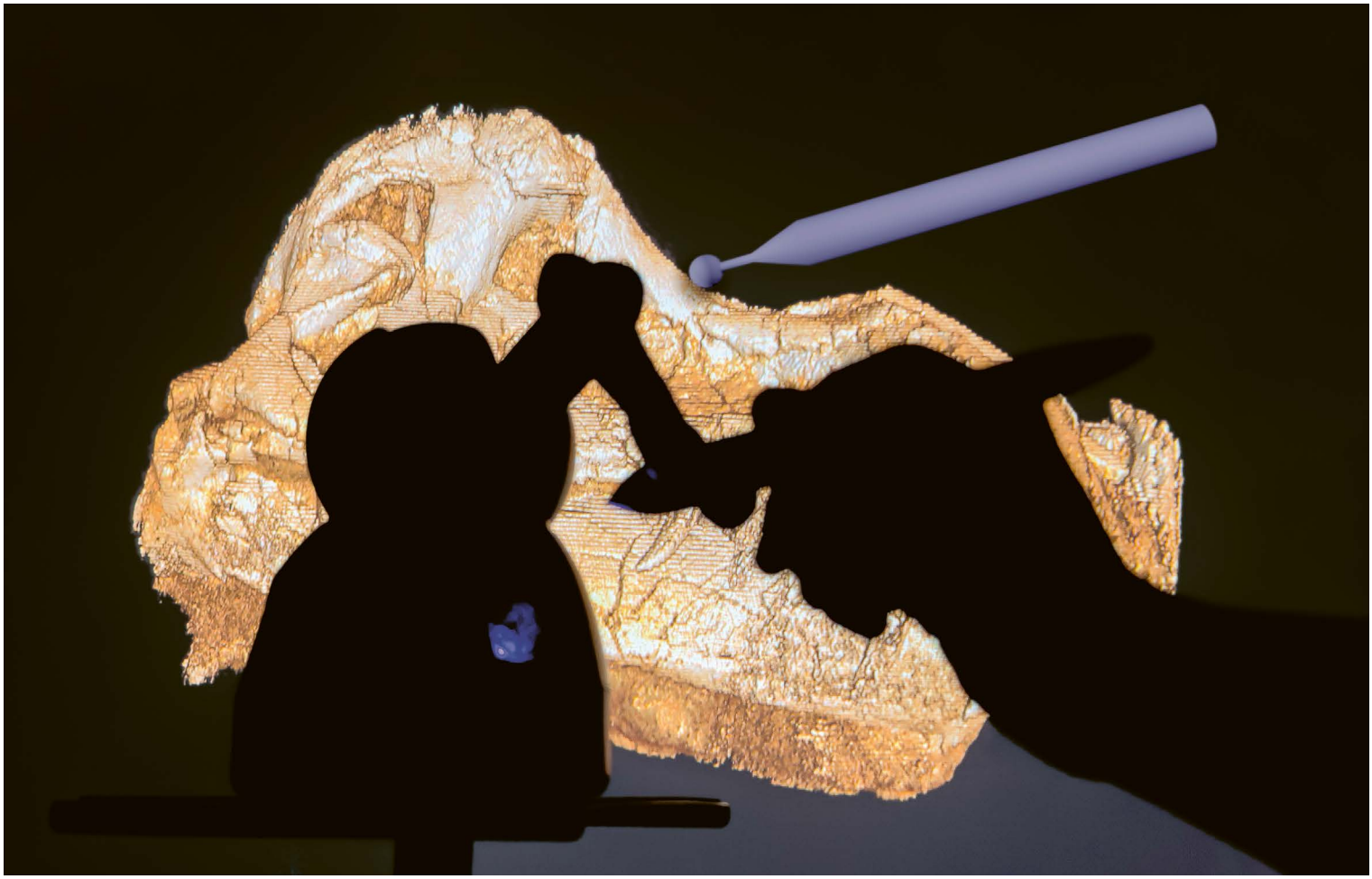

1 Virtual replica of a fossil digitized through computed tomography. Volume and haptic rendering transform radiodensity values into corresponding visual projections and force feedback.

