Embodied Notes: Re-imagining note-taking for academic discovery and learning in VR

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Abstract

Research has shown that note-taking serves as an essential cognitive support tool for learning and critical thinking. However, few educational and professional VR applications incorporate note-taking functionality despite its important role in learning and discovery. In this paper, we present the design and user study of Embodied Notes, a new multi-modal VR note-taking system. We present findings from a user study with 45 college students who used the system for a learning task. We describe how participants used Embodied Notes and their perceptions of how it affected their learning. We also highlight design considerations for supporting users' cognitive processes in future VR note-taking tools for discovery and learning.

Keywords: virtual reality, note-taking

1. Introduction

Note-taking is an essential skill in supporting the learning and discovery process (Canfield, 2011; Paul, 2021). A professor of ecology and evolutionary biology, Erick Greene, describes note-taking for research as not just a record of observations but "the main source of ideas that take my research in new directions" (Paul, 2021). Notes are used to capture observations, improve understanding, reflect, and can serve as a record for which approaches, or

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methods have been tried and which should be tried in the future. In a learning context, notes are used in a similar way with a larger emphasis on increasing understanding (Reisberg, 1987; Risko and Gilbert, 2016; Jansen et al., 2017).

With advances in virtual reality (VR) technology, applications for remote work and learning become increasingly available (Rawlins, 2022; Trentsios et al., 2020; Liou and Chang, 2018). The spatial and embodied nature of virtual reality provides certain affordances that can be advantageous for learning, discovery, and collaboration (Steffen et al., 2019; Shin, 2017; Bhargava et al., 2020). However, to deliver on the promise of VR for scientific collaboration and for student learning, it is important to understand the needs of such users and the type of tools and support they need to effectively use the VR environment for learning and discovery. In an exploratory need-finding study (Olaosebikan et al., 2022b), where scientists were observed collaborating remotely in VR, we found that one tool that was highly desired by users was a system for extensive note-taking within the virtual environment. However, few educational and professional VR applications explore note-taking in detail despite its critical role as cognitive support tool (Paul, 2021; Risko and Gilbert, 2016).

To investigate the use of note-taking in virtual environments for learning and discovery, we designed Embodied Notes - an initial prototype of a multi-modal note-taking system for VR for supporting cognitive work. Our concept prototype (Olaosebikan et al., 2022a) enables users to take multi-modal notes in VR using only their headset and controllers. We designed Embodied Notes to address some of the challenges of prior VR note-taking systems including virtual keyboards being slow to use, physical keyboards requiring users to be seated at a desk or to wear extra gear to hold the keyboard (Pham and Stuerzlinger, 2019), error prone speech to text requiring extra cognitive load to correct mistakes (Adhikary and Vertanen, 2021), and potentially cumbersome peripherals like tablets and pens (Lee et al., 2021; Poupyrev et al., 1998; Chen et al., 2019; Kern et al., 2021).

We designed, implemented and completed a preliminary evaluation of our system with students who were tasked with completing a learning activity about corals in VR while using Embodied Notes and found that Embodied Notes supports learning independent of interaction technique used. In our design and evaluation of Embodied Notes we investigated the following research questions:

RQ1: *What are participants perceptions of the functionality and usability of Embodied Notes and how did they use it to support "thinking outside the brain"?*

RQ2: *How does Embodied Notes influence cognitive load and learning perceptions during a learning session in VR?*

In this paper we present the design of Embodied Notes, a new multi-modal note-taking system, which re-imagines note-taking for academic discovery and learning in VR. We describe how participants used Embodied Notes and their perceptions of how it affected their learning. We also highlight design recommendations for supporting users' cognitive processes in future VR note-taking tools for enhancing discovery and learning.

2. Related Work

2.1. Note-taking as Cognitive Support for Discovery and Learning

Note-taking has been shown to be an effective tool for improving retention, recall and learning (Barnett et al., 1981). Another strategy that has been shown to improve learning is self-explanation (Chi et al., 1989) where learners explain to themselves what they have learned as they are learning. Prior research has shown that those who produced a higher number of self-explanations gained a better understanding than those with less (Chi et al., 1994). Note-taking is one way to facilitate self-explanations (Trafton and Trickett, 2001). We designed Embodied Notes to have voice-notes as the primary note-taking mechanism to take advantage of self explanation to increase learning. Additionally, note-taking has been shown to be vital for recording ideas and observations that lead to scientific discoveries (Paul, 2021). Researchers in the HCI community have designed and studied numerous systems for scientific note-taking, including the recent "augmented laboratory notebook" (Mackay et al., 2002), that creates a lens that bridges physical (paper) and virtual (computer) documents so that biologists can reap the benefits of having a physical notebook while accessing digital information in context.

In her book *Extended Mind* (Paul, 2021), Annie Murphy Paul synthesizes findings from the fields of embodied, situated, and distributed cognition to propose a framework for "thinking outside the brain". Her framework draws upon Clark and Chalmer's seminal article titled "The Extended Mind" (Clark and Chalmers, 1998) to define "thinking outside the brain" as "skillfully engaging entities external to our heads—the feelings and movements of our bodies, the physical spaces in which we learn and work, and the minds of the other people around us—drawing them into our own mental processes." Note-taking has an essential role in facilitating "thinking outside the brain" as it allows for: 1) offloading information into the world and 2) transforming information into an artifact, which can be interacted with (Paul, 2021).

2.2. Digital Note-taking

Many students use notebooks to take notes (Morehead et al., 2019). However, with the rise in technological advances, new ways to take notes have emerged. Students often use computers and smartphones to type textual notes, record their voice, and take pictures to generate rich notes. There has been much research into how digital note-taking affects students' performance (Artz et al., 2020; Allen et al., 2020). Recent research in voice note-taking has shown that taking voice notes can enable learners to gain a deeper conceptual understanding of the learning content (Khan et al., 2022). Research comparing long-hand notes with photo only notes found that students who only took photos performed the same as those who did not take any notes at all (Wong and Lim, 2021).

In his book *SuperSight* (Rose, 2021), David Rose proposes that immersive technologies can help boost semantic and episodic memory. Engaging users' sight, hearing and body position during learning, better positions them to recall information at a later time (Rose, 2021) and potentially create connections between new and existing knowledge using episodic memory. With VR, researchers and students can more readily engage in extended mind practices to make sense of information, taking advantage of the spatial and embodied interactions facilitated by VR applications to absorb complicated material.

2.3. Note-taking in VR

There are a few existing professional VR applications that have implemented some forms of support for note-taking in VR, using a variety of input methods. In Horizons Workrooms (Technologies, 2022), users use their computer and physical keyboard in VR to type notes using their preferred desktop application or can use the controller as a virtual marker. In Spatial (Systems, 2021), users can write on sticky notes visible to all in the room by pressing keys on a virtual keyboard or using the speech to text functionality. Research has explored using raycasting to write letters for text entry (Elmgren, 2017) and tablet and stylus tracking for writing long hand notes in VR (Poupyrev et al., 1998; Chen et al., 2019; Kern et al., 2021). However, these existing methods have several limitations: virtual keyboards are slow to use, physical keyboards require being seated at a desk or wearing extra gear to hold the keyboard (Pham and Stuerzlinger, 2019), speech to text is error prone requiring extra cognitive load to correct mistakes (Adhikary and Vertanen, 2021), and using extra peripherals (tablets, pens) can be cumbersome.

