

Evaluation of Personalized Above-Neck Gestures for Accessible Mobile Gaming

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Mobile gaming presents significant accessibility challenges for individuals with upper-limb impairments, as touchscreen interactions require precise finger movements and rapid reactions. While assistive technologies exist for general smartphone use, they are often incompatible with the time-constrained and simultaneous input requirements of video games. To address this issue, we investigate the use of fully personalizable, user-defined above-neck gestures (e.g., head movements or facial expressions) as a means to improve the accessibility of mobile video games for people with upper-limb impairments. Through a study with 12 participants, we explore the gestures that people with upper-limb impairments select during mobile gaming, and we assess performance and participants' perceptions using three popular commercial video games as well as custom evaluation probes. Participants commonly selected symmetric gesture pairs (e.g., left/right profile, looking up/down) and preferred slower-paced games, which resulted in significantly lower workload compared to faster-paced games. Our findings show that above-neck gestures allow people with upper-limb impairments to play games that would otherwise be inaccessible to them, achieving performance comparable to external buttons in terms of accuracy, response time, and perceived workload.

CCS Concepts: • **Applied computing** → *Computer games*; • **Human-centered computing** → **Empirical studies in accessibility**; *Accessibility technologies*; *Mobile devices*; **Gestural input**.

Additional Key Words and Phrases: Above-neck gestures; mobile accessibility; accessible gaming.

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1 Introduction

For individuals with upper-limb impairments, interacting with video games is challenging, as video games are usually controlled through hand-based interaction [18, 55]. For example, PC games are often played using mouse and keyboard or a joystick, while console games commonly use gamepad controllers. On mobile devices, gameplay primarily relies on touchscreen input, which also depends on the user's manual dexterity [7]. The specific challenges associated with touchscreen use vary depending on the individual's condition, as the effects of upper-limb impairments can differ significantly across users. Some users experience difficulties in executing or maintaining precise movements (e.g., due to tremors [63] or Parkinson's Disease [47]), while others may lack voluntary mobility in their upper limbs (e.g., due to spinal cord injury [53] or muscular dystrophy [19]).

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Assistive technologies have made everyday smartphone use more accessible. A common approach is to replace touchscreen interactions with sequences of simpler, more accessible actions, such as pressing an external button [27]. While these interaction paradigms are effective for many apps, they are unsuitable for mobile games, where users often need to perform the same actions repeatedly and under strict time constraints [11, 13]. As a result, players with upper limb impairments are often unable to play mobile games, one of the most widespread forms of digital entertainment [58, 66].

To address this limitation, prior research has proposed assistive technologies substituting on-screen gestures with alternative actions that the user can perform, such as pressing external buttons or producing non-verbal vocal sounds [5]. In particular, head movements and facial expressions – collectively referred to as above-neck gestures – are relevant for users with upper-limb impairments, as they enable interaction without residual upper-limb movement. Prior research [75] and commercial systems [29, 31, 64] proposing above-neck gestures for interacting with PCs or smartphones used predefined, fixed set of gestures. However, people with upper-limb impairments have a high variability of motor abilities, considering range of motion, control, and fatigue [44]. Thus, predefined gestures may still be inaccessible or suboptimal for many of them [65]. We have previously proposed a technical solution implementing the use of personalized above-neck gestures for controlling mobile video games [50]. However, how personalized gestures are designed and used in practice by players with upper-limb impairments has not yet been studied, leaving open questions about the applicability and effectiveness of this approach.

To answer these questions, we conducted a study with 12 participants who have upper-limb impairments, investigating how they design and use personalizable above-neck gestures for mobile gaming. We empirically evaluated the effectiveness of the approach for playing various mobile games, including commercial ones. Results show that personalized above-neck gestures enable people with upper-limb impairments – who would otherwise be unable to play – to access and enjoy mobile games, achieving comparable performance and perceived workload as when using external buttons, a common accessibility solution [54]. The study also unveils users' gesture choices and how playing games with different pacing affects the user experience. Overall, this work validates the feasibility and usability of personalized above-neck gestures for time-constrained mobile gaming and provides design implications for future assistive technologies that employ them.

2 Related Work

We review existing assistive technologies that enable smartphone access for users with upper-limb impairments, focusing first on general approaches for accessible mobile interaction (Section 2.1), then on accessibility solutions specifically designed for mobile video games (Section 2.2), and finally on previous efforts employing above-neck gestures as an alternative input modality (Section 2.3).

2.1 Accessibility of Mobile Devices

Mobile devices primarily rely on touchscreen interaction [12]. However, this interaction paradigm can pose significant challenges for users with upper-limb impairments [39], as it requires precise finger movements [7, 47, 63] and can easily lead to accidental touches or misinterpreted gestures [76]. For these reasons, people with upper-limb impairments often rely on assistive technologies that make mobile device interaction more accessible. Some of these substitute touchscreen interaction with a different pointing mechanism. For example, gaze and head-tracking enable hands-free pointing by interpreting eye or head movements [6, 84], with a secondary activation signal such as a blink or gaze dwell time used to activate the pointed interface element [22]. These approaches can improve accessibility for users with limited hand mobility, but they do not adapt well to video games, as they require time to perform each action. Moreover, specialized hardware might be required, which can limit their portability and practical adoption on mobile devices.

Another common alternative is the use of a scanning interface, such as *Switch Access* [27] on Android. These solutions sequentially traverse all the interface elements on the screen, one at a time. Usually, the scanner traverses automatically the user interface elements at a regular pace, and the user can activate an element of interest once it is highlighted by the scanner through an external switch or keyboard. This approach reduces physical effort, but it also introduces delays [62] and cognitive load, as users must track the highlighted element and activate the switch at the appropriate moment [68]. Additionally, scanning becomes ineffective when applications do not expose their interface structure to the operating system [52] or if they require time-constrained interactions [68].

Finally, interaction-substitution approaches allow the user to activate specific interface elements through alternative interactions. One common direct interaction modality is through verbal commands [30, 45, 87], which, however, are limited by environmental noise, pose privacy concerns [57, 63], and aren't effective when the user also has speech impairments [35]. Additionally, pronouncing verbal commands takes time and, therefore, is incompatible with time-constrained interaction. Other direct interaction modalities leverage gaze movements [85] and body gestures [4]. In this work, we focus specifically on above-neck gestures [49, 50, 86] (Section 2.3).

2.2 Accessibility of Video Games

Video game accessibility presents significant barriers for players with upper-limb impairments [11, 13, 18, 51]. Games often require fast-paced interactions, precise timing, and simultaneous inputs, which can be particularly challenging for individuals with limited upper-limb control [11, 13, 83]. Fine upper-limb motor control is also frequently required for precise targeting or movement, and extended gaming sessions can cause fatigue [43].

Since upper-limb impairments are highly heterogeneous [44, 80, 82], varying in type (e.g., musculoskeletal or neurological), onset (congenital or acquired), and extent (e.g., unilateral or bilateral), current approaches to address accessibility barriers also vary. Common approaches include specialized adaptive controllers [14, 17, 20, 54, 67, 81], game-level solutions such as configurable controls and adjustable difficulty settings, and platform-level features, including button remapping [38, 46] and shared control [3, 15, 56]. Players combine and customize these solutions based on their unique needs [51], often relying on community knowledge and trial-and-error to build a suitable gaming setup [9]. For example, using the Xbox Adaptive Controller [54], players can create custom gaming setups by connecting a wide range of external devices, including buttons, joysticks, sip-and-puff sensors [67] and foot-operated switches [25]. Beyond dedicated accessibility products, many players also use modified standard controllers [36] or 3D-printed controller add-ons [42].

