DigiGlo: Exploring the Palm as an Input and Display Mechanism through Digital Gloves

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Figure 1: *Space Traveller*, *Marble Runner*, *Noelle's Ark*: Three activities that use the palm of the hand as both input and display.

ABSTRACT

The shape and function of the human hand are intimately linked to our interaction with the physical world and sets us apart from our evolutionary ancestors. In the digital age, our hands still represent our main form of interaction. We use our hands to operate keyboards, mice, trackpads, and game controllers. This modality, however, separates content display and interaction. In this paper, we present Digital Gloves (***DigiGlo***), a system designed to evaluate the benefits of a unified hand display and interaction system. We explore this symbiosis in the context of gaming where users control games using hand gestures while the content is displayed on their bare hand. Building on established learning principles, we explore different hand gestures and other specially tailored interactions, through three carefully designed activities and two user studies. From these we show that this is an idea that has the potential to bring more intuitive, enjoyable, and effective gaming and learning experiences, and offer recommendations regarding how to better design such systems.

CCS CONCEPTS

• **Human-centered computing** → *Mixed / augmented reality*; **Virtual reality**; **Empirical studies in HCI**; **Gestural input**; **Interaction design theory, concepts and paradigms**.

KEYWORDS

virtual reality; games; hand gestures; embodiment; split-attention

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1 INTRODUCTION

Augmented Reality (AR) and Virtual Reality (VR) have received much interest in recent years, experiencing significant advancements [8]. They have been successfully employed for a wide variety of entertainment, teleconferencing, medical rehabilitation, sports, and gaming purposes, among others [41]. Immersive environments can lead to more entertaining and engaging experiences, where VR, compared to AR, provides a more immersive experience, but more discomfort and disturbance at the same time [10]. Furthermore, it has been shown that these technologies can potentially lead to games that provide more effective learning experiences [1], and faster and better medical rehabilitation [30].

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Along with, and in part due to, these advancements, visual tracking algorithms have also seen countless breakthroughs, mostly thanks to deep learning. It is feasible nowadays to track one's facial landmarks [11], body pose [42], or hand configuration [6] in real-time using modest equipment. Combining immersive and tracking technologies offers exciting new mechanisms to engage with the user. On the one hand, various poses and expressions can be identified, and used as a means of communication for the user, offering more intuitive control and language [37]. On the other hand, accurate and fast positioning can be exploited for visual augmentation and immersive game-play.

In this paper, we present Digital Gloves (***DigiGlo***) — a system through which we examine the symbiosis of hand input and hand display, and provide an encouraging basis to develop this approach further. In the explored setting, our most instrumental organ for interaction with the environment [47] is used both as input **and** display. Hands have been used to control games since the Microsoft Kinect, and other parts of our body, the face, for example, have been used as displays before [19]. However, to the best knowledge of the authors, no game has been developed that uses the palm of a hand both to depict the game and to control it.

We argue that the setting explored by ***DigiGlo*** has several advantages, and have designed activities, shown in Figure 1, to evaluate them. In addition to the novelty of the proposed gaming mechanism, these games examine three main advantages:

Intuitive Control. As the system parses raw hand motion, one can move the hand naturally. For example, when trying to move an object in the game, the player fully and naturally understands the expected end position of the moved object.

Split Attention. Typically, when using the hands for control, the user's gestures control effects that are seen somewhere else in the virtual world, forcing the user to look at the target, without observing the actual motion performed by the hand. This phenomenon is called *split-attention*, which has been shown in the past to impair concentration [43]. Seeing the game content on the hand, which also controls it, alleviates this problem.

Embodiment. It is well known that learners respond differently and more effectively to movements and bodily interaction, compared to only seeing and listening [27]. These concepts can be easily exploited for the design of educational games that portray objects on the player's hands, requiring some physical interaction.

To demonstrate the value and potential of a unified hand input and display system, we have designed three playful activities, described in detail in Section 3: *Space Traveller* examines the intuitive control offered by the setup, *Marble Runner* addresses split attention, and *Noelle's Ark* utilizes the concept of embodiment.

In this work, we focus on a VR implementation of ***DigiGlo***, as depicted in Figure 2a, where the user is wearing a VR head mounted display (HMD) to experience the activities. The activities however are equally appropriate for an AR setting, or more specifically for Spatial Augmented Reality (SAR), such as shown in Figure 2b. In SAR, digital content is laid over a real-world environment using projector-based illumination. This scenario has several advantages

(a) (b)

Figure 2: Concept art for *DigiGlo* depicting different settings. (a) Virtual reality setting. (b) Spatial augmented reality setting.

over traditional VR. These include a more natural, nauseous-free integration of the digital and physical worlds, the lack of equipment worn by the user, and user-friendliness for developmental or clinical populations. Using SAR on humans in entertainment has unquestionable advantages, and has been used in famous shows, such as *Lady Gaga's Tribute Performance* [5], Disney's *Frozen on Ice* [44], and others [2]. Employing SAR for unknown moving surfaces, such as hands, is challenging. As such, a system able to perform this task for novel performances of hands does not exist, as far as the authors are aware of. That said, research in the field has already proven this to be possible for other scenarios, such as facial performances [4], and clothing deformations [34]. We therefore believe that a system for projection on hands can indeed be developed. For this reason, we have designed our activities to display only flat content on the palm itself and consider this research to also provide motivation for developing such a system.

Through our three activities, we have evaluated the potential benefits of this interaction mechanism and the potential benefits of ***DigiGlo***. We have conducted a preliminary usability study using one of the activities, followed by another study that included all activities, and in-depth interviews. The latter has been done on a smaller scale due to the current world-wide emergency situation. Through these studies, we observe high acceptance of the mechanism by novice and experienced users alike and drew a set of recommendations that should be considered when designing the next system, or applications for it. Finally, we believe that introducing this concept to the gaming world could be quite impactful, and that this work poses as enough motivation for developing the aforementioned SAR system.

