

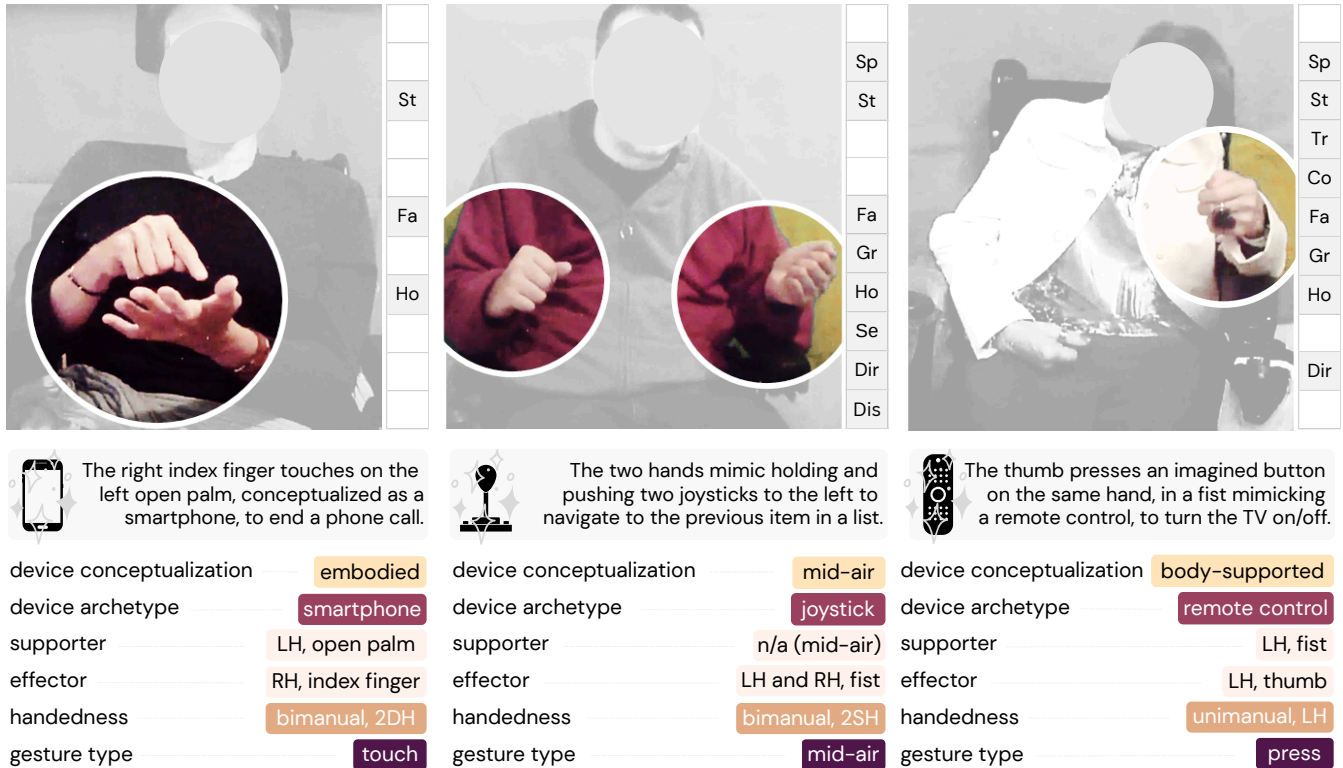
Imagine, Interact: Eliciting Accessible Interactions from Users with Motor Impairments via Imagined Input Devices

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Legend. Motor impairments: Mo = Slow movements; Sp = Spasm; St = Low strength; Tr = Tremor; Co = Poor coordination; Fa = Rapid fatigue; Gr = Difficulty gripping; Ho = Difficulty holding; Se = Lack of sensation; Dir = Difficulty controlling direction; Dis = Difficulty controlling distance.

Figure 1: Examples of imagined handheld input devices and corresponding gestures proposed by three users experiencing upper-body motor impairments, such as low strength (St), rapid fatigue (Fa), and tremor (Tr). Unlike their physical counterparts, imagined smartphones conceptualized with the open palm (top-left photo) require no effort to pick up and support their weight for someone experiencing low strength (St) and rapid fatigue (Fa); imagined joysticks can be effectively grasped even with a spastic hand (Sp) and lack of tactile sensation (Se) (top middle); and buttons on an imagined remote control can be pressed confidently against the hand forming a fist despite tremor (Tr), low strength (St), and difficulty holding (Ho) (top right).