3. Embodied Notes Prototype

3.1. Exploratory Studies

We conducted two exploratory qualitative studies, which informed the design of Embodied Notes. In the first (Olaosebikan et al., 2022b), we observed two interdisciplinary groups of scientists (n=14) studying corals use the professional VR application Spatial over a month for four, one hour long remote meetings. One of our findings from that study centered around note-taking. The scientists in the study felt frustrated with the inability to write personal notes or quickly capture thoughts as is often done with pen and paper or a physical keyboard (Olaosebikan et al., 2022b). That finding motivated us to focus on investigating ways we could improve note-taking in VR to overcome some of the challenges of existing systems.

We then developed the initial concept of Embodied Notes and in the second study, presented the design, using a concept video, to 10 scientists studying corals for preliminary feedback (Olaosebikan et al., 2022a). The scientists were receptive to the representation of a note as a tangible object: *"I really liked the question bubble"*, and a sphere in particular: *"The sphere is very inventive it's super creative"* and expressed a need for expanding the input modalities to include a keyboard and whiteboard for writing equations and sketching diagrams. An additional feature the scientists suggested is to attach notes to specific objects in the virtual environment for example placing questions near the relevant poster or having a designated "pocket" for them: *"sometimes you have a question related to something specific that you're looking at, so would it be possible to have a question and tie it to a poster, for example, and you know that the person that's created this space [...] can go and answer it and I think that might be helpful"*. Based on the initial feedback from the scientists on our concept video, we designed a user study to investigate the use of the prototype of Embodied Notes within an environment designed for college-level science learning.

3.2. Design Rationale

To explore how Embodied Notes might be useful in an education context we made the following design choices. We chose voice and photos as the primary input modalities to reduce the time and number of interactions needed to record notes and to increase understanding of the learning material. By not using a physical or virtual keyboard we sought to reduce the gap from abstract thought to embodied thought and free the user to move around in the virtual environment. We also did not use pen input to allow users to use controllers to interact with objects within the environment.

We chose to represent notes as "thought bubbles" - a representation that is inspired by the marble answering machine (Crampton Smith, 1995) and tangible message bubbles (Ryokai et al., 2009). Both systems used sphere forms for representing and capturing voice and video messages.

Our design aims to take advantage of the extended mind framework by making the notes physical and tangible, thus engaging multiple senses to facilitate sense-making. Our design also attempts to leverage proprioception, "a person's sense of the position and orientation of his body and limbs" (Mine et al., 1997) to make interactions with the system faster and more intuitive.

Gestures, buttons, and raycasting are interaction techniques frequently used in VR applications. Prior research in gesture-based interactions for VR have explored using hand gestures (Clark and Moodley, 2016; Schäfer et al., 2021), blinking (Lu et al., 2020), head movement (Yu et al., 2017; Lu et al., 2019, 2020), and touch (Dube et al., 2022). Button-based interactions include using controllers and keyboards to interact with the environment. Recent work in this area is described in Seibert and Shafer (2018). Research in raycasting has explored designing better UIs (Li et al., 2021) and writing (Venkatakrishnan et al., 2022). Since there are not yet standard interaction techniques used by all VR applications We developed a prototype for each of the interaction techniques to verify that students could interact with Embodied Notes successfully regardless of the interaction technique. In the following section we describe the learning environment we built to study Embodied Notes.

3.3. Learning Environment

Our VR learning environment consisted of three stations where users learned about corals and were tasked with taking notes using Embodied Notes (see Fig. 1). In station 1 (Fig. 2a), participants watched a video about coral anatomy and interacted with a model of a coral polyp. At station 2

(Fig. 2b), participants learned how ecologists identify corals and interacted with three different coral models by placing them under a microscope to see the corals' skeleton at three different zoom levels. Finally, at station 3 (Fig. 2c), participants learned about coral reef types from a video and then interacted with buttons that display pictures of reefs for them to try and identify. The educational videos, image and text content at the stations were reproduced from Khaled bin Sultan Living Oceans Foundation Coral Reef Ecology Curriculum (www.lof.org). The coral polyp model was from coralreef.noaa.gov. The coral skeleton models used were from sketchfab.com (Rlab, 2021; thehydrous, 2021b,a).

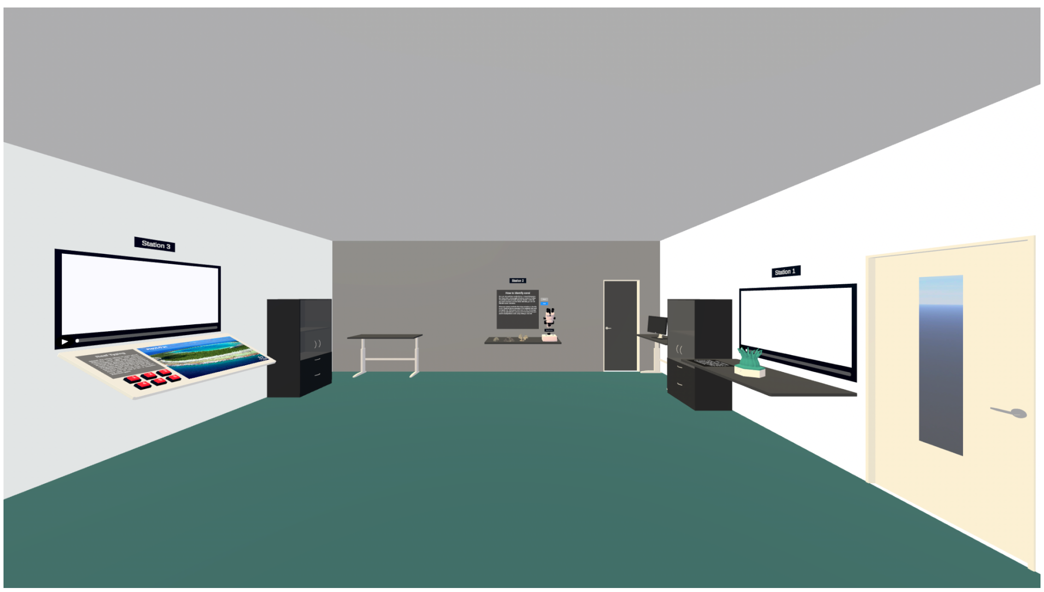
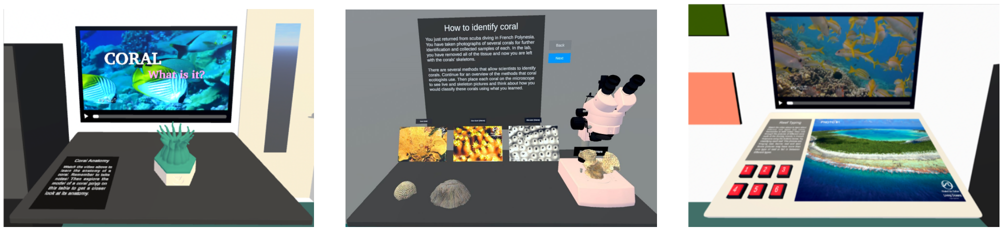


Figure 1: Overview of coral learning lab with Station 1 on the right, Station 2 in the center and Station 3 on the left

3.4. Embodied Notes System Design

We developed three design prototypes that use different interactions techniques: *gestures, buttons*, and *raycasting* to demonstrate that our design provides supports for learning, independent of interaction technique. In the *gestures* design, interactions with notes are primarily gesture based. For example, a user plays a note by grabbing it and shaking it. In the *buttons* design, interactions with notes are primarily button based. A user plays a



(a) (b) (c)

Figure 2: (a) Station 1: Learn coral anatomy (b) Station 2: Learn how ecologists identify corals (c) Station 3: Learn about coral reef types. Educational video, image and text content shown were reproduced from Khaled bin Sultan Living Oceans Foundation Coral Reef Ecology Curriculum www.lof.org. Coral polyp model from coralreef.noaa.gov.

note by grabbing it and pressing the trigger button on the controller. Finally, in the *raycasting* design, interactions with notes are primarily through a menu and raycasting. Each prototype was implemented using the Unity game engine and interactions were implemented using the VR Interaction Framework (Games, 2022).