2 RELATED WORK

DigiGlo builds upon several key components: a theoretical foundation upon which we base our conjecture that the proposed system is beneficial, the concept of hands as an input mechanism, and the concept of hands (or other body parts) as display. In the following, we address the state-of-the-art for each of these components.

2.1 Embodiment

For thousands of years, human beings have been interacting and exploring the world relying mostly on their perceptual and motor systems. Still, nowadays, the human body plays an important role in how we perceive and communicate with the environment. In the field of cognitive science, *embodiment* refers to "the understanding of the role of one's own body in everyday, situated cognition" [17].

Hands, in particular, are a crucial tool for supporting cognition and communication: we use our hands to learn how to count, we support speech with hand gestures. Howison et al. [21] showed that students managed to grow their understanding of proportions and even adopted the linguistic cues of mathematical discourse through gesturing different ratios with their hands.

Meaningful hand gestures have also proven to be helpful for learning more abstract content. Nathan et al. [35] implement a video game teaching students a set of gestures supporting mathematical proofs. This game helped students grow a deeper understanding of proofs, and helped them ground their mathematical speech in hand gestures.

Similarly, Kirsh describes how the theory of embodiment can improve HCI designs [27]. He observes that performing hand gestures to encode a dance phrase can improve dancers' performance more than just watching the phrase, and even more than only practicing the phrase with their full body.

The body can also be used to support play or even be experienced as play. Mueller et al. suggest considering two perspectives: the *Körper*, the material, physical, objectified body, and the *Leib*, the living body, the body that one experiences as oneself [33]. Mueller et al. elaborate on the example of designing a validation button. From the *Körper* perspective, a designer would place the button close to the average location of the hands of the user, that is, at the bottom of the display. However, when adopting a *Leib* perspective, the designer would consider that raising arms in the air is a pose with a positive connotation and would place the button at the top of the display.

Technology can support *embodiment* of different degrees, along three variables: motoric engagement, gestural congruency, and immersion [24, 45]. This continuum of experiences begins with simply staring at a small screen and extends to full-body engagement in a VR or AR environment.

From the perspective of the user, different mechanisms support the sense of *embodiment* in VR [26]. First, the sense of self-location: the sense of being physically located within the virtual body. Second, the sense of agency: the sense of controlling the virtual body and generating the actions of the body. Third, the sense of body ownership: the sense that the body is the origin of the experienced sensations.

Reducing physical disparities between the virtual body and the physical body is an important aspect of the sense of *embodiment* as it supports the sense of self-location. But this also has importance for cognition. The split-attention effect occurs when one tries to learn while needing to pay attention to two or more sources of information, either spatially or temporally [32]. This effect can impair learning, and hence reconnecting the information sources, both spatially and temporally, is advised [43].

DigiGlo offers exactly this connection. Displaying the content on the controlling hand places the information at the same spatial point, and lets the users see their own movement along with their effects, thus supporting the sense of *embodiment* and eliminating split-attention effects. As specified below, we hypothesize that this advantage has a significant impact on usability.

Moreover, we predict that users will have a more engaging experience when using gestures that are as meaningful as possible physically. This is most evident in the activities *Noelle's Ark*, where the hands imitate the twin-pan-balance device, and with *Marble Runner*, where the physical position of the hand emulates the same position in the virtual world.

2.2 Control and Hand Gestures

The mode of interaction between humans and computers is mainly dictated by technology. For decades the predominant form is a keyboard and a mouse. However, technological advancements have made the interaction less restrictive, with examples such as the Wiimote controller [15], or the more recent vision-based tracking from a monocular camera [6]. These advancements make the interaction through hand gestures more *natural* [12] and engaging [29]. Since the release of the Leap Motion sensor, much work has been focusing on evaluating the merits this technology can have on human-computer interactions. Studies have demonstrated that the interactiveness of hand gestures relies on accuracy [31], and has the potential to enhance the learning of sign languages [38], to help with rehabilitating stroke patients [25], and even to improve shopping experiences [12]. Piumsomboon et al. [37], for instance, constructed a set of usable gestures using an elicitation survey [37], and recommend using these for AR design. None of these works, however, have looked into the gestures' usability when a split-attention effect is not present. This is in contrast to our studies, which evaluate similar gestures but eliminate the confounding factor of split-attention.

In the context of gaming, Pirker et al. [36] provide evidence of higher levels of engagement when using hand gestures, but point out that this mode of interaction induces exhaustion. Khademi et al. [25] demonstrated that turning a physical task into a hand gesture game can motivate stroke patients to faster rehabilitation, and Silva et al. [40] have shown that the Leap Motion is a powerful tool to simulate musical instruments [40].

During our study, we have witnessed similar reactions in terms of high engagement at the cost of more bodily stress. Moreover, we similarly look at gestures that represent a physical metaphor, but we find added value in the fact that these gestures are aligned with the content displayed on the controlling hand.

2.3 Projection Mapping and Body Display

Digital playful activities are not restricted to screens. Mapping the activity's content onto physical objects makes the activity more tangible and allows us to create novel gaming experiences.

With *Inner Garden*, Roo et al. [39] show how projection mapping can turn a simple physical sandbox into a meditative environment to achieve a state of mindfulness and focus on one's body. Following up on this work, the *VRBox* system makes use of VR to provide new interactive capabilities to the sandbox user, and demonstrates how these support playfulness and creativity [14]. In both examples, the added value is created by letting users physically interact with the display, i.e. with the sandbox, using their hands. ***DigiGlo*** further improves the interactivity by mapping the display directly on the users' hands.

Mapping digital content to the body is not new. *Body display* is the concept of displaying virtual content on the player's body, for example, using VR or SAR. Bermano et al. [4] use the user's face as both controls and display to achieve real-time digital make-up. The position as well as the facial expression is captured allowing the system to simultaneously adjust the rendered graphics and project them back onto the player's face. The novelty of this work lies in the low latency achieved and the fact that the system does not require facial tracking markers. This enables a range of new possibilities.