Abstract

We present empirical results from a study conducted with eleven users with upper-body motor impairments who imagined input

devices and corresponding gestures to operate them for performing common tasks in interactive systems. We report a strong preference for embodying devices (80%), primarily through the hands, rather than holding them, and identify ten device archetypes, among which smartphones (36.4%) and remote controls (27.3%) were most prevalent. We also observed a diversity of gestures to operate imagined devices involving both unimanual and bimanual input with little consensus (.069) across participants, which we analyzed in relation to their self-reported motor impairments. Based on these



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findings, we propose design recommendations for accessible interactions involving imagined input devices, structured through the lenses of ability-based and ability-mediating design. We also outline future work opportunities for imagination-powered accessible computing, in which users' imagination plays a central role.

CCS Concepts

• **Human-centered computing** → **Gestural input**; **Accessibility technologies**; **Empirical studies in accessibility**.

Keywords

Gesture input, motor impairments, motor disabilities, imaginary devices, end-user elicitation, gesture analysis, imagination

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1 Introduction

Prevalent input devices, such as computer mice, remote controls, and touchscreens, can pose accessibility challenges for people with upper-body motor impairments, addressed through coping strategies [32,53,66] and adaptive interaction techniques [18,19,51] capitalizing on customization and personalization to individual abilities. For example, enhanced area cursors [19] improve target selection with mouse input, adaptive gesture recognition [51] increases the accuracy of attaining intended targets on touchscreens, and eyelid gestures [18] enable hands-free smartphone operation. While more accessible than non-adaptive alternatives, these techniques remain constrained by the physical characteristics of the input devices for which they were designed: computer mice still require directional force to push, smartphones still require physical handling and fine motor control for precise touch, and remote controls still require pressing buttons with sufficient force. These constraints stem from these devices' inherent physicality (through their mass, shape, size, and materials), their spatial and temporal availability (such as the need for retrieving a smartphone temporarily stored away in a pocket or bag), and from the contact-based interactions they afford through physical controls and touchscreens.

Since physicality is closely tied to these challenges, *bypassing it through design may enable new forms of interactions and novel approaches to accessible computing, based on input devices existing solely in users' imagination*. For example, a person with Spina Bifida, experiencing low strength and difficulty holding objects, may interact with their smartphone embodied as an open palm (Figure 1, left). A user with a Spinal Cord Injury, affecting their fine finger movements and causing hand spasticity, may simulate pushing an imagined joystick to navigate digital content (Figure 1, middle). A user with Parkinson's, who experiences tremor, poor coordination, and rapid fatigue, could tap with the thumb on the fist, conceptualized as a custom remote control, to turn the TV on (Figure 1, right). Such interactions, simultaneously capitalizing on users' individual motor abilities, their mental models of effective and meaningful input, and a new class of non-physical input devices exhibiting

unprecedented conceptual flexibility and adaptability, can open new opportunities for accessible computing. Unfortunately, we lack knowledge of how users with upper-body motor impairments imagine input devices suited to their motor abilities and of the corresponding gestures to operate them effectively. However, such insights are crucial for adaptive gesture-based interactions, in particular in ability-based design [74], where systems should provide the best match between the interface and users' individual abilities. In this context, the main goal of this work is to develop an understanding of gesture-based device operation under upper-body motor impairments when the input device is non-physical, and to explore how imagined devices metaphorically draw on physical analogs through archetypal relationships, embodied in and enacted through gesture movements. Our contributions are as follows:

- (1) We present empirical results from a study involving eleven participants with upper-body motor impairments, who were elicited for imagined input devices and corresponding gestures to operate them across twenty common system functions. Our findings reveal a strong preference for embodying devices, primarily through the hands, accounting for 80% of the elicited interactions, rather than mimicking holding them or having the imagined devices float in mid-air. We also report a balanced distribution of gesture types, from touch to mid-air, implemented with both unimanual and bimanual articulations, with a slight preference for the latter.
- (2) Following an agreement analysis over participants' proposed interactions, we find a moderate level of consensus regarding imagined input devices in terms of conceptualization and archetype (.345 on a scale from 0 to 1), but little agreement on their operation through gestures (.069), indicating that unique interactions arise from specific motor abilities.
- (3) Based on our empirical findings, we discuss implications for imagined input devices and accessible computing by adopting the lens of ability-based [74] and ability-mediating [69] design. We also propose future work opportunities where users' imagination plays a central part in the interaction with input devices that transcend physical limitations, remain always available, and can be operated flexibly.