Mobile gaming presents additional challenges compared to traditional gaming platforms. In particular, the reliance on touchscreen interfaces introduces unique obstacles: for example, multi-touch gestures are inherently difficult for users with limited hand mobility, and the smaller screen size of mobile devices reduces target sizes, increasing the precision required for accurate input [76]. Most importantly, standard mobile assistive technologies, while effective for many users in everyday mobile interaction, face two specific problems in video games that may prevent those same users from accessing them. First, most assistive technologies for accessing mobile devices fundamentally mismatch gaming requirements, as they do not enable users to perform the rapid and simultaneous actions required by most games [5]. For example, all scanning-based solutions require the user to wait for the target interface object to be selected. The second problem is technical and stems from the fact that many games are developed using game engines, such as Unity [77], which often do not expose their interface structure to the operating system [52]. This renders most assistive technologies – such as those based on scanning – ineffective, as they cannot identify the interface objects to interact with.

To address these issues, we have previously proposed the *RePlay* system [5], which allows the user to perform game actions rapidly, using alternative input modalities (e.g., by pronouncing a non-verbal vocal sound or through body movements [4]). *RePlay* can also be used to support third-party games, including the ones developed with various game engines. For these reasons we adopt *RePlay* for the user study presented in this paper (Section 3.1.1).

2.3 Above-Neck Gesture Interaction for Accessibility on Mobile Devices

Above-neck gestures have been proposed as an accessible alternative interaction modality for individuals with upper-limb impairments, on both PCs [6, 26, 84] and mobile devices [31, 50, 78, 86]. For example, on Android devices, *Camera Switches* [31] is a scanning interface controlled with above-neck gestures captured by the smartphone's front camera. Similarly, on PC, Taheri et al. [75] propose a game controller controlled with above-neck gestures. Both systems rely on a predefined set of gestures for users to choose from.

To understand which gestures are accessible and desirable by people with upper-limb impairments, Zhao et al. [86] conducted an elicitation study, identifying a coherent set of above-neck gestures for common smartphone interaction tasks. However, the gesture set is designed to be shared across users, while multiple studies [74, 86] show that some users may require gesture customization due to impairments that prevent them from performing certain gestures. Despite this need for personalization, some solutions rely on predefined above-neck gestures [6, 75, 84]. Others provide a degree of personalization. For example, *Project Activate* [29] allows users to select from a set of gestures and adjust their intensity according to individual abilities (e.g., defining the required width of a smile gesture). *PlayAbility* [64] instead supports the creation of new gestures as the combination of predefined base gestures that the system can already recognize. While these approaches increase personalization, they still confine users to a fixed set of predefined gestures. In our prior work, we have proposed a technical solution enabling fully personalizable user-defined above-neck gestures for mobile gaming [50], as a module within the *RePlay* system. However, it is unclear how users with upper-limb impairments could actually use such a solution: what above-neck gestures would they design to interact with video games, would they be able to play games with the proposed approach, and what outcomes and limitations would result? To answer these questions, we present an investigation with participants with upper-limb impairments, focusing on the design of personalized above-neck gestures for mobile gaming and their use during play.

3 Methodology

We conducted a user study with 12 representative participants using personalized above-neck gestures to play mobile video games. The study methodology was inspired by prior works investigating the use of alternative interaction modalities to substitute touchscreen interactions [5]. The experimental protocol was approved by the ethics committee of the University of Milan, approval: 4/19¹. In Section 3.1 we describe the study apparatus, while the games used as stimuli during the study are presented in Section 3.2. The experimental protocol is outlined in Section 3.3, and the demographic data of the participants of the study are presented in Section 3.4. Finally, Section 3.5 reports the metrics collected during the experiments and describes how they were analyzed.

3.1 Apparatus

The experimental apparatus consists of the *RePlay* system (Section 3.1.1), a custom web-based evaluation probe for collecting performance measurements (Section 3.1.2), and the hardware used during the study (Section 3.1.3).

¹Planning, conduct, and reporting of the work are consistent with the general principles enunciated in [1].

3.1.1 RePlay system. To conduct the study, we employed the *RePlay* [5], an interaction-substitution framework that enables replacing standard touchscreen interactions with alternative user actions when playing video games. Alternative user actions are physical movements or inputs that can be performed without directly touching the screen, such as vocal sounds or external button presses. The system is implemented as an *Android Accessibility Service* [28] that runs in the background while the user is playing a game and emulates on-screen gestures when the corresponding alternative user action is detected.

The architecture of the *RePlay* system currently supports various types of alternative actions, implemented as modules, including non-verbal vocal sounds [5], pressing external buttons, performing movements detected through wearable sensors [4], and making above-neck gestures detected using the device's video camera [50]. For example, a user can pronounce the vowel “a” to execute a tap in a predetermined area of the screen, which in turn causes the game character to jump. Users can freely combine different types of actions according to their individual preferences. In this study, we focus on the use of above-neck gesture actions, which have not been previously evaluated with users, and compare their effectiveness to that of external buttons alone and the combined use of above-neck gestures and external buttons (Section 4.2).

An essential characteristic of *RePlay* is that it allows define personalized above-neck gestures for each user. Thus, before starting to play, *RePlay* requires an initial setup phase in which users register the actions they intend to use and associate them with the corresponding game events. Fig. 1 shows an example of this setup procedure. First, the app records a short video of the user performing an above-neck gesture they want to use. Users are free to perform any gesture they prefer. For example, Fig. 1a shows a user recording a gesture with their mouth open. From the video, *RePlay* extracts a few representative camera frames and stores the user's facial landmarks as features representing the gesture. The user repeats this process for each gesture they want to define. Then, each recorded gesture can be associated with a different screen event, indicating the screen position where the event should be executed. Fig. 1b, for example, shows the “open mouth” gesture associated with a swipe down event executed in the center of the screen (indicated by the red dot in the image).

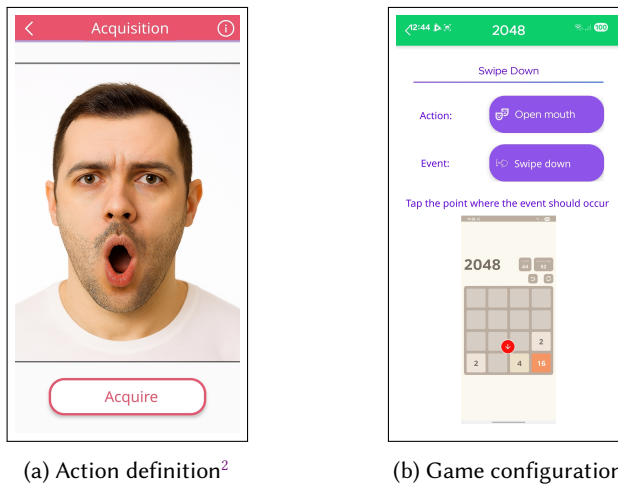


Fig. 1. *RePlay* configuration interface

²The face shown in the figure is AI-generated for privacy and anonymity.