Similarly, Hieda et al. [19] present *SharedFace*, a system enabling users to digitally draw on their faces using only their hands. This system uses the face as a deformable display and the hands as controls. Even though the system was tested with hundreds of users, this work does not include results regarding users' perception and enjoyment.

Only limited work exploring *Body Display* for gaming and education exists, and to the extent of our knowledge, mapping digital content onto the palm of the hand has not been explored yet.

3 SYSTEM AND ACTIVITIES

In this section, we present the design and implementation of ***DigiGlo***, including its three playful activities, *Space Traveller*, *Marble Runner*, and *Noelle's Ark*. These activities are designed to explore different aspects of our system. *Space Traveller* exploits the fact that the display is hand-shaped in a self-contained experience. *Marble Runner* is interested in the hand as a controller to explore the world, resulting in our view-port metaphor. *Noelle's Ark* focuses on embodiment for education, using the whole upper-body as a metaphor for a twin-plate balance. For each activity, we chose gestures following guidelines from the literature and exploiting our hand input-display mechanism when possible. The gestures were then refined through iterative processes with users.

3.1 System

We employ an off-the-shelf hand tracker (Leap Motion sensor) for game control and a VR HMD (HTC Vive) for display. The Leap Motion sensor is attached to the VR headset, a configuration that comes pre-calibrated with the hardware. We implemented all the activities using the Unity game engine.

As mentioned in Section 1, we have designed ***DigiGlo*** to be compatible with a potential SAR setup as well, in order to assess its potential utility. For this reason, our content is presented only on the surface of the virtual palm, and the chosen color schemes are of high contrast. In the following, we present the different activities implemented for ***DigiGlo***.

Figure 3: *Space Traveller* game visuals. (a) Sample level showing the player's ship with a trail, green fuel containers, blue bumpers, and wire-framed asteroids. (b) Hyperspace jump, the transition between two levels.

3.2 Space Traveller

Space Traveller is a pinball game on a hand-shaped playfield. The purpose of this implementation is to tie custom control gestures to the game setting. Through these controls, we demonstrate how using the palm as the display can naturally give intuition to complex movements, and how to avoid triggering a spatial split-attention effect.

3.2.1 Narrative. The player steers a spaceship to explore the broad expanses of the universe. The journey is dangerous and requires a lot of fuel. Therefore, the player must collect all fuel containers while avoiding asteroids and wormholes to trigger the next hyperspace jump, which starts the next game level.

3.2.2 Goal. This game uses a score-based objective. Collecting one fuel container awards one point while hitting an asteroid removes one point. The game ends when five ships are lost, or when the player completes the eighth, final level.

The levels are designed such that all the fuels can be collected in one hit of the flippers in order to inspire the players to think the levels through and grow a sense of mastery. The levels become increasingly difficult, starting by demonstrating each game mechanic and then combining them.

Figure 3a illustrates a sample level that contains all game elements: bumpers (blue arcs), fuel (green), spaceship (white with trail), asteroids (white chunks), flippers (white bars), and wormhole (black, emitting purple glow). Figure 3b depicts the hyperspace travel animation, displayed between levels. The game also includes sound feedback for the player's actions, such as collecting fuel or crashing into an asteroid.

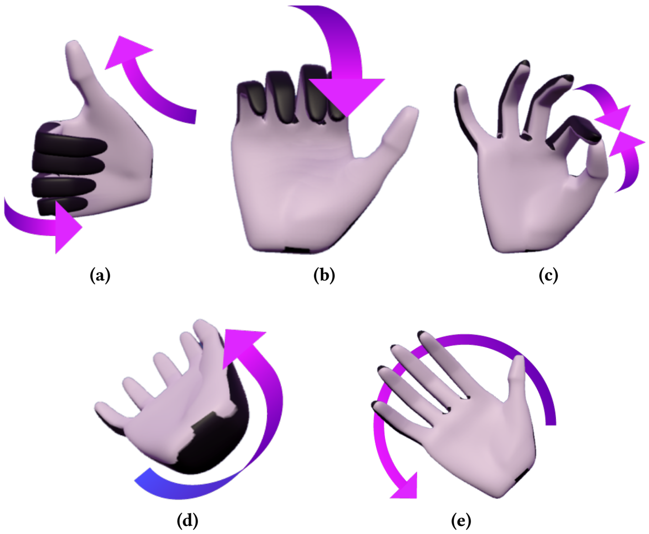

Figure 4: Hand gestures for *Space Traveller*. (a) Thumbs-Up starts the level. (b) Fingers Curl triggers the flippers. (c) Pinch is used both to transport the ship from the thumb to the index finger and to spawn a new ship. (d), (e) Hand rotation affects the direction of gravity.

3.2.3 Controls. Figure 4 shows the gestures to control the game. *Thumbs-Up* starts a new round of the game, *Fingers Curl* moves the flippers, *Pinch* is used both to transport the ship from the thumb to the index finger and to spawn a new ship, and *Hand Rotation* influences the direction of gravity.

3.2.4 Novelty. The game's controls are specifically designed for the hand-shaped playing field and give the sensation that the hand is the pinball machine itself. For example, the non-static playing field allows the player to connect the index finger and the thumb to create a passage through which the spaceship can fly, thus offering a super realistic experience [46]. We will further refer to this gesture as the Passage gesture. This new mode of interaction does not require the player to actively learn a new gesture and its function since it is intuitive that the spaceship can fly through connected areas. Thus, the player only needs to be aware that this interaction is possible. Certain levels require the player to perform this gesture to collect fuel containers that are located on the thumb.

Finally, *Space Traveller* also offers an interactive version of the traditional gravity mechanic: The wormhole located at the wrist of the hand attracts the spaceship and pulls it downwards. Additionally, the players can move the direction of gravity by tilting their hand. With this interactive mechanism, the player is able to steer the spaceship towards specific objects and to dodge other objects. On some levels, the fuel collectibles are only reachable through the use of this concept. This is an example of a mechanic that would be less intuitive and more cumbersome if the hand and the display were decoupled, as it would create a strong spatial split-attention effect.

