like us to know about your experience with the creative discovery project so far?

4. Did any of your students discuss universal design for learning outside of that specific science general education class?

5. What were some of the most common sorts of projects you would receive?

Appendix Table 3.1