After configuring these mappings, *RePlay* trains a model using the acquired gesture features, which is then used during gameplay to infer the gestures when performed by the user. The configuration process is currently touchscreen-based: users navigate the setup by selecting options on the screen and positioning target areas for the associated events. In our experiments, the supervisor supported the participants during the configuration process, as setup accessibility is outside of the paper's focus. However, we note that system accessibility options, such as switch access [27], can be used to support the user during setup. The entire process takes a few minutes, and therefore can be repeated whenever the user needs to change the recorded gestures (e.g., to adapt to a change in the user's abilities). Additionally, recorded gestures can be reused for different games, further reducing the configuration time.

3.1.2 Evaluation Probe. *Press the Button* (Fig. 2a) is the web app used as the experimental probe. It is adopted from previous work [5] to maintain consistency and enable comparability with prior studies. The interaction is organized in rounds: in each round, the player is shown either an image of a house or a tree at the top of the screen and must press the corresponding button at the bottom. A complete run with *Press the Button* consists of 24 rounds, half of which require a tap of the button, while the other half require a two-second long tap, thus testing both rapid and sustained interactions. To indicate the required interaction type, a finger icon is overlaid on the image for taps, while a timer icon is shown for long taps. The order of rounds is pseudo-randomized.

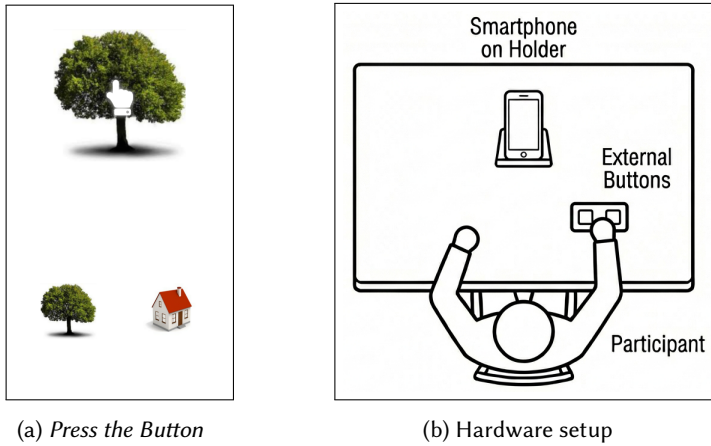


Fig. 2. Evaluation probe and hardware setup used in the study.

3.1.3 Hardware Setup. During the study, *RePlay* ran on a *Samsung Galaxy A53 5G* smartphone with Android 13. The device was mounted on a smartphone holder, positioned in front of each participant at approximately 30–45 cm. Fig. 2b shows a picture of the experimental setup. Before starting the experiment, each participant adjusted their position and the smartphone's angle to ensure proper framing by the front camera, which was used to recognize above-neck gestures during gameplay. For external button actions, we used the *Blue2 4th Generation Bluetooth Switch*³, which each participant could position according to their comfort and physical needs.

³<https://www.ablenetinc.com/switches>

3.2 Game Stimuli

During the study, we used three different video games as stimuli: *2048* [16], *Super Mario Run* [61], and *Subway Surfers* [40]. These video games were selected based on the number of actions they require and their pacing to assess how above-neck gesture interaction varies across different gameplay contexts.

2048 (Fig. 3a) is a puzzle game where players combine numbered tiles on a 4×4 grid by swiping in four directions (up, down, left, right). When two tiles with the same number touch, they merge into one tile with the sum of their numbers. The goal is to create a tile with the number 2048. The game requires four actions, one for each swipe direction, and has no time constraints, allowing players to think carefully before each move.

Super Mario Run (Fig. 3b) is an auto-runner platformer where the character runs automatically from left to right. The player controls the character's jumps with a single tap on the screen; the duration of the tap determines the jump height: the longer it is held, the higher the character jumps. The game has a moderate pace, requiring players to react to obstacles and enemies in real-time.

Subway Surfers (Fig. 3c) is a fast-paced endless runner where players control a character running through subway tracks while avoiding obstacles. Players swipe up to jump, down to roll, left and right to change lanes. The game progressively increases in speed, requiring quick reactions and precise timing. This represents the most demanding stimulus in terms of both the number of required actions (four, one for each swipe direction) and reaction speed.



Fig. 3. Game stimuli used in the study. Copyrights are the property of their respective owners⁴.

3.3 Experimental Protocol

In total, each experiment lasted approximately one and a half hours. Experiments began with a brief introduction to the study's goals and structure. After providing informed consent, participants completed a brief demographic questionnaire about their age, gender, type of motor impairment, gaming habits, and experience with smartphones and accessibility technologies. Each experiment was divided into two main tasks. Table 1 summarizes the study's overall structure. After the last task, a final questionnaire was administered, consisting of three statements rated by the participants on a 6-point Likert scale. The statements are reported in Fig. 4.

⁴These images are included under fair use for academic evaluation purposes in accordance with ACM's fair use guidelines [2].

Table 1. Study tasks. Factors varied in a task are underlined. EB: External Button, ANG: Above-Neck Gesture.

	Task 1			Task 2		
Condition	C1	C2	C3	C1	C2	C3
Evaluation probe / game stimulus	Press the Button			2048	<u>Super Mario Run</u>	<u>Subway Surfers</u>
Interaction modality	<u>2 EB</u>	<u>2 ANG</u>	<u>1 EB, 1 ANG</u>	4 ANG	1 ANG	4 ANG
Duration	24 rounds per condition			5 minutes each		

3.3.1 First Task: Comparison of Interaction Modalities. The first task compared three input modalities as conditions: external buttons, above-neck gestures, and a combination of one external button with one above-neck gesture (combined interaction modality). External buttons were selected as a baseline condition because they are a standard assistive technology widely adopted by players with upper-limb impairments [27]. The combined interaction modality, instead, was included to evaluate the feasibility of integrating different input types, which could be particularly beneficial for users who find it challenging to perform multiple distinct above-neck gestures but retain sufficient residual mobility to operate at least one physical switch. For this task, participants completed a run with the *Press the Button* evaluation probe with each of the three conditions. Condition order was counterbalanced across the participants using a Latin Square design. Before starting the task, participants were required to create two new above-neck gestures and test them with the evaluation probe, iteratively adjusting the gestures until they were satisfied. Additionally, at the end of each run, participants completed a NASA Task Load Index (NASA-TLX) questionnaire [34] to assess the perceived workload with different interaction modalities.

3.3.2 Second Task: Perceived Workload Across Different Video Games. In the second task, the considered conditions were the three game stimuli (Section 3.2). Participants played each game for 5 minutes using above-neck gestures. This aligns with the typical duration of mobile gaming sessions [37]. Participants could define new gestures or refine existing ones before starting each game. At the end of each run, participants completed a NASA-TLX questionnaire to assess the impact of game pacing on the perceived workload.