3.3 Marble Runner

Marble Runner is a rogue-like game where the movement of the main character, the marble, is controlled by the player's hand translation. The marble is fixed to the base of the hand, and hence moving the hand translates to moving the marble in the virtual world, exactly like one would move an object in the physical world.

3.3.1 Narrative. Marbles are meant to roll! On this spiky planet, however, it proves to be a challenge. Using all your agility, stay on the safe path, and shoot at the pointy enemies to roll to the next level! How far will you go?

3.3.2 Goal. The goal of the marble is to survive for as long as possible. Figure 5 presents the two phases composing each level. The first phase contains a labyrinth surrounded by spikes that force the marble to stay on the path or lose life energy. During the second phase, the marble faces enemies and traps in an arena. By destroying enemies, the marble gains life energy. In each level, the labyrinth path moves faster and the enemies and obstacles in the arena fire at a higher rate and with greater force than in the previous levels. The game ends when the marble's life energy is lost.

3.3.3 Controls. The player starts the game by curling the index finger. By moving the hand left and right, the player moves the marble left and right while the labyrinth path passes below the marble at a speed that increases in each level. The player can give small acceleration boosts to the marble or slow it down momentarily by moving the hand forward or backward. Finally, the player can fire a shooting star to destroy enemies by curling their thumb during the area phase. The initial gesture to fire bullets involved curling the index, mimicking pulling a trigger. However, this gesture was reducing the field of view in a meaningful area of the game display, so we replaced it by the thumb curl gesture.

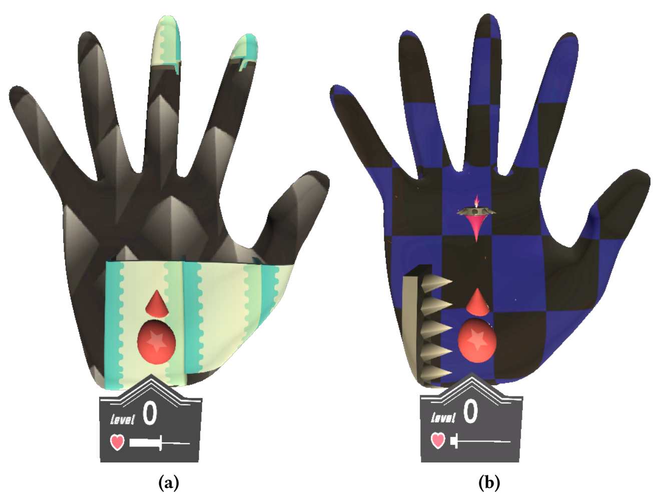

Figure 5: *Marble Runner* game visuals. (a) The marble follows a treacherous path in the labyrinth. (b) The marble is pitted against charging enemies and obstacles in the arena.

Figure 6: *Noelle's Ark* game visuals. The player needs to show which object, a bike or a Goldfinch, is heavier by mimicking a twin-pan balance with the hands.

3.3.4 Novelty. This game builds on two novel mechanics. First, the marble is directly controlled by the position of the player's hand. Second, the hand is used as a viewport into the game world. The player only sees the area around the marble and discovers the rest of the labyrinth only by moving the hand. As it feels natural to move an object placed in your own hand, *Marble Runner* offers intuitive control to players by placing the game's central object virtually into their hand and letting them control it directly through their hand.

3.4 Noelle's Ark

Noelle's Ark is an educational playful activity to help children learn about the weights of different objects. This activity builds on the principles of embodiment and benefits from intuitive hand gestures as well as reduced split-attention.

3.4.1 Narrative. Planet Earth is losing its last fight against global warming. Noelle built a space-ark to save as many objects and animals as possible. Unfortunately, the ark cannot carry too much weight, therefore the player must help Noelle figure out which objects are lightest.

3.4.2 Goal. The goal of the user is to correctly evaluate as many pairs of objects as possible in 1 minute. For each pair, one object is displayed on the left hand and another object on the right hand, as depicted in Figure 6. The user then mimics a twin-pan balance and moves the hands to reflect the weight relationship between the two objects: the hand containing the heavier object should be lower than the hand containing the lighter object. If the user guesses correctly a score point is awarded and the hands turn green, shown in Figure 7a. If the user guesses wrong, a point is lost and the hands turn red, as depicted in Figure 7b. By displaying the correct weights of the objects after the user guesses, the game gives the user the opportunity to learn the objects' weights.

The game includes objects weighing from 4 grams (a pea) to 5.75 million tons (the Great Pyramid of Giza). The comparisons are generated randomly from a pool of objects, but the maximum weight difference between the two compared objects decreases with time, making the activity increasingly difficult.

3.4.3 Controls. The game is launched using the Thumbs-Up gesture. The scale pans are displayed on the hands of the user and are moved accordingly. Finally, the user can finalize an answer by closing the fingers of both hands as shown in Figure 7.

3.4.4 Novelty. The role of this activity is to offer a playful way to learn about weight comparisons. The design of this activity is inspired by three main aspects described in the literature. First, the work on the *Mathematics Imagery Trainer* [21] notes how moving one's hands meaningfully can help to understand the concept of proportions. We follow the same approach for weights. Second, because the hand movements have a direct physical meaning, which is weight and gravity, our activity follows the recommendations of using hand gestures with a physical meaning over other kinds of gestures [37]. Finally, because the pans of the balance are displayed directly on the hands that are used to move them we avoid the spatial split-attention effect that might occur with a screen-based desktop setup [43]. The combination of these three aspects is enabled by our novel palm input and display mechanism.

4 USER STUDIES

We have conducted two user studies to identify the benefits of ***DigiGlo*** and guide the implementation of future systems.

The first study focuses on evaluating the overall usability of ***DigiGlo***, while the second study provides an in-depth analysis of the system and extracts design recommendations for future implementations.

(a) (b)

Figure 7: *Noelle's Ark* game visuals. The virtual hands turn green or red to indicate that the player's guess was correct (a) or wrong (b), respectively.