3.4.1. Note Design

In Embodied Notes, notes are represented as spheres or thought bubbles where the outer texture of the sphere represents the visual context of where the note was taken (see Fig. 4). Empty notes are represented as transparent spheres (see Fig. 3). Users create notes by grabbing a new one from a pocket located on their left wrist (see Fig. 3). By reaching into the pocket a new empty note is spawned. They can record audio in the note, take a picture, and delete the note. Looking down towards their waist, there is a notebook in a pocket that follows the user around (see Fig. 5). The user can grab the notebook out of the pocket and store notes within it. The notebook is separated into 3 sections to mimic the Cornell notes (Pauk and Owens, 2013) method of note-taking with notes on the left, questions on the right and a summary section at the bottom (see Fig. 5). When users grab a note with stored content, any image they have taken is displayed next to the note sphere along with the timestamp of when the note was taken (see Fig. 8). We further describe the interaction mechanism of each prototype below.

3.4.2. Gestures Prototype

In the gestures prototype, we designed the interactions based on real world metaphors to make the gestures naturally easy to remember (Mine

Figure 3: User of Embodied Notes grabbing a new note from their wrist

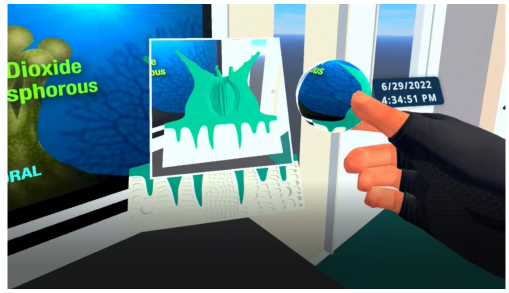


Figure 4: User of Embodied Notes viewing the image note they took

Figure 5: User of Embodied Notes grabbing the notebook from their front pocket

et al., 1997; Jacob et al., 2008). For example, users start recording audio in a note by moving the empty note towards their mouth like a voice recorder after which a red outline appears around the note to indicate that they are recording audio (see Fig. 6). After expressing what they want to capture in the note they bring the note back towards their mouth again to end the recording. To play back their recording, they only need to shake the note while holding it. To take a picture they press the trigger button once to open the camera and again to take the picture. To delete a note, they throw it towards the ground.

3.4.3. Buttons Prototype

In the buttons prototype, we mapped buttons on the Oculus Quest 2 controller to certain interactions to enable users to make quick repetitive actions. In this prototype, users start recording audio by pressing the trigger button on the controller. A red outline appears on the note to indicate to them that they are recording. They are then able to say what they want to capture in the note and then press the trigger again to end the recording. To play back the recording they press the trigger again while holding the note.

Figure 6: Left: User of Embodied Notes using the gestures design brings the note close to their mouth to trigger audio recording. Right: audio recording is successfully triggered

To take a picture they press the A button on their right controller once to open the camera and again to take the picture. To delete a note, they press the B button on their right controller.

3.4.4. Raycasting Prototype

In the raycasting prototype, we created an action menu that floated above each note to enable users to interact with it. In this design, users do not need to remember any specific buttons. Users interact with notes using an action menu and a raycasting pointer (see Fig. 7). They open and close the action menu by pointing at the note and pressing the trigger. In the menu there are corresponding buttons for recording, taking a picture, playing back the note and deleting the note. Each of these buttons are triggered by pointing and pressing the trigger button.

4. User Study of Embodied Notes

We conducted a user study with 45 college students to investigate the following questions:

> RQ1: What are participants perceptions of the functionality and usability of Embodied Notes and how did they use it to support “thinking outside the brain”?

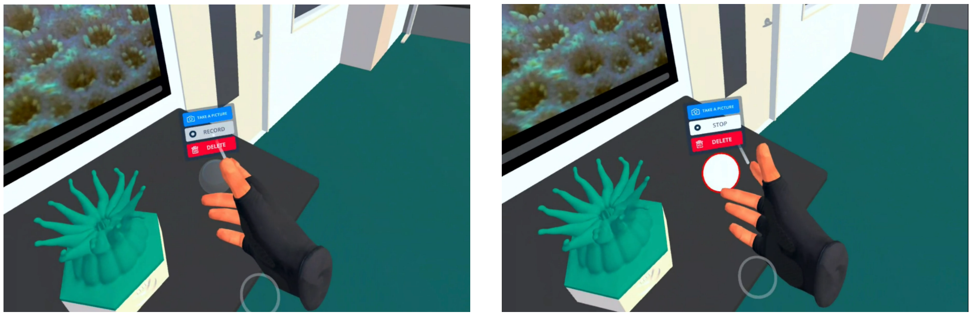


Figure 7: Left: User of Embodied Notes using the raycasting design to record audio. Coral polyp model from coralreef.noaa.gov. Right: audio recording successfully started

Figure 8: User of Embodied Notes reviewing a note they took

> RQ2: How does Embodied Notes influence cognitive load and learning perceptions during a learning session in VR?

4.1. Procedure

We recruited 45 college students (26 women, 15 men, 2 non-binary, 2 prefer not to disclose), age range between 18-36. Each student was placed randomly in one of 3 note interaction technique conditions: gestures (n=15), buttons (n=15), and raycasting (n=15). First, students were given a 10 minute training session on how to use the Oculus Quest 2 and the Embodied Notes system. Next, they were instructed to spend 30 minutes visiting the three learning stations described in Section 3.3 and to try to take at least 5 notes at each station. Once the 30 minutes were up or if the participant finished earlier, they were instructed to take some time to review their notes and to remove their headset once done. All first person interactions within the learning environment, apart from the training phase, were recorded for further analysis. After the learning phase, participants completed a post-task survey on Qualtrics which included a knowledge-test on the material they learned, and then a short interview about their experience using Embodied Notes. Participants were compensated with a $15 visa gift card.

4.2. Measures & Data Analysis

To answer RQ1, we analyzed the videos of students interacting with Embodied Notes using tags (see Table 1) to annotate note content, note type, interaction, review, storage arrangement and location, and time spent at each station. Four researchers completed the video analysis and inter-coder reliability was established based on 51% of the data with 82.65% agreement. We also collected subjective usability scores for each feature (Table 2) in the post-task survey and conducted semi-structured interviews with students afterwards to learn about their experience using the note-taking system. We conducted a thematic analysis (Braun and Clarke, 2012) to analyze the interviews, first identifying codes based on the interview questions and through iterative review of the content, collated the codes into 10 themes, which are shown in Table 3. Table 4 lists the questions we asked participants.

To answer RQ2 we administered a knowledge test on corals after the VR session and collected the following measures in the post-task survey from each student: cognitive load using Paas (Paas, 1992), subjective learning perceptions (Table 5), and subjective task difficulty.

Finally, to confirm that the interaction technique used does not have a significant effect on students' learning we collected the following additional measures in the post-task survey from each student: knowledge-test scores, work load using NASA-TLX (Hart and Staveland, 1988), spatial presence using MEC-SPQ (Vorderer et al., 2004), and system usability using the System Usability Scale (SUS) (Brooke, 1995). Knowledge-test scores, NASA-TLX, Paas, SUS, and MEC-SPQ were tested for statistical significance using one-way ANOVA and subjective learning perceptions, subjective task difficulty, and subjective feature usability were tested using the Kruskal-Wallis H test.