3.4 Participants

Participants' recruitment was carried out with the support of local associations for people with motor impairments: the Milan and Monza's branches of UILDM⁵, and Spazio Vita⁶ of Niguarda Hospital in Milan. These associations facilitated contact with potential participants and provided locations for conducting the experiments. The following inclusion criteria were adopted:

- Being at least 13 years old.
- Having an upper-limb impairment that limits the ability to use a smartphone.
- Being able to perform (at least some) above-neck gestures.

The only exclusion criterion was the presence of multiple disabilities, which could act as a confounding factor during the experiments.

We recruited a total of 12 participants, with an average age of 32.42 ± 18.04 ⁷. Eight participants identified as male, and four as female. During the experimental tasks, two participants were unable to complete all activities: **P2** stopped after the first game of the second task due to fatigue, while **P7** did not perform the first task due to difficulties in using the external buttons. Table 2 reports the participants' demographic profiles.

⁵Unione Italiana Lotta Distrofia Muscolare: <https://www.uildm.org>

⁶<https://spaziovitaniguarda.it>

⁷Notation: *mean* $\pm$ *std*

Table 2. Participants' Demographic Data.

ID	Age	Gen.	Disability		Gaming Frequency		Difficulties With	
			Type	Onset	General	Smartphone	Video games	Smartphone
P1	16	M	Muscular dystrophy	Birth	Always	Sometimes	Easy	Very difficult
P2	66	M	Neurogenic atrophy	Birth	Sometimes	Rarely	Difficult	Difficult
P3	23	M	Muscular dystrophy	Birth	Always	Always	Very easy	Very difficult
P4	21	F	Muscular dystrophy	Birth	Never	Rarely	Difficult	Moderate
P5	28	M	Muscular dystrophy	Birth	Always	Rarely	Very easy	Very difficult
P6	23	M	Muscular dystrophy	Birth	Always	Never	Very easy	Very difficult
P7	44	M	SMA 2	Birth	Rarely	Rarely	Difficult	Very difficult
P8	13	F	Muscular dystrophy	Birth	Often	Sometimes	Very easy	Very difficult
P9	23	M	Muscular ataxia	Birth	Sometimes	Never	Very easy	Easy
P10	29	F	CMT4A	Birth	Sometimes	Sometimes	Moderate	Difficult
P11	72	M	Right upper limb paresis	At 42	Never	Never	Very difficult	Easy
P12	31	F	Spastic dystonic tetraplegia	Birth	Never	Rarely	Moderate	Difficult

All participants had upper-limb impairments that affected their ability to use smartphones. Most conditions were congenital, with only **P11** having acquired their disability later in life (30 years prior to the study). The majority of participants had good control of head movements and facial expressions. Only **P9** and **P10** reported some limitations: **P9** experienced moderate difficulty with certain above-neck gestures, while **P10** used a respirator. However, both were able to perform a sufficient number of gestures to complete the experiment's tasks. The impact of motor impairments on smartphone use varied considerably across participants. Ten participants reported at least moderate difficulty using their smartphones, with six describing it as very difficult. Only **P9** and **P11** found smartphone interaction relatively easy, despite their motor limitations.

Regarding gaming habits, eight participants reported playing video games at least sometimes, while the others played rarely or never. Smartphone gaming was less common: only five participants reported playing on smartphones at least sometimes, while seven played rarely or never. Notably, participants who reported little to no difficulty playing video games in general (**P1**, **P5**, **P6**, **P8**, **P9**) had lower smartphone gaming engagement compared to their overall gaming frequency. Among these, only **P3** declared to play on smartphones with the same frequency as other platforms. None of the participants had previous experience with gaming accessibility solutions or interaction with above-neck gestures, making this study their first exposure to such technologies.

3.5 Metrics and Data Analysis

To evaluate participants' performance and workload during the experiments, we collected quantitative metrics (Section 3.5.1), which we analyzed through hypothesis testing (Section 3.5.2).

3.5.1 Metrics. During the experiments, we collected the following metrics:

(1) **Performance data** collected in the first task:

- **Stimulus-to-interaction time**, computed as the duration from when the stimulus is displayed to when the evaluation probe receives the participant's interaction. Stimulus-to-interaction time includes the participant's reaction time, the time needed to perform the gesture, and *RePlay*'s processing time.
- **Round outcomes**: *success* or *selection error* for tap rounds; *success*, *selection error*, or *duration error* for long tap rounds. A *selection error* occurs when the user activates the wrong input, while a *duration error* occurs when the input duration is shorter than the defined prolonged tap threshold (2 seconds).

- (2) **Perceived workload** measured with the NASA-TLX [34], at the end of each condition.
- (3) **Above-neck gestures** selected by participants during each task.
- (4) **User feedback** collected at the end of the study with a final questionnaire consisting of three statements rated on a 6-point Likert scale (Section 3.3).
- (5) **Preferred game** in the second task.

3.5.2 Data Analysis. Continuous variables, such as stimulus-to-interaction times and NASA-TLX scores, were analyzed using the Aligned Rank Transform (ART) procedure [79]. Categorical variables, such as round outcomes, were analyzed using Fisher's exact tests [23]. Post-hoc analysis was conducted using estimated marginal means [69]. Multiple comparison corrections were applied using the Benjamini-Hochberg procedure [10]. Finally, above-neck gestures selected by the participants are reported in the results section and later discussed in comparison with those observed in prior studies in the literature. Statistical results and reporting conventions follow the guidelines of the American Psychological Association (APA) [8].

4 Results

Overall, participants reported high enjoyment while playing and stated that they would use the system to play games they normally avoid due to their complexity or pace.

Additionally, most participants preferred playing using above-neck gestures rather than the touchscreen (Fig. 4). We report the above-neck gestures participants selected and used during each task (Section 4.1), we compare performance across interaction modalities (Section 4.2) and, finally, we examine gameplay experience using above-neck gestures across different video games (Section 4.3).

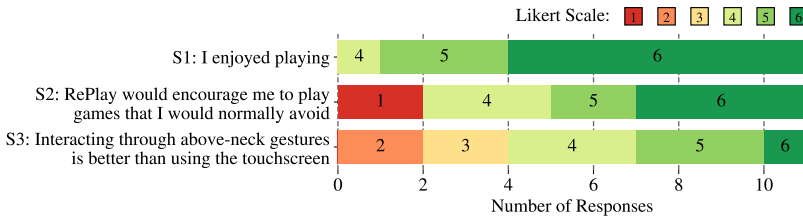


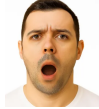
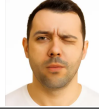
Fig. 4. Participants' responses to the final questionnaire.

4.1 Selected Above-Neck Gestures

Table 3 reports all the above-neck gestures selected by participants during the study. Importantly, the gesture set reported in the table does not represent a recommended gesture set, but the outcome of a fully personalized, participant-driven design process. Consequently, the absence or low frequency of gestures commonly used in other systems is a direct result of this process rather than a design choice of the system. The most used gestures were the *head right* and *head left* gestures (9 participants each), followed by *head up* (8 participants), *head down* (7 participants), *open mouth* and *smile* (4 participants each), *raise eyebrows*, *close right eye* and *close left eye* (2 participants each), *tilt right*, *tilt left*, and *kiss* (1 participant each).