4.1 Preliminary Usability Study

In our first study, we focused on evaluating ***DigiGlo***'s usability, using our activity *Space Traveller*. This activity best reflects the novelty of our palm input and display mechanisms. The field is hand-shaped, and various kinds of novel hand inputs are directly linked to the coupling between palm input and palm display, such as the gravity, controlled by the hand orientation, and the Passage gesture, virtually connecting areas according to those physically touching.

4.1.1 Protocol. The study took place in our lab. Each participant was presented with an instruction sheet explaining the narrative and the goal of the game as well as the different gestures involved. The participants were allowed to ask questions if anything was unclear. The participants played the game for 10 minutes. After the play phase, the participants filled in several questionnaires: the System Usability Scale questionnaire [9], a Game Experience Questionnaire [22], an immersion questionnaire [23], and gestures-specific items and demographic questions. The gesture items were based on a 5-points Likert scale and followed the template of these examples: "The Passage gesture was easy to use" and "I enjoyed using the Passage gesture". The possible answers ranged from "strongly disagree" (1) to "strongly agree" (5).

4.1.2 Demographics. 24 people participated in this study. 7 participants identified as female, and 17 participants identified as male. The average age was 31.6 ($s = 14.9$, range 13 to 69 years). 12 participants indicated having high experience with computer games, 5 indicated having moderate experience with computer games, and 7 participants indicated having no previous experience. 22 participants were right-handed and 2 were left-handed.

4.1.3 Results. Our system ranked 77 on the System Usability Score (SUS) ($s = 12$, range 53 to 100), which can be qualified as "Good" [3].

We analyzed how participants ranked the different gestures. Figure 8 summarizes the scores. For the *enjoyment* criterion, the Mauchly's test for sphericity was not significant ($W = 0.55$, $p = 0.18$), so we performed a within-participants ANOVA ($F(4, 92) = 1.72$, $p = 0.15$, $\eta^2 = 0.051$) and found no significant effect of the gesture on the enjoyment score. Regarding the *ease of use* criterion, sphericity was violated ($W = 0.35$, $p = 0.008$, $\epsilon = 0.71$), so we report the Greenhouse-Geisser corrected results: $F(2.83, 64.99) = 20.41$, $p = 3\text{e}{-9}$, $\eta^2 = 0.42$). The ANOVA reveals significant differences between gestures, so we performed post-hoc pairwise Bonferroni-adjusted t-tests. We also compared different kinds of gestures using an ANOVA with orthogonal contrasts. These tests revealed that non-physical gestures were found easier to use than physical gestures, contradicting our initial expectations and previous research in the field [37]. Specifically, the Passage and the Rotation gestures were found less easy to use compared to others ($p < 0.01$ for all comparisons). The difficulty with the Passage gesture comes from the fact that it is used in a challenging moment of the game, where the player first needs to aim at the right finger, and then perform the gesture with perfect timing. Additionally, the tracking was unfortunately not always accurate and caused some frustrations. Indeed, when the same gesture was used for spawning, it was significantly better appreciated as it happened at a less intense moment. The issue with the Rotation Gesture is identified in the second study. However, even if these gestures ranked lower, they were still appreciated and received positive qualitative feedback: "The Passage gesture is really cool, it would be awesome if it worked with all fingers", "The Passage Gesture was pretty hard to use but it's a cool feature". Furthermore, symbolic gestures were found easier to use than abstract ones. This might be due to the fact that the Thumbs Up is a well-known gesture, is performed at a calm moment of the game, and has a positive connotation when we consider a *Leib* perspective [33]. In addition, we performed a covariance analysis of the game performance and gesture scores. The ANCOVA revealed no significant effect of the player's performance on the gestures scores ($F(1, 114) = 0.064$, $p = 0.80$, $r = 0.024$).

We now present the results of the *Game Experience Questionnaire*, aggregated against the different components. The results range from 0 - "Not at all" to 4 - "Extremely". Due to an experimental error, the *Positive Affect* component is computed over one item only. Participants reported in average a score of 2.21 ($s = 0.76$) on the *Competence* component, 2.75 ($s = 0.79$) on the *Sensory and Imaginative Immersion* component, 3.29 ($s = 0.80$) on the *Flow* component, 2.58 ($s = 0.79$) on the *Challenge* component, 0.64 ($s = 0.58$) on the *Negative Affect* component, 3.33 ($s = 0.70$) on the *Positive Affect* component. We compared the results for different gender groups, age groups, and gaming experiences groups using ANOVAs and post-hoc t-tests. We found a significant difference between the group with less gaming experience and the group with more gaming experience on the *Sensory and Imaginative Immersion* item. Participants with higher gaming experience felt less immersed than those with lower gaming experience ($p < 0.05$). We believe participants with gaming experience had higher expectations as they are more used to virtual environments.

Regarding the *Immersion Questionnaire*, possible answers ranged from 1 - "Not at all" to 5 - "Very much so". Participants reported

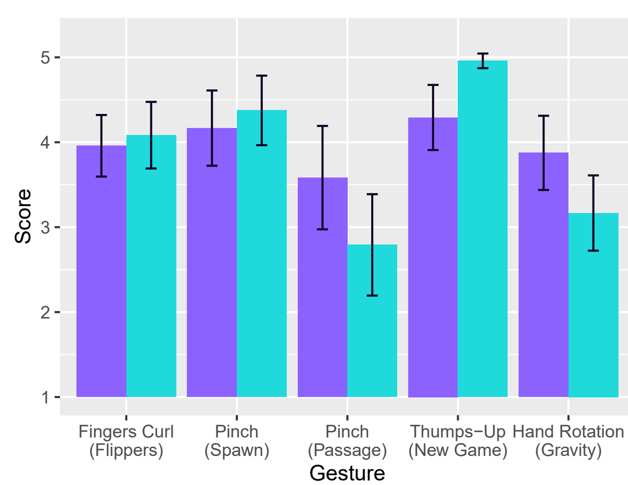

Figure 8: Evaluation of the different gestures for item "I enjoyed using this gesture" (purple) and "I found this gesture easy to use" (cyan). Range: 1 - Strongly disagree, 5 - Strongly agree. The black bars represent the 95% confidence interval.

in average a score of 4.08 ($s = 0.39$). We compared the results for different gender groups, age groups, and gaming experiences groups using independent t-tests. These tests revealed a significant difference between participants younger than 40 years old, and older ($p = 0.048$). Older participants felt more immersed ($m = 4.30$) than younger participants ($m = 4.03$). This might be due to the fact that older participants have less experience with video games and virtual reality systems.