These contributions mark a first step in accessibility research for understanding interactions mediated by imagined input devices, via a design approach that considers not only users' abilities but also the mental models and natural gesture behaviors that emerge once physical device form factors and constraints are removed.

2 Related Work

We build on prior work in accessible interaction design involving gesture-based input, and connect to research on imaginary user interfaces, which has so far been explored outside the accessibility community. We also draw on prior work in end-user elicitation, from which we inform the methodology applied in our study.

2.1 Accessible Input for Users with Motor Impairments

Prior work has reported on the accessibility of input devices for users with various motor abilities, including remote controls [66], conventional mice [19], mobile devices [53], and wearables [67]. For

example, Ungurean and Vatavu [66] documented the challenges and coping strategies of people with upper-body motor impairments when using conventional TV remote controls, exposing do-it-yourself modifications to make them more accessible. Among these challenges, common ones include gripping, holding, pointing the remote control, and pressing its buttons. Findlater et al. [19] studied mouse input performance, often challenging due to the fine motor corrections required in the final stage of target acquisition. Naftali and Findlater [53] investigated the mobile experiences of users with motor impairments, and reported specific challenges, such as grabbing and lifting the phone, pressing buttons, and performing gesture-based interactions for text entry, zooming, and tapping. For smart wearables, Ungurean and Vatavu [67] identified wearable comfort and the ease of donning and doffing devices as key factors affecting accessibility. Kane et al. [32] discussed situational factors affecting mobile interactions, such as crowded spaces, interruptions, and mobile device use while walking.

To address these challenges, researchers have proposed adaptive interaction techniques. Examples include enhanced area cursors for mouse input [19], eyelid pattern-based gaze input for smartphones [18], gaze input for controlling electronic devices in everyday living and work environments [62], and voice commands that enable fluid, continuous, hands-free interaction with PCs [24]. Another line of work has examined delivery of proprioceptive cues to aid movement tasks, such as compensating sensory information loss after a stroke [65] and learning inter-limb sensory-motor associations [55]. Besides being effective as assistive technologies, such techniques also maximize the use of existing abilities, resulting in not only more accessible but also more positive experiences of engaging with interactive computer systems. For example, Huang et al. [30] evaluated a high-fidelity free-eye drawing method based on unimodal gaze control, which participants with motor impairments rated highly for its usability. For computer games, Huang and Westin [29] revealed that the accuracy of gaze control and the challenge of game mechanics represent two significant impact factors for more accessible experiences. Similarly, Move-IT [1], a VR game deployed on the Oculus Rift HMD, was found to increase users' motivation for engaging with rehabilitation exercises.

In this space, gesture input has also been studied, especially due to the prevalence of touchscreens. For example, SmartTouch [51] is a gesture recognizer enabling users to interact however their motor abilities allow and still accurately resolving the intended touch targets. Bilius et al. [7] explored gesture preferences among wheelchair users for on-body, mid-air, and on-wheelchair input to control remote devices, such as turning the lights on. Carrington et al. [9] introduced Gest-Rest, a family of gesture input devices designed to fit into wheelchair armrests, enabling input without requiring large hand movements. In the same line of reducing fatigue during input, Yoda et al. [79] developed a gesture interface for users with motor impairments who cannot operate standard interface switches, with a home position for the head that allows both gestures and the use of a mouth stick for regular laptop interactions. An alternative input method for the same context involves foot-gesture recognition [78], which replaces switch-based input with a contactless interface. These innovations aim to address the physical challenges of gripping, holding, and operating input devices through gestures spanning from light touches to mid-air movements, according to

each user's individual motor abilities. Next, we turn to a different class of input devices, lacking physical form entirely.

2.2 Imaginary User Interfaces and Devices

A distinctive line of work, outside the accessibility research community, originated with Gustafson et al.'s [21] concept of imaginary interfaces, representing spatial interaction in a body-referenced frame without visual feedback. Subsequent implementations included the imaginary phone [22], imaginary remote control [16], imaginary gamepad [63], ballgames with an imagined ball [5], and imagined digital files placed in physical pockets [68]. Other system implementations, such as Reality Rifts [14], omit components central to their operation yet maintain plausible end-to-end interactions, such as an imagined ball producing a physical effect when it appears to strike a tank of water. In contrast to conventional devices, imaginary ones lack both physical form and feedback, existing entirely in users' imagination and memory.