Regarding gesture combinations, the first task required the use of two above-neck gestures. Seven participants used the *head right* and *head left* gestures together, while other participants chose different gesture pairs: **P4** selected *smile* and *raise eyebrows*, **P6** chose *head up* and *head down*, **P8** opted for *smile* and *head up*, and **P9** used *open mouth* and *tilted to the right*. Two of the game

Table 3. Selected above-neck gestures² (✓ gesture used for the specified task and condition, – task not performed).

Above-neck gesture	Task - Condition	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
 Head right	T1-C2	✓	✓	✓		✓		–			✓	✓	✓
	T1-C3					✓		–				✓	✓
	T2-C1	✓	–	✓		✓	✓		✓		✓	✓	✓
	T2-C2		–										✓
	T2-C3	✓	–	✓		✓	✓		✓		✓	✓	✓
 Head left	T1-C2	✓	✓	✓		✓		–			✓	✓	✓
	T1-C3	✓						–				✓	✓
	T2-C1	✓	–	✓		✓	✓		✓		✓	✓	✓
	T2-C2		–										
	T2-C3	✓	–	✓		✓	✓		✓		✓	✓	✓
 Head up	T1-C2						✓	–	✓				
	T1-C3		✓					–			✓	✓	
	T2-C1	✓	–	✓		✓	✓		✓		✓	✓	
	T2-C2	✓	–	✓		✓	✓					✓	✓
	T2-C3	✓	–	✓		✓	✓		✓		✓	✓	
 Head down	T1-C2						✓	–					
	T1-C3							–					
	T2-C1		–	✓		✓	✓			✓		✓	✓
	T2-C2		–										
	T2-C3		–	✓		✓	✓			✓		✓	✓
 Open mouth	T1-C2							–		✓			
	T1-C3							–		✓			
	T2-C1	✓	–					✓		✓			✓
	T2-C2	✓	–							✓			
	T2-C3	✓	–					✓		✓			✓
 Smile	T1-C2							–		✓			
	T1-C3							–		✓			
	T2-C1	✓	–					✓		✓			✓
	T2-C2	✓	–							✓			
	T2-C3	✓	–					✓		✓			✓
 Raise eyebrows	T1-C2				✓			–					
	T1-C3							–					
	T2-C1		–		✓								
	T2-C2		–		✓								
	T2-C3		–										
 Close right eye	T1-C2							–					
	T1-C3							–					
	T2-C1		–		✓			✓					
	T2-C2		–		✓			✓					
	T2-C3		–					✓					
 Close left eye	T1-C2							–					
	T1-C3							–					
	T2-C1		–		✓			✓					
	T2-C2		–		✓								
	T2-C3		–					✓					
 Tilt right	T1-C2							–		✓			
	T1-C3							–					
	T2-C1		–							✓			
	T2-C2		–										
	T2-C3		–							✓			
 Tilt left	T1-C2							–					
	T1-C3							–					
	T2-C1		–							✓			
	T2-C2		–										
	T2-C3		–							✓			
 Kiss	T1-C2							–					
	T1-C3							–					
	T2-C1		–					✓					
	T2-C2		–										
	T2-C3		–					✓					

stimuli used in the second task required four actions each. The most frequently used four-gesture combination was *head right*, *head left*, *head up*, and *head down* (5 participants), which covers all four directional head movements. **P8** and **P10** replaced the *head down* gesture with *smile*, while **P1** substituted it with *open mouth*. **P12**, instead, replaced the *head up* gesture with *open mouth*. Other gesture combinations were also used. **P4** used *smile* for the down button, *raise eyebrows* for the up button, *close right eye* for the right button, and *close left eye* for the left button. **P7** selected *open mouth* for the up button, *kiss* for the down button, *close right eye* for the right button, and *close left eye* for the left button. Finally, **P9** chose *head down* for the down button, *open mouth* for the up button, *tilt left* for the left button, and *tilt right* for the right button.

Participants often selected pairs of symmetric gestures. The six participants who used *head right* also used *head left*. Similarly, both participants who used *close right eye* also used *close left eye*, and the participant who used *tilt right* also used *tilt left*. Among the 10 who selected either *head up* or *head down*, 5 also selected the other.

4.2 Comparison of Interaction Modalities

We assess differences among the above-neck gestures, external buttons, and combined interaction modalities by analyzing results from the study's first task. We evaluate round outcomes (Section 4.2.1), stimulus-to-interaction time (Section 4.2.2), and perceived workload (Section 4.2.3) across the three interaction modalities.

4.2.1 Interaction Accuracy. Fig. 5 presents the distribution of round outcomes across the three interaction modalities for both taps and long taps. For taps, selection errors occurred in 6.82% (9/132) of rounds with above-neck gestures, 1.53% (2/131) with external buttons, and 3.03% (4/132) with the combined modality. For long taps, selection errors were observed in 6.06% (8/132) of above-neck gesture rounds, 3.05% (4/131) of external button rounds, and 3.79% (5/132) of combined modality rounds. Duration errors in long taps occurred in 6.06% (8/132) of above-neck gesture rounds, 4.58% (6/131) of external button rounds, and 6.06% (8/132) of combined modality rounds. Statistical analysis did not reveal significant differences between interaction modalities for round outcomes. Round outcomes for each participant are reported in Appendix A.

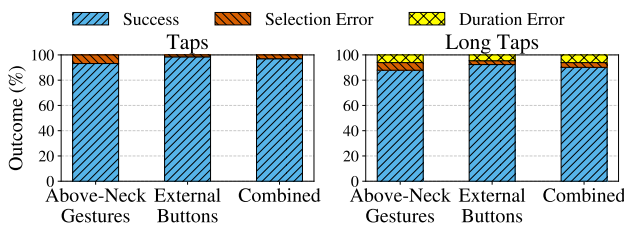


Fig. 5. Distributions of task 1 round outcomes across interaction modalities.

4.2.2 Stimulus-to-Interaction Time. Fig. 6 shows the distribution of stimulus-to-interaction times across the three interaction modalities. Mean times were 1583.75 ± 296.70 ms for above-neck gestures, 1165.09 ± 279.92 ms for external buttons, and 1357.95 ± 256.28 ms for the combined modality. Statistical analysis did not reveal significant differences among the three modalities.

4.2.3 Perceived Workload. Fig. 7 presents the distribution of NASA-TLX scores collected for above-neck gestures, external buttons, and combined interaction modalities in the first task. Mean total workload scores were 16.95 ± 10.70 for above-neck gestures, 15.97 ± 10.24 for external buttons, and

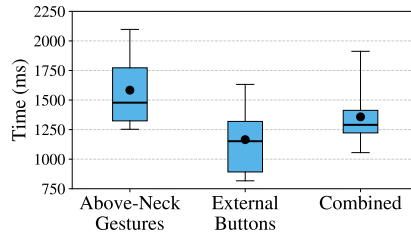


Fig. 6. Distribution of stimulus-to-interaction times across interaction modalities (• Mean, — Median).