4.2 System Design Study

The goal of the second user study is to evaluate the potential of ***DigiGlo*** through different activities and to gather feedback for future iterations of the design process, following a research through design approach [48].

4.2.1 Protocol. We conducted the study with each participant individually. Each participant started by answering questions about their profile and their experience with technology. Afterwards, the study was split into two parts of 30 minutes each: *test* and *interview*.

During the *test* phase, the participants played the three activities in random order. Before starting an activity, the participants read a document describing the activity and the different gestures involved. The participants were given the opportunity to play each activity several times for a total of 8 minutes per activity. During the first attempt, the experimenter provided guidance to the participants with respect to the interaction techniques and the goal of the activity. This ensured that all the participants comprehend the activity. The participants were asked to provide think-aloud comments as they went through testing. The experimenter took notes about the participant's comments and behaviour in order to gather in-game data about the participant's experience, as it might be difficult for them to recall all the details afterwards.

During the *interview* phase, the experimenter started by asking the participant various questions, about the hand gestures, the hand display, ***DigiGlo***, the game experience, and further uses of the system. This was followed by an open conversation with the participant. During the whole session, pictures of the different activities were available to the participant, to help them recall the experience. The entire interview process was recorded.

4.2.2 Demographics. Table 1 summarizes the profiles of the participants. All participants are right-handed. P4 used a Valve Index VR HMD instead of the HTC Vive. P2 has limited vision in one eye and reduced perception of 3D effects but insisted that this did not affect his experience negatively. P3 also participated in our preliminary study and hence had a deeper understanding of our system and experienced reduced novelty effect. P2 and P3 mentioned hobbies requiring high body awareness and provided useful feedback regarding the ergonomic aspects of ***DigiGlo***. P1 and P2 had low experience with video games and VR systems while P4 and P5 used them very often.

4.2.3 Method. We performed our analysis using an inductive thematic approach [7]. First, we transcribed the interviews and think-aloud comments. We coded the different items of the dataset with the topic they addressed, for example, "Natural hand gestures" or "Physical discomfort". Through iteration, we identified several main themes, for example, "Hand input" or "Sense of body". We qualified themes as most relevant if they were mentioned by several participants, if they were mentioned in think-aloud comments without explicit questioning from the interviewer, and if they were related to the expertise of the participant (e.g. body awareness and artistic sensibility).

4.3 Discussion

We analysed the results of the observation and interview process and identified several main items of consideration for ***DigiGlo***. Below we present a summary of our findings and offer design recommendations to address each aspect. To illustrate each point, we quote participants comments, translated to English or edited for readability when necessary. We then list different suggestions for promising ***DigiGlo*** applications.

Select Meaningful and Simple Hand Gestures. Overall, participants enjoyed the hand gestures and movements. They found them very natural: "It's the easiest, it's natural. You don't have to think that much. It's simple to interact", “My hand is free”, "It's gadget-less. It's as simple as possible to interact" (P5), "I liked it. I really enjoyed it in fact" (P1). Some participants even found these activities to be a great way to exercise the dexterity of their hands: "My favourite game is *Space Traveller* because it's the one that required the most dexterity with my hand" (P3).

The participants enjoyed simple, natural gestures more: "The simpler, more intuitive gestures are closing the hands, or do a Thumbs-Up" (P4), and struggled with more unusual gestures: "but curling the index with an open hand is not very natural" (P4). Participants expected consistent gestures across the different activities: "I think a standardised way of starting the game makes sense" (P3). Participants also enjoyed gestures with a meaningful explanation. For example, in *Noelle's Ark*, the movement of the hands according to a twin-pan scale was mostly appreciated: "It feels more natural and feels like a scale" (P2), "this control gives you the explicit explanation that heavier things are more difficult to carry therefore they go down" (P3), even though they would have preferred to have their hands horizontal to push the metaphor even further.

During the *test* phase, all participants had the chance to try each activity once in order to familiarize themselves with the gestures, and we noticed that in most cases, they did not need more trials to achieve this goal. We also noticed that during the interviews, the participants used the gestures of the games as part of their description of the game. This shows the potential of ***DigiGlo*** from an embodiment standpoint, for example, for mathematics education where the use of gestures can improve students' understanding [35]. In particular, (P3) mentioned that ***DigiGlo*** helped him "feel the problem-solving".

We conclude that ***DigiGlo*** activities should exploit a vocabulary of gestures that are simple, meaningful, and consistent across activities. For educational activities, in particular, the gestures should be strongly connected to their effect. These findings are consistent with previous hand gestures design guidelines [37]. However, with ***DigiGlo***, new gestures can be qualified as meaningful. For example, a rather abstract gesture like pinching the index and the thumb to bend the playfield becomes meaningful when the playfield is displayed on these fingers. In our work, we present a first exploration of hand gestures within the ***DigiGlo*** paradigm, but we believe future work should explore a wider range of gestures in order to generate a language of meaningful gestures in this context. Considering gestures involving both hands is particularly interesting in that context, as connecting the hands also accounts for a connection of the game space. Exploring asymmetrical configurations could also be interesting, for example using one hand as a tool to interact on the other one.

Train and Calibrate Hand Gestures. In our study, the participants read a descriptive document before playing an activity. The document contains a list of gestures as well as their effect in the game. Many participants did not like this way of learning gestures, and struggled to perform them properly on their first attempts: "I would have liked more progressive instructions as well as a tutorial instead of a document" (P4), "The challenging part was remembering the movements that you need" (P1).