Table 1: Tags used in video analysis

Category	Tags
note content	3D model, accidental audio, accidental image, diagram, image, other, paraphrase, personal reflection, verbatim, text
note interaction	delete note, listen to note, look at note
note review	review by column, review by row, review by station, review randomly
note storage arrangement	cluster by station, rows, columns, unclear
note storage location	at staion, in notebook, near object
note type	audio, image, mixed
time	station 1, station 2, station 3, review

5. Findings

On average participants spent 31:47 minutes (SD=5:48) learning about corals at 3 different stations within the VR environment. They spent on average 6:53 minutes (SD=2:23) at station 1, 10:02 minutes (sD=3:15) at station 2, 10:45 minutes (SD=2:17) at station 3 and 4:00 minutes (SD=1:40) reviewing their notes at the end. After completing the learning tasks in VR, as part of the post-task survey, participants completed a 10 question knowledge-test to assess their knowledge of corals. The average knowledge-test score was 64.67% or 6.47/10 (SD=1.249). The lowest scoring participant scored a 3.5/10 and the highest scored a 9/10. The median score was a 6.5/10. In the following sections we describe how participants used Embodied Notes, their perceptions of how the note-taking system affected their learning, and post-task survey results.

5.1. How participants used Embodied Notes to support "thinking outside the brain" and their perceptions of its functionality and usability

To answer RQ1: What are participants' perceptions of the functionality and usability of Embodied Notes and how did they use it to support "thinking

Table 2: Feature Usability Questions

How difficult or easy was it to use each feature?
Recording a note
Deleting a note
Taking a picture
Playing back a recording
Storing a note in the notebook
Retrieving a note from the notebook

outside the brain?, we observed how participants used our research prototype, interviewed them about their experiences (Table 4), and had them complete a usability scoring (Table 2). In this section we describe how participants used Embodied Notes, including the type and contents of the notes they took. How they organized their notes in and outside of the provided notebook, their review process and their perception of the note-taking system's representation, utility and usability.

5.1.1. Types and Contents of Notes

On average, participants took a total of 17.93 (SD=4.58) notes which were a mix of audio, image, and mixed notes. More specifically, they took an average of 1.75 voice-notes (SD=1.90), 6.62 image notes (SD=5.89) and 9.55 mixed notes (SD=5.56). The average duration of audio and mixed notes was 11.9 seconds (SD=8.31). Participants took pictures of 3D models, diagrams, text and other images found at the different stations (see Fig. 9). They primarily paraphrased the learning content in their audio and mixed notes but some participants also recorded a personal reflection on what they learned. For example, P30 recorded a voice-note paraphrasing the content at station 2 and P14 tried to apply what they learned:

> *"So corals have a skeleton that's made up of carbonate called corallite, and then there are blades that exist within this corallite called septa, when these blades exit the coral they are called costae." (P30)*

> *"Okay this is the first coral. It appears that the corallite share a wall. It's like an off white-yellowish color. Yeah and the live*

Table 3: Themes and codes from interview analysis

Theme	**Codes**
Usability	ease of use for each feature, issues using each feature, unintended actions
Suggestions for Improvement	suggestions for improving each feature
Voice Recording	uncomfortable with voice, comments on voice, awkward to use around others
Note Representation	body placement, appreciated multi-modality
Note Interaction	body movement, confusion with hands, appreciated gestures
Learning Curve	learning curve, needing more practice
Perceptions	likes and dislikes of each feature
Learning Outcomes	encouraged thinking, mental load, helped learning, improved recall
Preferences	preferences for audio, writing, drawing; speech to text, labels
Organization	notebook organization, general organization

> *coral it looks pretty yellow and pretty big. And on the micro level you can see that each corallite has its own wall and then on the skeleton you can see it almost has like a spine-like thing going on inside." (P14)*

In interviews 12/45 participants expressed appreciating that the notes were multi-modal: *"I like how it is pretty simple in that you had like different options at once so taking a picture or a voice recording. I thought that was pretty useful" (P6).* However, they also expressed that they wanted additional ways to create notes. 12/45 participants preferred writing their notes and wanted a pen to write out their thoughts or to annotate the images they took. 4/45 wanted speech to text so that they could quickly skim the

Table 4: Post-Task Interview Questions

How was your experience using the note taking system?
Can you tell me 3 things you liked about the note-taking system?
Can you tell me 3 things you didn't like about the note-taking system?
How did using the note-taking system affect your learning experience?
How was your experience using the recording feature?
How was your experience using the play feature?
How was your experience using the picture feature?
How was your experience using the delete feature?
How was your experience using the notebook?

Table 5: Learning Perceptions Questions

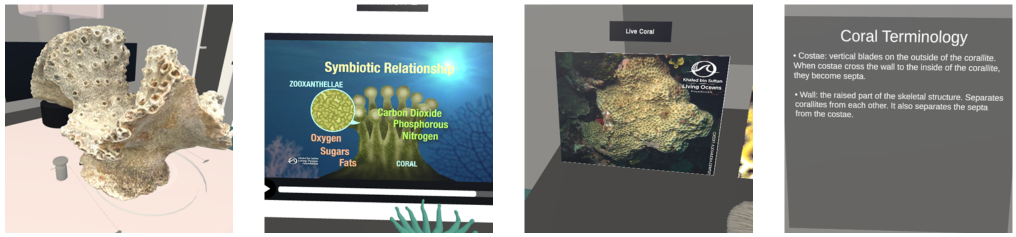
Using the note-taking system helped me understand the learning material.
Using the note-taking system helped me think more critically about the learning material.
Using the note-taking system disrupted my learning.
Using the note-taking system increased my learning.

contents of their notes without having to listen to the whole note over again and 7/45 wanted to be able to record video.

> *"I would like to be able to just write the notes down as well to summarize everything nicer" (P21)*

> *"Or maybe be able to highlight something within the picture that might have been more helpful because taking pictures it's good, but maybe you want to add your own idea to it" (P34)*

> *"I know I'm much faster reading than I am listening so going through the whole thing without the ability to scrub through the notes seems like it would slow me down a little bit, you know. So maybe just having like a scrubbing feature or like some live*



(a) (b) (c) (d)

Figure 9: Examples of pictures taken by participants: (a) 3D model (b) diagram (c) image (d) text

> *captioning doesn't have to be like fully accurate because I know I've recorded the notes would be super nice" (P30)*

> *"I wish I could record a video as a short clip instead of just a photo" (P40)*

5.1.2. Note Representation and Storage

5/45 participants mentioned the note representation as motivating for taking notes. According to P49: *"It looked like bubbles and I thought that was very cool. It made me want to use the note-taking system more"*. They found the preview useful for keeping track of different notes: *"I like the little thing that kind of showed you what the image that it contained was. It was a nice way of keeping track of what the things were that I was taking a picture of." (P7)*. They liked *"the accessibility of the notes on the left wrist" (P24)* and *"how my notebook was always there" (P49)*. 10/45 participants mentioned liking the physicality of the notes and notebook. P48 said: *"I like having the notebook and that it could be in the air and I could just grab it wherever and same thing with the notes."* and P19 mentioned *"It was just nice to grab onto it and then bring it closer and closer and farther and like kind of reality with that gap."* Especially because it allowed them to manipulate their notes in a physical way: *"Something that I did like is being able to kind of manipulate everything. That is something that when I'm in a piece of paper I cannot do it like I cannot take it out like from that. That's something interesting" (P34)*.