21.04 ± 13.94 for the combined modality. All three scores fall within the first quartile for gaming applications [33]. Overall, the total scores differed significantly among modalities ($F(2, 20) = 10.687$, $p < .001$). Post-hoc pairwise comparisons revealed significant differences between the combined modality and both above-neck gestures and external buttons ($t(20) = 3.100$, $p = .006$ and $t(20) = 4.520$, $p = .009$, respectively). We did not find any significant differences between above-neck gestures and external buttons. In particular, when analyzing individual dimensions, we observed significant differences for the mental demand dimension only ($F(2, 20) = 6.916$, $p = .031$). Post-hoc analysis revealed a significant difference between the external buttons and the combined interaction modality ($t(20) = -3.709$, $p = .004$). Mean ratings and standard deviations for each dimension are reported in Appendix B.

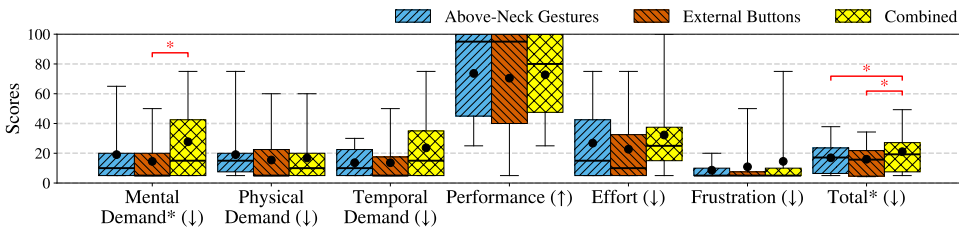


Fig. 7. Distribution of NASA-TLX scores across interaction modalities (• Mean, — Median, * Significant difference).

4.3 Perceived Workload Using Above-Neck Gestures Across Different Video Games

Fig. 8 presents the distribution of NASA-TLX scores collected for each game stimulus in the third task. Mean ratings and standard deviations for each dimension are reported in the Appendix (Table 7). Mean total workload scores were 22.08 ± 12.74 for *2048*, 35.65 ± 13.07 for *Super Mario Run*, and 34.61 ± 13.18 for *Subway Surfers*. All three scores fall within the first quartile for gaming applications [33].

Statistical analysis revealed a significant difference among the three games ($F(2, 20) = 7.005$, $p = 0.005$). Post-hoc tests identified that *2048* differed significantly from both *Subway Surfers* ($t(20) = -3.242$, $p = .006$) and *Super Mario Run* ($t(20) = -3.242$, $p = .006$), while no significant difference was found between *Subway Surfers* and *Super Mario Run*. When analyzing individual dimensions of the questionnaire, we found significant differences for the physical demand ($F(2, 20) = 8.009$, $p = .007$), temporal demand ($F(2, 20) = 8.129$, $p = .007$), effort ($F(2, 20) = 7.516$, $p = .007$), and frustration ($F(2, 20) = 5.652$, $p = .017$) dimensions. Post-hoc analysis revealed that *2048* differed significantly from both *Super Mario Run* and *Subway Surfers* for all four dimensions:

- Physical demand: 2048 vs *Super Mario Run* ($t(20) = -3.977$, $p = .002$), 2048 vs *Subway Surfers* ($t(20) = -2.381$, $p = .041$).
- Temporal demand: 2048 vs *Super Mario Run* ($t(20) = -3.689$, $p = .004$), 2048 vs *Subway Surfers* ($t(20) = -3.254$, $p = .006$).
- Effort: 2048 vs *Super Mario Run* ($t(20) = -3.411$, $p = .005$), 2048 vs *Subway Surfers* ($t(20) = -3.301$, $p = .005$).
- Frustration: 2048 vs *Super Mario Run* ($t(20) = -3.017$, $p = .017$), 2048 vs *Subway Surfers* ($t(20) = -2.793$, $p = .017$).

Consistent with the lower workload scores, when asked which game they preferred playing with above-neck gestures, nine participants selected 2048, one chose *Super Mario Run*, and one chose *Subway Surfers*.

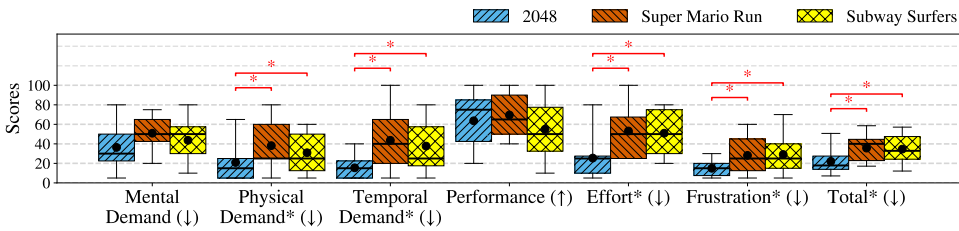


Fig. 8. Distribution of NASA-TLX scores across game stimuli (• Mean, — Median, * Significant difference).

5 Discussion

We discuss the implications of our findings for the design and future research on mobile gaming assistive technologies utilizing above-neck gestures. First, we compare participants' gesture choices with the results of prior elicitation studies, highlighting similarities and differences (Section 5.1). We then argue the importance of personalization of above-neck gestures (Section 5.2), evaluate the effectiveness of above-neck gestures as an alternative to existing interaction modalities (Section 5.3), and analyze how game genre and pacing affect user experience while playing with above-neck gestures (Section 5.4). Based on these findings, we derive a set of recommendations for using above-neck gestures in mobile gaming (Table 4). Finally, we discuss how above-neck gestures may also be utilized for PC and console gaming (Section 5.5) and report the limitations of both the *RePlay* system and our study design (Section 5.6).

Table 4. Recommendations for using above-neck gestures for mobile gaming.

Recommendations	
R1	Prefer simple gestures
R2	Favor symmetric gestures for opposing actions
R3	Personalize gestures to specific users abilities
R4	Avoid combined interaction modalities unless necessary
R5	Prioritize slower-paced games for above-neck gesture interaction

5.1 Choice of Above-Neck Gestures

Recent studies have investigated how users select above-neck gestures for interaction with mobile devices. Zhao et al.[86] conducted an elicitation study with 17 people with upper-body motor impairments, asking them to design above-neck gestures for 26 common smartphone commands, while Sun et al.[74] extended this work, focusing specifically on people with dystonia. Our study differs from theirs in its primary objective: rather than seeking a universal gesture set for daily smartphone use, our objective was to understand how personalized gestures are designed and can be used in practice during mobile gaming by users with upper-limb impairments. Due to this reason, our work and prior studies differ in the number and variety of observed gestures. Indeed, in the study by Zhao et al. participants were required to select multiple above-neck gestures in order to control a variety of typical actions used on mobile devices. The authors found that, although simple gestures were generally preferred, participants had to select a large number of actions, thus some gestures were more complex (e.g., combining eye movements and head rotations). Instead, our participants had no reason to define complex gestures, since only a maximum of four actions were required, and thus they **naturally gravitated toward movements that they could easily perform while gaming [R1]**. However, this also means that the participants explored only a small set of possible gestures, potentially missing some mappings that could result in being easier or more effective for gaming.