As If It Were a Physical Object: Virtual Tools Toward the "Holy Grail" of Working with Organismal Remains

The analysis of fossils or type specimens of modern organisms is a key to our understanding of our planet's currently threatened biological inventory and of the diversification of life on earth. These specimens are often fragile, rare, or difficult to access, limiting their potential use in answering diverse research questions. Therefore, a major advance in the investigation of both modern and extinct organisms over recent decades was the use of virtual representations of specimens based on diverse imaging techniques (Cunningham et al. 2014). This allowed for non-destructive investigations and, perhaps even more importantly, the sharing of data between researchers across the globe. But working with images is different from working with physical objects. Even though 3D datasets can be rotated and zoomed in on on screens, we usually interact with such 3D representations via a computer mouse and a keyboard while looking at the object on a 2D screen. More recently, virtual reality (VR) has been employed to study 3D datasets using 3D models.

Creating VR setups for working on specimens and interacting with these specimens using virtual tools offers exciting possibilities that we build upon in our project. Tools can be used not only to measure or to visualize certain aspects, but also to virtually cut, separate, repair, or retro-deform specimens. Potentially, this development can also bring preparators and researchers together again, because the digitized specimen can be investigated and manipulated in a VR setup as if it were a physical object.

In our interdisciplinary setup, we are aiming for the next substantial methodological advance, pursuing the "holy grail" of working with such 3D representations of organismal remains. To further refine the impression of working with actual physical specimens in VR, it is necessary to be able to touch these specimens and to receive sensory feedback about the haptic quality of the object. Achieving this goal might be several years down the line, but the *Virtual Dissection* experimental setting explored possibilities and developed a prototype that allows one to feel differences in a material's shape and other properties. In a first application of this, segmentation tools can be improved, guiding preparators and researchers alike as they decide whether a structure belongs to one material or another. In terms of fossils, this could enable them to differentiate between a fossil and the surrounding material. And such segmentation results, agreed upon in collaborative VR settings, can, for example, be the input for a robot that then precisely conducts the preparation of the fossil out of the slab of rock.

John A. Nyakatura, Evolutionary Biology

Advancing Virtual Dissection: Using Computer Haptics for Easier, Non-Destructive Fossil Analysis

The background of fig. 1 illustrates the virtual replica of a fossil that was digitized through computed tomography and transformed into this projection via the volume rendering of radiodensity values. Although digitalization has significantly improved morphology and enabled researchers to process specimens in a non-destructive manner, interaction with such technology as digital fossils remains challenging in many workflows. Researchers must use 2D tools to interact with 3D data, which is a time-consuming and challenging way of processing data into meaningful parts. As depicted in fig. 2, we employed ethnographic methods to further explore this issue, listening to morphology researchers and traditional fossil preparators, and observing their workflows through a human-computer interaction lens (Siqueira Rodrigues et al. 2023a).

Of the different challenges faced by participants in our study, we decided to focus on digital morphology tasks that require the retention of accurate mental representations of 3D data. Given that our qualitative results indicated that direct manipulation of specimens appeared to provide technical preparators with better mental representations of fossils than current scientific visualization interactions, reshaping the interaction with fossil data to resemble the physical work performed by technical preparators with tangible fossils suggested a promising direction to address this challenge. We were particularly interested in whether the tangible nature of traditional fossil preparation, in which vision and touch are leveraged to separate fossilized specimens from their matrices, could improve the retention of fossil representations in digital workflows. Thus, our research aimed to employ haptics to evolve digital data interaction to resemble physical workflows.

Before engaging in applied research, we sought to understand whether the application of haptics in this context would support the formation of better mental representations of morphological structures. As illustrated in fig. 3, we conducted a series of behavioral studies comparing participant performance under visual, haptic, and visuohaptic conditions, to measure the impact of visuohaptic interaction on the accuracy of object representations. Our studies provided evidence that the visuohaptic encoding of objects can improve memory retention in VR (Siqueira Rodrigues et al. 2024b) and desktop environments (Siqueira Rodrigues et al. 2024a). Our results also indicated that these findings extend to the morphology use case when tomographic data are presented (Siqueira Rodrigues et al. 2024d).

As our behavioral studies indicated that visuohaptic integration improves the formation and retention of accurate object representations, we proceeded to create open-source tools that enable morphologists to explore digital fossils through an interaction that resembles the physical work of technical preparators (Siqueira Rodrigues et al. 2023b; 2024c). In fig. 1, the foreground silhouette shows a user holding the stylus of a grounded force-feedback device, which captures physical movements and translates them to the digital stylus (shown here in lilac), communicating the forces that stem from interactions between the probe and the digital fossil. Our tool modulates such forces through radiodensity values, simulating aspects of the material properties of digital fossils.