Moreover, the neutral hand position for P2 and P3 is with curled fingers. This triggered undesired events, like the flippers in *Space Traveller* and the comparison validation in *Noelle's Ark*: "I didn't feel the need to stretch my fingers, which is less natural for me" (P2), "I think for me the challenge was to keep my hand actively flat" (P3).

To solve these issues, it is important to include a tutorial phase at the beginning of the activities to let the users get used to the gestures, or to calibrate the gesture recognition.

Adapt to the Hand Display. The hand is a small surface to display content on. When asked to imagine applications for ***DigiGlo***, many participants found this to be a restricting factor and wished to expand the display surface: "I would expect to use that not only to project on my hand but also on the environment" (P5), "I would like this on my whole body" (P1), "You should also have the back of the hand" (P4). However, with respect to the activities, they only found the display restrictive when playing *Marble Runner*: "Hard to tell when the path will stop" (P2), "If I want to move back I don't see what's behind me so I'm just moving blindly" (P3), "It felt like I had more load on my mind because I had to move the screen. There's no kind of reference point, it's just an abstract screen" (P1). To summarize: "In *Marble Runner*, the surface is mainly small. *Space Traveller* was fun because it's contained, and everything is taken into account." (P1). *Marble Runner* is a fast-paced game, and the hand is used as a viewport on an ever-changing terrain. The combination of high-frequency visual updates and fast-paced gestures overwhelmed the users. We believe that the viewport metaphor could still be interesting to explore, with two modifications: the activity should be slower-paced (for example, by zooming out more), and the main point of focus should be located at the center of the hand, rather than at its root.

Several participants mentioned an interest in using both hands, either as a duo palm input-display mechanism or as a mean to decouple input and display: "I would like to have both hands, to do something with both" (P1), "I think that using one hand for input and one hand for display would greatly simplify understanding" (P4). In this paper, we are focusing on the palm input-display mechanism, so we will only analyse the first option. *Noelle's Ark* implements this approach, with simple gameplay and a limited set of gestures. Yet, some participants struggled to grasp all the information: "You can't look at your left-hand wrist: you lose focus on the object and it's mentally demanding to focus on that" (P3). In general, we noticed that the wrist area is difficult to focus on as some participants even asked the interviewer to read it for them, but this issue was amplified in the two-hands set-up. We would advise against displaying crucial information in this area.

Only P4 mentioned that he would have enjoyed 3D objects for *Noelle's Ark*. For the other participants the quality of the visuals seemed less crucial for the experience. However, as P4 is a professional 3D technical artist, we believe that his perspective is interesting to explore in future work.

In order to account for the limited display space, it is important to carefully design the activity within and with respect to the hand shape. Using both hands can solve part of this issue, but implies limited focus available for each hand. Future work could also explore magnifying the hand in VR, with special care for possible negative effects on the sense of embodiment.

Combine Hand Gestures and Display. ***DigiGlo*** uses the hand both as a display and an input. This enables some novel game mechanisms, based on intuitive and natural controls: "The User Experience is very nice, it's so natural, you don't feel the game imposing so much" (P5), "I have to solve a problem and then my hand does whatever it needs to do to solve the problem, you have this high-level idea 'I need to go right' and it just happens" (P3), "I wonder why there are no other games like this" (P1). In this study, unlike in the preliminary study, the participants enjoyed the Passage Gesture in *Space Traveller* as it made the best use of the palm input-display mechanism: "I like it, I feel like I am curving space and time" (P3). We believe that these controls are particularly appreciated because of the reduced spatial split-attention effect.

However, ***DigiGlo*** also raises specific design constraints. Participants suggested that the Fingers Curl gesture used to activate the flippers in *Space Traveller* restricted their experience. Indeed, as they tried to aim for a specific finger, they had to close this very finger: "When you close the hand to shoot, you have to imagine where the spaceship goes" (P4), "You have to fold your fingers and you lose visibility of the game space. The game design needs to make sure that there's nothing relevant that you lose by closing your fist" (P3).

We also noticed that, because the system is based on the hand, the participants had strong expectations with respect to the physics of the games. For example, most of them struggled to grasp how gravity varied as they rotated their hand in *Space Traveller*: "I wish gravity would listen to me more" (P1), "It was about understanding how the physics worked" (P4). When we designed the balance metaphor for *Noelle's Ark*, we realised that keeping the hands horizontal reduced the readability of the content. Instead, we designed the activity so that the hands are positioned vertically, closer to the user's face. However, when playing *Noelle's Ark*, several participants kept holding their hands horizontally (P2 and P3).

In order to make the full use of ***DigiGlo***, the input and the display should be designed in an intertwined manner: one should not limit the other. Moreover, because the hand is used intensively, the users expect the game to follow the laws of physics of the real world and can struggle to adapt to dissonances. This is a form of

Table 1: System Design - User Study: Participants profiles

ID	Age	Gender	Profession	Hobbies	Video games exp.	VR exp.
P1	30	F	Software Engineer	Gardening, Reading, Exercise	Low	Low
P2	30	M	Software Engineer	Skiing, Hiking, Reading	Low	Low
P3	32	M	Security Engineer	Music, Brazilian Jiu-Jitsu, Yoga	Low	High
P4	28	M	3D Technical Artist	Video games, Music, Drawing	High	High
P5	30	M	Software Engineer	Reading, Developing apps, Learning German	High	High

Tactile Illusion [18]. These illusions arise when touch perception and visual perception are not in agreement. ***DigiGlo*** is particularly prone to this kind of illusions as the visual cues and the hand, our main touch agent, are co-located. Future work should explore how the participants' expectations and preferences for different body configurations influence their experience, and how to design accordingly.

Another important aspect is the effect on the sense of embodiment [26]. In its current version, ***DigiGlo*** supports the sense of self-location by mapping the game content onto the user's hand and the sense of agency by updating the game world in 100 ms. The sense of body-ownership could be improved by adapting the shape of the virtual hand to the user's hand. Further work should empirically evaluate the influence of these factors on the sense of embodiment.