When multiple gestures were needed, our participants frequently selected symmetric gestures for opposing game actions. For example, the *head left / head right* pair was often used for interaction with the tree button (on the left) and the house button (on the right) in *Press the Button*. Similarly, the *close left eye / close right eye* pair was used in *2048* for left and right movements. This tendency toward symmetrical mappings aligns with both Zhao et al.'s observation of logical pairings (e.g., looking left and right for swipe left and right gestures, respectively) and Sun et al.'s finding that scroll up and down gestures naturally mapped to upward and downward head movements, respectively. This suggests that **symmetrical gestures should be preferred for opposing actions [R2]**. Notably, almost all our participants maintained the same gestures across different tasks, echoing Sun et al.'s observation that users maintain consistent gestures for related commands.

Finally, participants' choice of gestures may also be partially related to social acceptability. While the study participants operated in a controlled environment without external social constraints, they might still have implicitly preferred subtle and less conspicuous gestures, as above-neck gestures are inherently visible to others compared to less observable input modalities (e.g., external buttons). Indeed, only a few participants selected gestures such as the *kiss* (1 participant). This interpretation is consistent with Sun et al.'s findings [74], where participants deliberately avoided gestures perceived as embarrassing or visually marked in public settings.

5.2 Importance of Personalization

We demonstrated the effectiveness of above-neck gestures as an accessible alternative interaction modality for gaming, in particular when traditional assistive technologies are not effective. For example, **P7**, who was unable to use external buttons due to their disability, was able to interact with the games using above-neck gestures.

Furthermore, our study highlights that the choice of **gestures should be personalized for users' specific needs [R3]**, as opposed to prior work that employed predefined gestures [29, 31, 64, 75]. This finding aligns with ability-based design, which argues that accessible systems should focus on what users can do and provide interfaces that are matched to individual abilities [80]. This is particularly critical in the context of upper-limb impairments, where users exhibit substantial variability in motor abilities, range of motion, and physical constraints [44]. Indeed, as also observed

in prior work on personalized upper-body and above-neck gestures, static gesture sets can embed assumptions about users' abilities and may therefore be inaccessible or suboptimal for some individuals [24, 82, 86]. For example, **P2** uses a respirator that covers part of their face and limits their movement. This could make some gestures – such as the *smile* – impractical because the user cannot perform them or because they cannot be detected by the system due to occlusion by the respirator. Despite this limitation, **P2** was able to define personalized gestures and use them during the experiment, showing how user-defined mappings can accommodate individual constraints that would otherwise prevent interaction.

Finally, *RePlay* allows to define above-neck gestures through a simple and quick configuration procedure (Section 3.1.1). This enables users to redefine gestures based on changes in their abilities, thus supporting adaptability. More broadly, this reflects the principle of designing for dynamic diversity, which argues that accessible systems should account not only for differences across users, but also for changes in users' abilities and contexts over time [32].

5.3 Effectiveness of Gestures

The results of the first task demonstrate that above-neck gestures achieve comparable performance to external buttons, a common assistive technology widely adopted by players with upper-limb impairments [54], across all measured dimensions. Indeed, statistical analysis revealed no significant differences in round outcomes, stimulus-to-interaction times, or NASA-TLX scores between the two modalities. These findings suggest that above-neck gestures constitute a viable alternative interaction modality in terms of accuracy and responsiveness. At the same time, above-neck gestures have several practical advantages over external buttons. First, they do not require additional hardware, thus being more affordable and portable. Second, they are completely hands-free, meaning that they are a viable solution also for users – such as **P7** – who cannot use external buttons.

In contrast, the combined modality resulted in a significantly higher perceived workload, particularly in the mental demand dimension, despite maintaining similar task performance. We therefore suggest **avoiding combined interaction modalities unless necessary** [R4]. These findings are in agreement with prior literature [5, 72]. In particular, in a previous study involving the *RePlay* system [5], combining vocal sound actions with external buttons resulted in more cognitively demanding tasks and reduced task performance.

As a consequence, combined interaction modalities should be avoided to align with the universal design principle of “simple and intuitive use” [73], which emphasizes avoiding unnecessary complexity in interaction, and with Nielsen's heuristic “recognition rather than recall” [60], which recommends minimizing users' memory load.

5.4 User Experience Across Video Games

Participants' engagement with commercial video games during the third task of the study revealed a stark preference for *2048*. Indeed, nine out of the eleven participants who completed the task selected *2048* as their preferred game. We hypothesize that this preference pattern is due to the fact that *2048*'s turn-based nature provided participants with time to deliberate on which gesture to perform next and opportunities to rest between moves. Since the participants had no prior experience with above-neck gestures, slower pacing and pauses enabled them to focus on mastering this unfamiliar interaction modality.

This hypothesis is validated by the NASA-TLX results. Indeed, *2048* also consistently yielded the lowest perceived workload scores across all NASA-TLX dimensions. In contrast, *Super Mario Run* and *Subway Surfers* – both requiring faster reactions and sustained attention – resulted in significantly higher workload, particularly in the physical demand, temporal demand, effort, and frustration dimensions.

These findings have important implications for onboarding users to above-neck gesture interaction. Rather than immediately exposing users to fast-paced video games that may overwhelm and frustrate them, accessibility solutions should guide users through a progressive difficulty curve, **starting with slower, turn-based video games that allow users to familiarize themselves with this interaction modality** [R5]. This aligns with the “regime of competence” and “practice” principles of game tutorial design [59], which suggest that users should be challenged beyond their current abilities without making tasks unattainable, and that they should have opportunities to practice in low-risk contexts before applying learned actions to the main task. Such progressive onboarding may also help reduce early frustration, which is a relevant concern in assistive technology adoption and abandonment [21]. To assess this hypothesis, a longitudinal study could be conducted to examine how recognition accuracy, response times, and perceived workload evolve over weeks or months of regular use.

5.5 Generalizability Beyond the Mobile Gaming Context

In this work, we focused on mobile gaming, where interaction is typically based on a small set of discrete commands that can be easily mapped to above-neck gestures. In fact, mobile games are generally controlled through a limited number of actions [41]. This was the case in our game stimuli as well (Section 3.2). In contrast, standard console and PC controllers require a much larger number of inputs: a typical console controller features over 10 buttons plus two analog sticks [55, 70, 71]. Furthermore, PC games often rely on complex combinations of keyboard inputs (e.g., WASD for movement, spacebar for jumping, numeric keys for inventory management, and several others) along with mouse usage. Thus, adopting above-neck gestures for PC and console games would require investigating the feasibility of controlling a larger number of possibly concurrent inputs.

Additionally, we observed that participants naturally tended to select pairs of symmetric gestures (Section 4.1), suggesting a preference for simple intuitive mappings. With a larger number of required gestures, this strategy might no longer be sufficient, requiring more complex or less natural gestures that could be harder to execute and remember. A possible solution for reducing the number of required gestures would be to combine them with different input modalities (e.g., physical buttons). However, our results suggest that such an approach may introduce a significant additional cognitive load (Section 4.2.3).

Another difference in the application of above-neck gestures in console and PC games is related to the duration of the gaming sessions. Indeed, console and PC games have a longer duration of gaming sessions compared to mobile gaming [37], which could result in added fatigue when using above-neck gestures.

5.6 Limitations

Here we discuss apparatus limitations (Section 5.6.1) and study limitations (Section 5.6.2).