The interaction style implemented here, where users cannot directly touch and manipulate the digital fossil (i.e., the domain object) but have to use a tool (i.e., the stylus instrument), can be called instrumental interaction (Beaudouin-Lafon 2000). It corresponds to the conventional practice of fossil preparation—even if the instruments there are much more sophisticated—and allows the object to be grasped with several fingers and precisely controlled with fine motor skills, but with the disadvantage that the domain object can only be touched selectively and not over a large area. The stylus can be tracked with much greater precision than with hand tracking. Therefore, this form of interaction can allow for more precise and faster feedback than typical hand-tracking systems.

Lucas Siqueira Rodrigues and Johann Habakuk Israel, Computer Science

A Paradigm Shift in Medical Education, Training, and Treatment Planning

Virtual dissection (VD) refers to the digital simulation of dissection procedures that would normally be performed through the physical dissection of tissue or body parts, such as in human anatomy studies. VD allows students and professionals to "dissect" virtual bodies, analyzing parts individually, thereby gaining a better understanding of complex inner structures and spatial relationships. In medicine, VD is a promising tool for examining anatomical structures without having to use and cut open real body parts.

A major prerequisite for VD is realistic and faithful 3D patient models, so-called "digital twins," which are derived from medical image data such as tomography (CT or MRI), where anatomical structures are three-dimensionally captured. The resulting image data are then transformed into 3D models of anatomy by so-called image segmentation (i.e., the spatial decomposition of semantic regions and classification of these on the basis of intensity values and visible boundaries). Medical image segmentation has been a hot research topic in computer science for decades, and AI-based methods have given it a major boost in the past decade.

A second important ingredient for VD is software that includes 3D visualization as well as human-computer interaction (HCI). Research in the field of VR is attempting to develop modeling, simulation, and visualization methods that enable fully immersive interaction with digital objects. Although existing solutions already enable photorealistic visualization, the interaction with virtual bodies still lacks realism and is far from corresponding to the real physical experience. If one wants to interact realistically with digital objects by, for example, touching them or perhaps deforming or even breaking or cutting them realistically, then the limits of immersive, graphically interactive systems have still not been reached. Realistic model behavior, as well as tactile feedback in real time, will be the next big steps in VR research (Coles et al. 2010). The ultimate goal for VD is an interaction with digital objects in VR that is indistinguishable to the user from an interaction with real objects.

A realistic interaction with matter, however, involves sensing as well as Newton's principle of "actio and reactio." Any matter reacts differently based on its properties. This way, humans gain experience and have particular expectations when interacting with matter. The major challenge is to replicate tissue properties and physical behavior in such a way that virtual interaction matches real-world experience. If objects feel real and behave realistically while being handled, the illusion of real human-matter interaction will be achieved. Another challenge is the discrete representation of digital objects. If the objective is to realistically represent effects on different scales, this often fails due to insufficient spatial resolution. Either the digital twin is too coarse a representation, or the computational effort becomes too high to achieve real-time behavior. This limits the realistic simulation of the deformation and destruction of digital objects. For this reason, surgical training simulators are currently still inadequate. The representation of living tissue or an entire body, on which surgical procedures can be carried out so realistically that they appear credible, is still a long way off.

Stefan Zachow, Computer Science

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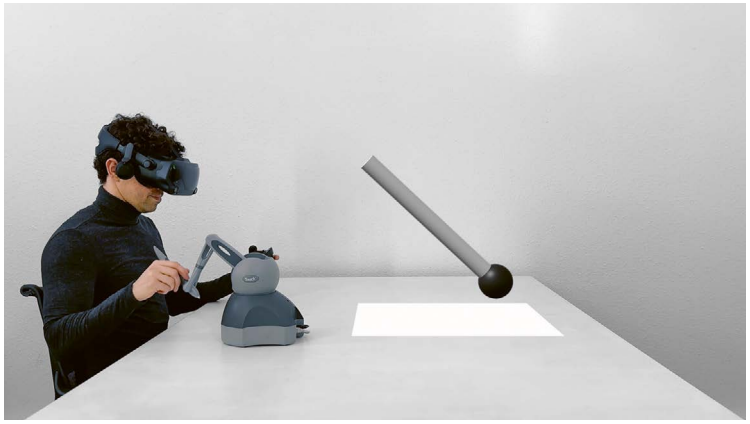
2 Contextual inquiries and ethnographic methods: documenting the physical workflows of traditional fossil preparation to inform digital morphology interactions.



3 Behavioral studies comparing participant performance under visual, haptic, and visuohaptic conditions to measure the impact of visuohaptic interaction on the accuracy of object representations