5.1.3. Organization of Notes

In the learning phase of the study participants stored and organized their notes spatially in multiple ways as they progressed through each station.

Within the notebook some participants (6/45) clustered their notes by station at certain times, some (42/45) used rows to group their notes, while others (8/45) did not seem to have a clear process for organizing their notes (Fig. 10). All participants placed notes into the notebook at some point, however, some participants (8/45) left notes in space at the station (Fig. 11) and only gathered them into the notebook when they were ready to move onto the next station. For example:

> *"I had a notebook, so I could just dump them all there, but at the same time I could also take a few of them out at the same time and just have them hanging in front of me, kind of floating in the air and review them one by one in a random order" (P32)*

5/45 participants expressed being able to spatially organize their notes as a positive:

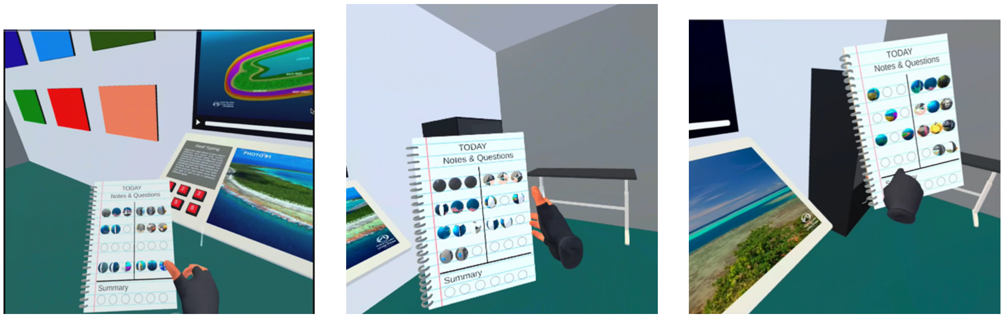
> *"It was kind of neat being able to sort of hang things around, especially as I got more comfortable with the note-taking process. It's kind of nice just to have this sort of room where you can just go full out like putting your notes in different places and kind of placing them so you can see them and kind of like have like a 360 view." (P41)*

At the end of the learning phase participants spent some time reviewing the notes they had taken. During this review time 14/45 participants reviewed their notes by row in the notebook, others by station (11/45 participants) and others had no clear review process (20/45 participants).

In interviews participants described some limitations they found while trying to organize their notes in their preferred way. They found the slots in the notebook for storing notes spaced too close together and expressed that they would have an easier time organizing notes if it was easier to grab the exact note they wanted and place it exactly where they wanted it:

> *"I wish it was easier to pick them, like put them back and take them out of the notebook more precisely." (P40)*

In the current design notes are labeled with a timestamp, however, some participants wanted to be able to color code and label their notes:



(a) (b) (c)

Figure 10: Examples of how participants organized their notes: (a) clustered by station: station 3 notes are clustered at the bottom away from station 1 and 2 notes (b) by row: notebook was filled row by row (c) unclear: notes on left side of notebook have no clear organization scheme

> *"I should be able to when I'm storing it, even just allocate a number, so I can remember. I think even tagging them would have been helpful" (P4).*

They also preferred to spatially organize their notes but may need guidance on how to do so:

> *"So you had like rows, but you had to remember what the rows were, but if I could like put my notes for video one over by video one, I put my notes for video two over by the video two and just have all these things arranged around me in a panorama. Which this has support for you, just you have to figure out how to do that yourself, like I think that's a much better interface, and I thought that was pretty neat once I figured that out." (P22).*

They wanted to define their own sections or ordering of the slots within the notebook:

> *"I wish there would have been more space because that way you could have like space them out. I like categories or things you know and if I had taken anymore notes I probably want more space of some sort." (P24)*

And finally, the ability to quickly find or index specific notes:

(a) (b)

Figure 11: Examples of participants storing notes in space until they have completed the station

> *"I think it's difficult to index it right like you don't know where you recorded something and you have to look into all of the recordings to find out what actually you recorded, right? So difficult if you have like 100 recording and you will not be able to find out where you are recording it right now, right? So I think indexing is one of the bigger problem here.*

5.1.4. Perceptions of System Feature Utility and Usability

For each feature of the system (see Fig. 12) we asked participants to rate it's usability on a 5 point Likert scale *"How difficult or easy was it to use each feature?"* (1-very difficult, 5-very easy). We also asked participants to elaborate on their experience using each feature during the interview. Here we describe quantitative and qualitative results by feature.

Learning Curve. 25/45 participants mentioned that the note-taking system had an initial learning curve, however with continued usage at each station they started to become more comfortable with the system. In the words of two participants:

> *"So I think the summarizing learning part by mouth it's pretty cool. I could see potential in that. I could see myself trying to learn this way more. I know I had trouble getting it down at first but it was relatively intuitive." (P21)*

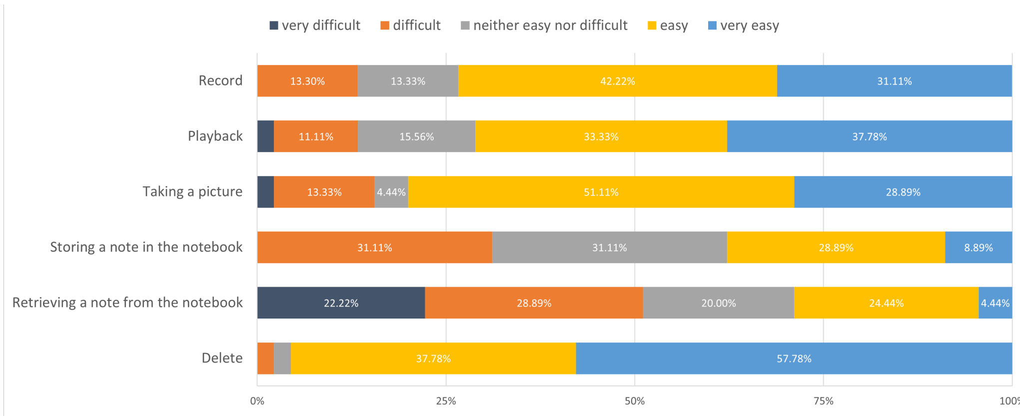


Figure 12: Feature usability ratings, "How difficult or easy was it to use each feature?"

> *"It was difficult to learn in the beginning, but I guess I got used to it after the first section." (P2)*

Audio Recording. The average usability rating for recording voice-notes was 4.02 (SD=1.06) and about 73% of participants found it easy and straightforward to use. Some difficulties participants experienced included having to listen to the video and trying to record audio at the same time and they wanted to be able to pause in the middle of recording to gather their thoughts:

> *"I feel like it's limited in that you have to repeat everything that you're hearing or seeing, and I feel like that sometimes sort of was a bit detrimental." (P44)*

> *"I feel like being able to sort of pause the recording and like resume it would be good, especially if I'm like collecting my thoughts for like a test or recording." (P41)*

Also, being able to have multiple recording in one note:

> *"I felt like I wanted to be able to like blow it up look at the picture and maybe add a recording on top of the recording that I'd already captured." (P3)*

Audio Playback. The average usability rating for playing back voice-notes was 3.89 (SD=1.07) and 78% of participants reported that the playback feature was easy to use. Some participants, however, had issues with the playback being choppy but still found it usable:

> *"There were issues with the choppy audio playback, but that didn't affect what I actually said, my comprehension." (P42)*

One improvement participants suggested was the ability to adjust playback speed:

> *"I watch all of my YouTube on like two times speed and, at least for like some of the notes, I know that I had a gap between some of the information I wanted to say, and so if I was able to listen back quicker or slow down. Or, just like be able to tune it so it's closer to my preference I think would be also be helpful" (P18).*

Many participants (16/45) found the act of recording voice-notes and listening back to them uncomfortable. For example, P45 and P7 said:

> *"I felt a little awkward recording my voice and listening back to it" (P45)*

> *"At points, it was embarrassing just listening to my own voice and how like ridiculous I was being" (P7).*

Taking a Photo. The average usability rating for taking a photo was 4.13 (SD=1.14), almost 80% of participants found it easy to take a picture as part of their note. The main difficulty participants had were that the picture was too small and sometimes blurry so it was difficult to read any text in the picture:

> *"I think the pictures when you look at them again are very small, so it's hard to look at details if that's what you're trying to capture." (P29)*

Some suggestions for improvements participants expressed were making the picture sharper, zoomable, re-sizable and the ability to associate multiple pictures with one note.