5.6.1 Apparatus Limitations. To enable the use of alternative actions to interact with the smartphone, we used the *RePlay* system, which was proposed in a prior work [5]. *RePlay* presents several advantages, including its high configurability, which allows it to support additional modules that extend the set of user actions, and its ability to control existing third-party games. However, *RePlay* presents key limitations that restrict its applicability to all video games. Specifically, it does not support mapping actions to combinations of touchscreen events (e.g., a tap and a long tap performed simultaneously) nor interactions triggered at dynamic screen positions (e.g., tapping a moving object). This means that games requiring these kinds of interactions cannot be fully supported. For this reason, our study did not test these types of games. Additionally, as highlighted in Section 3.1.1, the accessibility of the configuration process used in *RePlay* has not been addressed in this paper.

Indeed, during the study, the supervisor assisted participants in setting up the system, recording above-neck gestures and mapping user actions to screen events. While system accessibility options can be used to support this process, as future work we will also investigate the accessibility of the configuration procedure, without requiring touchscreen interactions.

5.6.2 Study Limitations. One limitation of our study was the short amount of time available to select and get acquainted with above-neck gestures. This may have affected the types of gestures participants selected for gameplay. For this reason, a longitudinal study may be necessary to explore how gesture selection evolves as participants become accustomed to this interaction modality. Additionally, our study involved 12 representative participants, a number in line with the current accessibility literature [48]. However, our participants were from a relatively homogeneous group: six had muscular dystrophy, and all 12 participants were from the same geographical region. In particular, the geographical homogeneity may have limited the types of above-neck gestures we observed during the experiments, as above-neck gestures may differ significantly according to local culture and customs. Moreover, our study was conducted in a controlled laboratory setting with a fixed device, and we did not explore the social acceptability of the gestures selected for gameplay. This aspect is particularly relevant, as above-neck gestures are inherently visible to others, unlike less conspicuous input modalities such as external buttons. The controlled setting may have limited participants' consideration of social factors; however, their gesture choices (e.g., preference for simple and less conspicuous movements) suggest an implicit awareness of these aspects. Nonetheless, these observations remain indirect and do not allow us to draw definitive conclusions. Thus, future work should explicitly investigate the social and contextual implications of above-neck gesture interaction in real-world settings.

6 Conclusions and Future Work

This paper presented the first empirical evaluation of personalized above-neck gestures as an alternative input modality for accessible mobile gaming. Our findings show that users with upper-limb impairments can successfully play a variety of mobile games using above-neck gestures, including games they would otherwise be unable to enjoy. Moreover, the performance and workload are comparable to those of traditional assistive solutions, such as external buttons. These results demonstrate the feasibility of fully hands-free, camera-based control in time-constrained mobile contexts. We also observed that participants preferred simple, symmetric, and socially acceptable gestures, confirming results previously observed in the literature [74, 86].

Many avenues for future work extending the current research are possible. First, one open question is how people with upper-limb impairments would choose above-neck gestures for gaming during day-to-day use of *RePlay*. Various factors may influence this choice, including the effectiveness of the gestures for gaming and potential fatigue during prolonged use. Longitudinal studies in everyday settings could be conducted to assess this aspect and explore the evolution of gestures over time, as well as the impact of learning and continuous use of the gestures on gaming performance. Second, future research should focus on eliciting gestures across a broader range of game genres and specific in-game actions. While our study primarily addressed common directional inputs and taps, an elicitation study could identify which above-neck gestures users perceive as most intuitive for diverse mechanics, such as character navigation, inventory management, or continuous actions, across different genres like role-playing games, strategy games, or shooters. A third aspect relates to the choice of above-neck gestures for different populations. Most of the participants in our study had muscular dystrophy, while other conditions were underrepresented. Future work may therefore assess how specific upper-limb impairments affect the choice of above-neck gestures through a series of user studies. Finally, another relevant aspect that could be investigated as future

work is the social acceptability of above-neck gesture interactions for gaming across different socio-cultural contexts (e.g., countries, age ranges) or places (e.g., public spaces, mobility).

Acknowledgments

Generative AI was used to create images of above-neck gestures in Fig. 1a and Table 3. The base image of a person was generated using Microsoft Copilot⁸ (latest version available on October 28, 2025) with the prompt: “Generate an image of a person with a neutral expression. White background.” Gesture images were created by manipulating this base image using the Expression Editor tool⁹.

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A Comparison of Interaction Modalities: Round Outcomes

Table 5. Round outcomes per participant in the first task.

(a) Above-neck gestures				(b) External buttons				(c) Combined interaction			
P#	Success	Selection errors	Duration errors	P#	Success	Selection errors	Duration errors	P#	Success	Selection errors	Duration errors
P1	24	0	0	P1	21	2	1	P1	23	1	0
P2	21	3	0	P2	22	1	1	P2	18	5	1
P3	22	0	2	P3	24	0	0	P3	24	0	0
P4	17	3	4	P4	24	0	0	P4	23	1	0
P5	24	0	0	P5	24	0	0	P5	22	0	2
P6	20	3	1	P6	24	0	0	P6	24	0	0
P8	23	1	0	P8	22	0	2	P8	21	2	1
P9	16	7	1	P9	20	3	1	P9	22	0	2
P10	24	0	0	P10	24	0	0	P10	23	0	1
P11	24	0	0	P11	24	0	0	P11	23	0	1
P12	24	0	0	P12	23	0	1	P12	24	0	0
Total	239	17	8	Total	252	6	6	Total	247	9	8

B Comparison of Interaction Modalities: NASA-TLX Scores

Table 6. NASA-TLX scores for interaction modality.

Dimension	Above-Neck Gestures	External Buttons	Combined
Mental Demand (↓)	19.09 ± 21.30	14.55 ± 14.84	27.73 ± 26.23
Physical Demand (↓)	19.09 ± 19.28	15.45 ± 16.16	16.82 ± 17.22
Temporal Demand (↓)	13.64 ± 9.32	13.64 ± 13.99	23.64 ± 24.41
Performance (↑)	73.64 ± 30.68	70.46 ± 34.54	72.73 ± 29.57
Effort (↓)	26.82 ± 24.70	22.73 ± 24.71	32.27 ± 27.50
Frustration (↓)	8.64 ± 5.68	10.91 ± 13.11	14.55 ± 20.39
Total Score (↓)	16.95 ± 10.70	15.97 ± 10.24	21.04 ± 13.94

C Perceived Workload Across Different Video Games: NASA-TLX Scores

Table 7. NASA-TLX scores for game stimulus.

Dimension	2048	Super Mario Run	Subway Surfers
Mental Demand (↓)	36.36 ± 23.94	50.91 ± 17.94	43.64 ± 20.12
Physical Demand (↓)	20.91 ± 17.69	38.18 ± 25.52	30.91 ± 20.98
Temporal Demand (↓)	15.45 ± 11.57	43.64 ± 29.55	37.73 ± 25.62
Effort (↓)	25.45 ± 21.47	53.18 ± 27.16	50.91 ± 21.62
Performance (↑)	63.63 ± 27.72	69.65 ± 22.31	55.00 ± 30.60
Frustration (↓)	15.00 ± 8.26	28.18 ± 18.37	29.09 ± 18.69
Total Score (↓)	22.08 ± 12.74	35.65 ± 13.07	34.61 ± 13.18

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