Provide Multimodal Feedback. Feedback played an important role in the participants' enjoyment and empowerment. The sound feedback in *Space Traveller* helped the participants' awareness: "I loved *Space Traveller* because of the music and how it reinforces the game, for example when I crash into asteroids or go into the wormhole" (P3). The coupling of feedback with hand movement and position was also helpful: "In *Noelle's Ark* I feel like they're re-enforcing the decision: I just have this mapping between green and the position of my hands when I see these two pictures" (P3).

Because the display is limited, it is particularly important to rely on multimodal feedback, including sounds, visuals, and proprioception factors such as body position and body movement. Previous work on multimodal feedback [13] demonstrates how adequate sound and tactile feedback can improve performance on visual tasks. We suggest grounding ***DigiGlo*** activity design according to this line of research.

Reduce Physical Constraints. The use of ***DigiGlo*** can create physical discomfort if the hand stays immobile or performs uncomfortable gestures, or if the user stares down for too long, especially for participants with high body-awareness: "It puts pressure on the shoulders" (P2), "Our palm has to be constantly facing up, this puts some constraints on your neck" (P3), "As long as I can't keep my head straight and my spine straight it's a problem" (P3), "The hand is always in front for you, it's tiring" (P4). We suggest to design interaction that keeps the hand active, and allows the user to drop the hand or move it to a more comfortable place when necessary: "Having things like *Noelle's Ark* where you keep your hands in front without having to look down is a lot helpful for me" (P3).

Previous work showed that users experience discomfort after playing a hand gestures-based video game for an average of 23 minutes [36]. As the body of the user is heavily involved when using ***DigiGlo***, we advise being mindful of possible discomforts and design accordingly. For example, future work could explore how to integrate specific movements and pauses in the activity to avoid negative effects on the body. Similarly, exploring different body configurations such as laying down on one's belly is relevant. The body-awareness raised from such experiences can also be positive. In particular, as ***DigiGlo*** enables non-invasive visual feedback, provides space to focus on one's hand, and exists as an extension of one's body, we believe ***DigiGlo*** is a promising system to offer somaesthetic appreciative experiences [20].

We conclude this section by listing several applications envisioned by the study participants: small multiplayer games with friends (P5), ninja game with hand gestures for incantations (P4), whack-a-mole (P4), nail polish preview (P1), cooking handbook and tutorial (P2), gamified recovery exercises for hand injuries (P5), gamified hand-yoga (P3), fine-tuned gestures trainer for music (P3).

5 CONCLUSION

In this paper, we demonstrate how the palm of the hand can be used as both an input and a display mechanism for gaming and educational activities. We present Digital Gloves (***DigiGlo***), a system comprising a hand tracker and a Virtual Reality (VR) head mounted display (HMD), which virtually projects content on the user's hand and lets the user control an activity solely by hand movement and gestures. Through three activities, we demonstrate that ***DigiGlo*** is stimulating and introduces a mode of interaction that warrants further investigation.

A preliminary user study conducted with *Space Traveller* focuses on the usability of ***DigiGlo*** and demonstrates that participants enjoyed the game and its mechanics. A total of 24 participants rated the system with an average System Usability Score (SUS) of 77 and agree that the majority of gestures were both enjoyable and easy to use.

We conducted a second user study on a smaller scale than originally planned because of the current world-wide emergency situation. Five selected participants thoroughly evaluated all three activities and participated in a discussion about ***DigiGlo***, its activities, and possible future uses. From the discussions we conclude that ***DigiGlo*** requires activities to involve meaningful and simple hand gestures, which are consistent across all activities. Gestures should be taught and practiced in an in-game tutorial, in order for the users to adapt to the gestures and calibrate their hand movement to the hand tracker's gesture recognition. A combination of visual high-frequency details and fast-paced gesture input can quickly overwhelm users and should be avoided. To account for the limited display space of a palm, activities must be carefully designed to make the best use of the shape of the palm and should additionally include multi-modal feedback, such as sounds and proprioception effects.

Limitations. As prototype implementations, the three activities lack in-game tutorials that help the users become comfortable with the gestures before starting the actual gameplay. *Space Traveller* and *Marble Runner* are implemented mainly for right-handed users and it would be relevant to study how to adjust such activities for left-handed users. *Marble Runner* and *Noelle's Ark* lack sound effects and music. As identified during the user studies, sound and other multi-modal feedback greatly improves the experience and augments the limited display space of the hand. ***DigiGlo*** uses a compelling 3D model of a hand, which, however, never matches the user's real hand accurately. This may lead to a reduced sense of body-ownership. Further limitations in our current implementation motivate a number of future research directions. For instance, haptic feedback integrated into ***DigiGlo*** would greatly improve the sense of immersion [16] and enable new types of games and activities. Haptic feedback especially enhances embodied learning experiences. Regarding our empirical results, a complementary comparative study to evaluate the effects of embodiment and reduced split-attention on the users would be beneficial.

Outlook. Our VR implementation of ***DigiGlo*** presents the game content to the user on a virtual hand through an HMD. We believe a Spatial Augmented Reality (SAR) implementation of ***DigiGlo***, where the game content is directly projected onto the users' physical hands, presents a compelling future research direction. A SAR implementation does not require the user to provide any equipment. Instead, engaging with an activity is instantaneous, which makes it well-suited for public spaces, museums, schools, training, and healthcare settings. Hygiene concerns that arise when using VR in public spaces also become obsolete.

In addition to being an interesting testbed for future embodiment research, we believe ***DigiGlo*** offers a framework and inspiration for a plethora of future games and activities. A few examples are a guitar-hero-like rhythm game in which one plays a virtual musical instrument on the hand using the fingers, a puppeteering game in which the user can make a character dance on the palm, an educational activity for children, teaching them mathematics with their hands [28], and a hand rehabilitation therapy game. All these could be promising ideas for fun and exciting future ***DigiGlo*** activities.

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