Prior research has shown that such interactions are not only technically feasible [16,22,28], but also accurate due to transfer learning from physical counterparts [22], flexible to accommodate contextual changes [63], and fast to perform [68]. For example, imaginary devices save users the effort of retrieving the physical counterparts, thereby enabling faster interactions, such as when interacting with the phone by tapping and sliding on the open palm [22]. Despite the lack of visual feedback, empirical findings revealed that targets as small as 9.5mm wide can be reliably acquired on the palm conceptualizing a mobile device. Steins et al. [63] extended imaginary interfaces to video games to enable quickly switching to the best-suited input device as the game scenario changed, and explored imagined steering wheels, joysticks, gamepads, gaming gun controllers, keyboards, mice, and touchpads. A guessability study revealed 92.7% gesture recognition accuracy for mimicking mouse input, while a user performance experiment showed throughputs of 2.5 and 2.3 bits/s for imagined steering wheels and mice, comparable to those of physical devices. PalmRC [16], an imaginary TV remote control conceptualized on the palm, achieved 90% input accuracy for targets of 28mm in diameter with interactions detected using a Kinect depth sensor. Finally, Mouseless [50] is an imagined input device that replicates the familiar interactions afforded by a computer mouse, but without the physical device itself—in this case, the hand conceptualizes both the mouse and its operation through hand movements and finger taps.

Imaginary devices have been implemented with gloves and motion tracking systems [63], wearable cameras [21], and depth sensors [16,22], and have spurred development of new algorithmic approaches to support gesture-based interaction. For example, Holz and Wilson [28] introduced Data Miming, a technique for inferring spatial object descriptions from user gestures, with 60% accuracy across a set of forty objects and 87% for the top three most likely candidates. The VirtualGrasp technique [77] enables users to retrieve virtual objects through grasping gestures as if they were reaching for the actual physical counterparts, with 76% accuracy under no prior exposure and 93% a week after learning the mappings between grasping gestures and objects. Interactions with digital files placed in pockets [68] were found to be 99% accurate, under user-independent testing, for a set of twenty gesture-pocket

combinations. Moreover, production times of body-referenced gestures to reach impalpable digital content in physical pockets were comparable to those of touch interactions on mobile devices [68].

2.3 End-User Gesture Elicitation Studies

In this work, we adopt the method of end-user elicitation, originally introduced for guessability studies involving symbolic input [73] and later applied to gesture interaction [76]. Since its introduction, this method has been widely adopted in HCI research to identify consensus gesture sets for various application domains, including mobile interactions [60], augmented reality [56], smart homes [38], drones [11], and deformable displays [39]. In these studies, participants are prompted to propose gestures they find suitable for effecting specific tasks, such as zooming into a map or turning on a TV. We refer to Villarreal et al.'s [72] systematic review for an overview of the scope and impact of gesture elicitation studies.

According to the most recent formalization of the method [71], outcomes may include consensus gesture sets, such as for smart home control [38], and empirical insights into user preferences, behavior, and performance, as in examining gesture memorability on touchscreens [52]. Notably, prior elicitation studies have revealed user preferences for imaginary devices, such as knobs, keyboards, or remote controls operated in mid-air. For example, Arora et al. [2] recorded 133 interactions involving imaginary menus, buttons, and sliders; Wobbrock et al. [76] observed user interactions within an imaginary digital space around a tabletop; and Gheran et al. [20] reported preferences for imagined devices, such as holding a remote control, in their study of smart ring gestures. These findings suggest that imaginary devices, beyond a design exercise [21,22,63], are an intuitive mode of interaction as they emerge naturally when users are prompted to propose commands for interactive systems. However, these instances were only sporadic, as these studies neither involved participants with motor impairments nor explicitly prompted users to imagine devices for a systematic investigation.