Notebook. The average usability rating for storing notes in the notebook was 3.36 (SD=1.21) and only about 38% of participants found it easy to use while 31% found it difficult. For retrieving notes from the notebook the average usability was 2.80 (SD=1.47) and only about 28% of participants found it easy to use. In interviews, 14/45 participants mentioned the notebook being easy to use and useful. In the words of one participant:

> *"I like being able to place it somewhere and then carry it with me, that was nice." (P7).*

22/45 participants had difficulty with retrieving notes out of the notebook:

> *"I like managing the notes. The one exception was sometimes it's hard to grab a specific note on the notebook but other than that I thought, it was aesthetically really cool and I thought it was useful because I think it did help me on the quiz." (P9)*

Areas for improvement included having more slots/pages in the notebook for organizing notes, the ability to add labels, and more spacing between notes for precise grabbing.

Delete. The average usability rating for deleting notes was 4.31 (SD=0.63), about 95% of participants found the delete feature easy to use.

5.2. How Embodied Notes influenced cognitive load and learning perceptions during learning in VR

To address RQ2: How does Embodied Notes influence cognitive load and learning perceptions during learning in VR?, we examine cognitive load and learning perceptions post-task survey results contextualized with participants perceptions of their learning process while using Embodied Notes from interviews.

5.2.1. Cognitive Load of using Embodied Notes

In the post-task survey we asked participants *"How difficult or easy did you find learning about corals?"* using a 5 point Likert scale (1-very difficult, 5-very easy) to measure perceived task difficulty. 40% (18/45) of participants found the task easy and 22.2% (10/45) found it difficult (see Fig. 13).

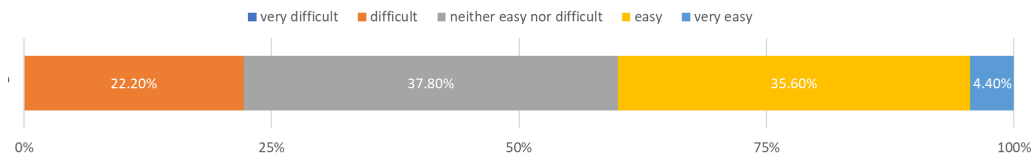


Figure 13: Task difficulty ratings, "How difficult or easy did you find learning about corals?"

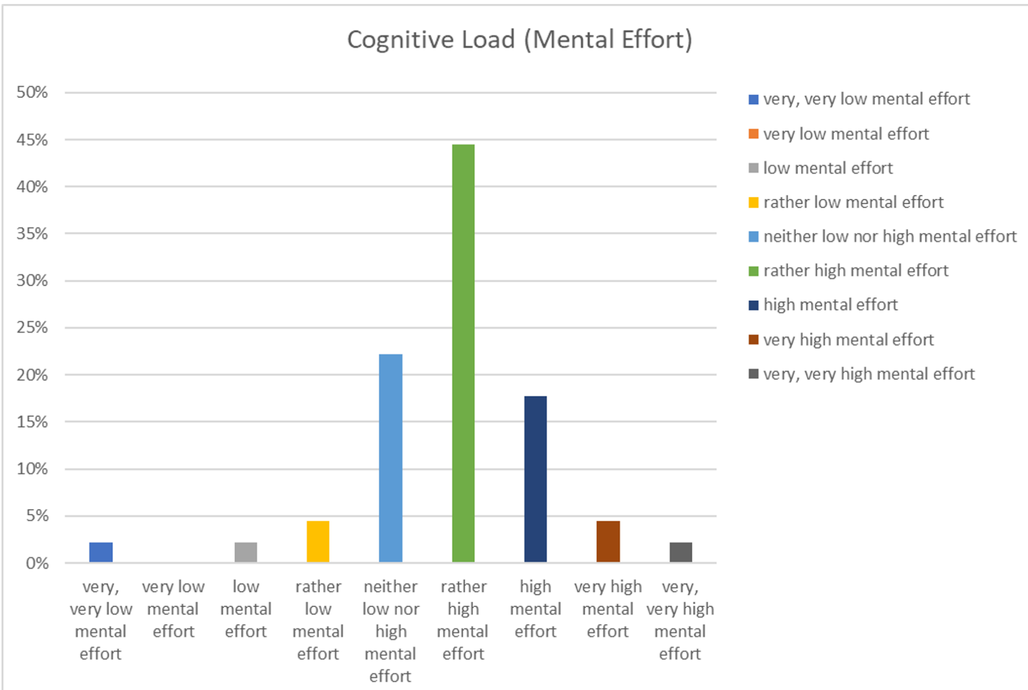


Figure 14: Cognitive load ratings, "In learning about coral reefs using VR, I invested..."

We also measured the cognitive load (mental effort) required to use the system to learn using Paas. The mean Paas score was 5.84/9, almost 45% of participants reported investing rather high mental effort (see Fig. 14).

6/45 participants reported that they expended more mental effort taking notes than learning the content. In the words of one participant:

> *"I would have to take them out of notebook and put them in the notebook and just do all this stuff to manipulate them and it felt like I was doing a lot more work to manipulate the notes then I*

was like actually thinking about the content of notes." (P22)

However, 15/45 participants reported the act of note-taking made them feel more active and engaged in the learning process:

> *"I think it really pushed me to learn, I mean, to the extent that it was discomforting, not discomforting enough in a physical sense, but in the mental strain of having to pay attention. And I think I can say that's overall a good thing." (P42)*

5.2.2. Learning Perceptions

We asked participants 4 questions (Table 5) about their subjective perceptions of their own learning on a 5 point Likert scale (1-strongly disagree, 5-strongly agree).

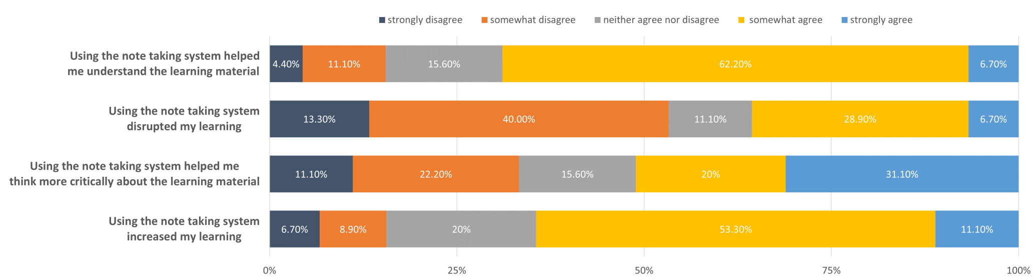


Figure 15: Learning Perceptions

68.9% (31/45) of participants agreed that *"Using the note-taking system helped me understand the learning material"* (see Fig. 15). Multiple participants (10/45) mentioned that having to vocalize what they learned at each station helped reinforce their understanding of what they were learning because they needed to understand what they heard or read to create coherent voice-notes that would be useful later. For example:

> *"I think it was good in that I was able to talk my thoughts out or kind of paraphrase the source material in a way that would be a bit more easier to understand for me." (P27)*

53.3% (24/45) disagreed that *"Using the note-taking system disrupted my learning"*. Some participants found the addition of a note-taking system important for motivating them to learn while others found that having to juggle the note-taking and learning at the same time caused them to focus less on the learning content. In the words of two different participants:

"I think without doing note-taking system, I would just be looking and like not thinking about the content." (P19)

"It definitely worked. I mean at the end when I was reviewing I'm able to like review all the stuff, especially when I was actually like going through the materials I think a lot of my attention goes to how to take pictures or when to take pictures, and I wasn't really learning the content. It was not until the very last when I was trying to like review the notes that I could finally understand, oh, what does it mean." (P33)

51.1% (23/45) of participants agreed that *"Using the note-taking system helped me think more critically about the learning material"*. In the words of one participant:

"I had to be far more active. I think usually when I take notes I'm very passive about it. But now that, maybe it's just because I had to put stuff into little sockets. It made me actively think about what is it that I really want to put in here and like recall at a later time rather than having something unstructured and text. I think it adds structure to say the least" (P30).

Finally, 64.4% (29/45) of participants agreed that *"Using the note-taking system increased my learning"*. For example:

"I think it actually forced me to like go back and look at previous slides to make sure that I knew what I was talking about. And if I didn't have to take notes I probably would just like have breezed through it and then just forgotten something. But I feel like I actually learned something and like what I was saying about the corals, I had no clue why it was important that the reef was destroyed, but now I know why." (P48)

Multiple participants also mentioned how the note-taking system activated their spatial memory, helping them learn:

"At points, it was embarrassing just listening to my own voice and how like ridiculous I was being. On the other hand, like at the end it was helpful. And it kind of was helpful because it also helped to queue me back to where I was learning that stuff." (P7)

"And when I'm reviewing the notes, when I hear myself speaking it, I can immediately think of what I was looking at. It's just more helpful that I hear my own voice" (P20).

5.3. Comparing Gestures, Buttons, and Raycasting Interaction Techniques

We did not find a statistically significant difference between interaction groups as determined by one-way ANOVA (see Table 6) for knowledge-test scores, system usability scores, spatial presence (MEC-SPQ), and mental effort (Paas). For raw NASA-TLX mean scores in relation to using the note-taking system and learning about corals we did not find a statistically significant difference between groups as determined by one-way ANOVA. However, we did find a statistically significant difference between groups for the Effort subscale of the NASA TLX for note-taking as determined by one-way ANOVA ($F(2, 42) = 3.882$, $p = .028$). Post-hoc tests (Tukey) show that participants in the gestures condition felt they exerted less effort than participants using raycasting when taking notes.

We also did not find a statistically significant difference for task difficulty between interaction groups using a Kruskal Wallis H test (see Table 7). For each of the main 6 features (record, delete, play, picture, store, retrieve) we asked participants on a 5 point Likert scale (1-very difficult, 5-very easy) *"How difficult or easy was it to use each feature?"*. We only found found a statistically significant difference in feature usability for retrieving notes from the notebook using a Kruskal-Wallis H test ($H(2) = 757$, $p = .023$) (see Table 7). A post-hoc pairwise comparisons test shows that participants in the buttons condition reported significantly different feature usability scores for retrieving notes from the notebook than those in the gestures condition ($p = 0.013$) and raycasting condition ($p = 0.024$).

6. Discussion

In the previous sections, we introduced the concept of Embodied Notes and reported the results of a user study with 45 college students using it within a VR learning environment to learn about corals. Our findings have shown that: 1) students were able to successfully use Embodied Notes to support their learning by externalizing their thoughts into image and voice-notes, arranging the notes spatially, and reviewing them (RQ1); 2) more than 50% of students reported that using Embodied notes helped them understand and think more critically about the learning material and almost

Table 6: Means, Standard Deviations, and One-Way Analyses of Variance for study measures

One-Way ANOVA Results

Measure	Gestures		Buttons		Raycasting		F(2,42)	p-value
	Mean	SD	Mean	SD	Mean	SD		
Knowledge Test	63.67	13.29	65.67	11.63	64.67	13.29	0.09	0.912
Mental Effort (Paas)	5.73	1.79	5.67	0.90	6.13	1.13	0.54	0.585
System Usability Score (SUS)	66.17	15.23	59.00	19.61	60.33	16.55	0.73	0.486
MEC-SPQ								
— Attention Allocation	3.80	0.81	3.75	0.71	4.08	0.98	0.69	0.510
— Spatial Situation Model	4.05	0.53	3.95	0.59	4.15	0.61	0.45	0.641
— Spatial Presence: Self Location	3.75	0.91	3.88	0.54	4.18	0.77	1.30	0.282
— Spatial Presence: Possible Actions	3.72	0.81	3.72	0.53	3.98	0.62	0.81	0.451
— Higher Cognitive Involvement	3.43	0.53	3.52	0.67	3.58	0.62	0.23	0.798
— Suspension of Disbelief	3.02	0.89	3.30	0.81	3.38	0.95	0.70	0.502
NASA-TLX note-taking	38.63	11.51	44.63	16.77	49.22	11.69	2.31	0.112
— Mental Demand	42.73	24.13	42.27	26.29	42.60	16.33	0.00	0.998
— Physical Demand	25.20	18.89	31.47	27.38	35.47	27.23	0.65	0.526
— Temporal Demand	24.53	23.64	29.00	18.79	40.93	26.77	1.99	0.150
— Performance	73.87	22.84	71.93	18.52	70.47	16.93	0.11	0.893
— Effort	42.00	15.72	54.00	22.80	60.80	16.83	3.88	0.028**
— Frustration	23.47	21.73	39.13	31.88	45.07	30.69	2.31	0.112
NASA-TLX learning	37.01	11.65	38.74	11.85	46.03	13.32	2.28	0.115
— Mental Demand	47.00	26.04	41.80	19.65	48.80	20.64	0.40	0.673
— Physical Demand	25.53	19.07	21.21	23.15	33.73	24.11	1.20	0.312
— Temporal Demand	21.33	21.66	25.20	21.50	34.40	26.44	1.24	0.299
— Performance	67.60	23.44	64.33	18.28	65.60	18.97	0.10	0.907
— Effort	41.27	26.14	49.33	13.81	55.73	20.14	1.85	0.170
— Frustration	19.33	24.16	29.00	24.73	37.93	30.65	1.83	0.174

Note: $**p < .05$

45% invested rather high mental effort when learning about corals (RQ2); and 3) Embodied Notes supports learning, independent of interaction technique.

Table 7: Kruskal Wallis H test results for study measures

Measure	H(2)	p-value
Task Difficulty	4.14	0.126
Learning Perceptions		
— Helped understanding	0.21	0.901
— Disrupted learning	2.27	0.322
— Think critically	1.15	0.563
— Increased learning	0.13	0.938
Feature Usability		
— Record	0.15	0.927
— Delete	4.85	0.089
— Taking a picture	3.87	0.144
— Playback	3.42	0.181
— Store in notebook	0.35	0.840
— Retrieve from notebook	7.57	0.023**

Note: $**p < .05$

In the following sections we discuss our findings and their implications for the design of future VR note-taking tools.

6.1. Embodied Notes' usability

All participants were able to successfully use Embodied Notes to take a variety of notes independent of interaction technique. Most participants expressed that there was a substantial learning curve for using the system but once they used it at the first learning station it became easier. This finding is consistent with our exploratory study where scientists reported steep learning curve for working in VR (Olaosebikan et al., 2022b). We anticipate that as the use of VR applications increase, more users will become familiar with interaction in VR, which will, in turn, reduce the learning curve for note-taking tools and increase efficiency of note-taking.

On average participants created more mixed-notes than audio or image only notes. The visual cue that the images provided reminded participants about *what* they were learning and *where* that learning took place, activating their spatial memory which has been found to be helpful for learning (Scarr et al., 2013). This extra step of externalizing their thoughts seemed to contribute to further solidify their knowledge. We found that participants also wanted to be able to to write notes and record video which suggests that future work should explore additional modalities for note-taking.

The physical (spherical) and playful nature of the notes encouraged participants to take more notes than required. Other form factors that have been explored in prior work include virtual notepads (Poupyrev et al., 1998; Clergeaud and Guitton, 2017; Chen et al., 2019) and sticky notes (Lee et al., 2021). Future work might explore new form factors such as different shapes (e.g. spheres, cubes), sizes and colors and compare its effectiveness in supporting learning. Participants also attempted to organize and cluster the notes in different ways and appreciated the flexibility of having notes that could be shuffled around compared to a linear page in a physical notebook. However, the limited nature of our notebook sometimes got in the way of a participants preferred organizing practice. Recent work has explored spatial organization strategies for sense-making (Luo et al., 2022; Liu et al., 2022) and using wearables for organization (Simonson, 2021). Future work could further investigate effective strategies for spatial placement and organization of notes in VR.

Most participants found the audio recording, playback, and picture taking functionality easy to use. In interviews our participants remarked that they had to juggle between watching the video, remembering what they wanted to record and pausing the video to do so. Prior work on digital note-taking has explored using gaze to assist note-taking when watching a lecture video on a desktop computer (Nguyen and Liu, 2016). Future work could explore if using gaze to automatically pause, play and modify the playback speed of a video (Nguyen and Liu, 2016) could prove beneficial for note-taking in VR.

Another issue we discovered is that the resulting images were sometimes blurry or difficult to read if they contained text. This could be improved in future versions by enabling users to physically zoom in or stretch the images for better viewing, such object resizing interactions are feasible and have been implemented in prior research (Lucas et al., 2005).

Overall, participants found Embodied Notes easy to use and highlighted ways for expanding its functionality to better match existing workflows and improve usability. More research is needed to explore how usage patterns might change over time.

6.2. Embodied Notes' influence on cognitive load and learning perceptions

Many participants reported that note-taking took "rather high mental effort". Prior studies show that note-taking has some cognitive overhead associated with it (Jansen et al., 2017). However, this added cognitive load could be seen as beneficial because it forced participants to think more deeply about what they were learning in order to take good notes that would be useful later. Prior work on the influence of cognitive load on learning outcomes in VR environments has shown that it positively predicts learning satisfaction (Huang et al., 2020). Some participants commented that the extra mental effort of taking notes made them more active and engaged in the learning process. This suggests that adding some friction to the learning process could make users more active participants in the learning process.

Despite reporting that hearing back their own recorded voice was uncomfortable, a known phenomenon called voice confrontation (Weston and Rousey, 1970), several participants reported that vocalizing their thoughts using the voice note feature helped reinforce the learning content and proved beneficial when reviewing their notes at the end of the learning exercises. This suggests that the act of self-explanation induced by using our note-taking system was helpful for their learning (Chi et al., 1994, 1989). Prior research has also shown that non-linear note-taking (e.g. graphs and concept maps) can enable learners to gain a deeper understanding of the learning material and increase their academic performance (Makany et al., 2009). Future work might explore extending Embodied Notes to enable non-linear note-taking through annotations and links between notes to improve learning outcomes.

More than 50% of participants expressed that using the note-taking system encouraged them to think critically about the learning material presented to them and that using it increased their learning. They commented that they might not have learned as much if they had not been asked to take notes. Prior research has shown that people who take notes retain more information in organic memory (Kalnikaitŏ and Whittaker; Kalnikaité and Whittaker, 2008) and interventions in students' note-taking processes can increase the the benefits of note-taking (Kobayashi, 2006). Future VR learning environments might consider not only providing note-taking functionality but also actively encouraging its use.

In the next section we detail design considerations for researchers and practitioners designing future VR note-taking tools.

6.3. Design Considerations

Based on our findings we identify several design considerations for future VR note-taking tools.

Incorporate flexibility & delight to encourage note-taking. Designers should consider adding an element of fun and delight into the act of note-taking to encourage students to take more notes. In our study we found that participants had unique ways they wanted to arrange their notes but still appreciated the structure the notebook gave them. Future systems should consider allowing more flexibility for arranging notes while still providing some structure.

Leverage multiple modalities and consider user comfort. Most participants in our study valued being able to take audio and image notes to support their learning. Future tools, should consider leveraging multi sensory cues, allowing users to benefit from visual, spatial, tactile and kinesthetic cues when encoding and recalling information (Quak et al., 2015). Future tools could also consider exploring the potential of using synthetic voices when retrieving notes when compared to listening to one's own voice and support further means for external representation such as free-form gesture-based sketching and writing. Such means were requested by users as well as found in the literature to further support learning (Tversky, 2018).

Balance cognitive load. Participants in our study reported that using Embodied Notes required "rather high mental effort" and 46.7% reported that using the note-taking system disrupted their learning. This suggests that to take notes the participants had to actively think about taking notes and how to use the note-taking system, potentially losing their train of thought. Future work should consider giving participants more time to familiarize themselves with the tool to lessen this. Future tool designers should also carefully consider the need to balance the cognitive load introduced by using the tool and the cognitive load needed to induce learning.

Incorporate multiple interaction techniques to decrease learning curve. Many participants reported using our system had a learning curve. Previous studies indicated that virtual reality applications for remote meeting and collaboration still pose a steep learning curve (Olaosebikan et al., 2022b). Since we found no difference in how interaction techniques affects learning, designers should consider incorporating multiple interaction techniques to provide options for users, and can incorporate Embodied Notes in different VR platforms. Enabling users to choose their preferred interaction technique could decrease the learning curve and let the controls fade into the background while learning and discovery come to the forefront.

6.4. Limitations and Future Work

One limitation of our study is that we observed participants complete a short learning module during a limited time span (about 30 minutes). More research is needed to explore how using Embodied Notes over time affects learning outcomes. We plan to integrate the system into a college course in the future to study its longitudinal usage and impact. Another limitation is that as a research prototype there is still much room for improvement in terms of the user experience of taking notes. Future work should also explore the use of this system in the context of *collaborative* learning and sense making.

7. Conclusion

We presented the design of a Embodied Notes - a new system for multimodal note-taking in VR. We also presented findings from a user study of 45 students using Embodied Notes during a learning activity in VR. We found that all participants were able to use the system to successfully learn about a new science topic - corals. Based on our findings we suggest that future tools for note-taking in VR should: enable flexible spatial note organization while also providing structure for storing notes, strike a balance between the cognitive load required for using the tool and learning, provide multiple modalities to engage learners and support information coding, and incorporate multiple interaction techniques to decrease the learning curve and increase efficiency.

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