2.4 Summary

Prior research has explored custom gesture-based interaction techniques for users with diverse motor abilities, but these approaches have typically been tied to physical devices. Meanwhile, work on imaginary devices and user interfaces has revealed benefits of leveraging transfer learning from physical counterparts, enabling users to bypass physical device manipulation for always-available input, yet this research has been conducted outside the accessibility community. To date, these two lines of research have progressed in parallel, but their intersection offers an opportunity to address accessibility challenges associated with physical devices. In the next section, we present a study designed to examine the preferences of users with upper-body motor impairments for imagined input devices and accessible gestures to conceptualize and operate them.

3 Study

We conducted a study to collect preferences from users with upper-body motor impairments regarding imagined input devices and their operation through gestures. The goal of this investigation was to develop an understanding of gesture-based device operation under motor impairments when the input device is not physical

toward design of accessible input bypassing physical devices. This scope encompasses challenges of operating non-physical entities from the perspective of how they are metaphorically grounded in physical analogs through archetypal relationships, e.g., using the fist as a remote control, and how they are enacted under specific motor impairments, e.g., rapid fatigue. To this end, we adopted the end-user gesture elicitation method [76], in its most recent formalization [71], to explore how such devices are conceptualized in relation to the users' body, proximal space, and motor abilities.

3.1 Participants

Eleven people (eight male and three female), aged between 32 and 60 years ($M=47.7$, $SD=7.8$), took part in the study. Inclusion criteria required upper-body motor impairments that affected hand functioning. Most of the participants reported low strength, rapid fatigue, and difficulties experienced while gripping and holding objects. All participants also had mobility impairments and were wheelchair users. More demographic details are available in Table 1.

3.2 Procedure

Participants signed a consent form and filled out a questionnaire with demographic information. They were then elicited about preferences for imagined input devices in a smart home context, following prior work [18,67] highlighting needs of users with motor and mobility impairments for remotely controlling appliances. According to terminology in end-user elicitation [76], interactive tasks are referred to as "referents." Following Villarreal-Narvaez et al.'s [72] systematic literature review, twenty frequently used referents were selected based on the most-cited gesture elicitation studies. The referents were presented using textual descriptions, available in Table 2, and the following instructions:

Imagine a suitable input device to perform each of these tasks. You may imagine one device for all tasks or multiple devices that best fit each individual task. Since these devices exist only in your imagination, they can take any form, shape, and size to best accommodate your motor abilities, and may include any controls you wish, e.g., buttons, sliders, displays, or others. You may use one or both hands to operate them. The interactions should be a good fit to each task, easy to perform, easy to recall, and distinct enough to be easily recognized by both you and an external observer.

The order of referents was randomized per participant. For each referent, both an imagined input device and a corresponding gesture to operate it were elicited. The sessions were video-recorded.

3.3 Design

The study was a within-subjects experiment with one independent variable, REFERENT, nominal with twenty conditions representing common system functions. Following established practice of end-user elicitation studies [7,45,52,56,60], referents were grouped into categories, specified with the REFERENT-CATEGORY nominal variable, with four conditions—*Devices*, *Content*, *Actions*, and *Navigation*—each with an equal number of referents; see Table 2. Dependent variables consisted of measures collected directly from participants or extracted from the video recordings; see next.

Table 1: Demographics of participants with self-reported motor impairments described using the categories from [19].

Participant (age, gender)	Health condition [‡]	Years with imp.	Self-reported impairments [†]											Total	
			Mo	Sp	St	Tr	Co	Fa	Gr	Ho	Se	Dir	Dis		
P ₁ (48 yrs., female)	Spina Bifida	48	-	-	■	-	-	■	-	■	-	-	-	-	3
P ₂ (38 yrs., male)	Spinal Cord Injury (C5)	15	-	-	■	-	-	■	■	■	-	■	■	■	6
P ₃ (48 yrs., male)	Spinal Cord Injury (C5)	18	-	-	-	-	-	-	■	■	■	■	■	■	5
P ₄ (32 yrs., male)	Spinal Cord Injury (C7)	16	-	-	-	-	-	-	■	-	-	-	-	-	1
P ₅ (51 yrs., male)	Multiple Sclerosis	37	■	-	■	-	■	■	-	■	-	-	-	-	5
P ₆ (47 yrs., male)	Traumatic Brain Injury	28	■	-	-	-	■	■	-	-	-	-	-	■	4
P ₇ (49 yrs., female)	Cerebral Palsy	47	-	■	■	-	■	-	■	■	-	■	■	■	7
P ₈ (60 yrs., male)	Spinal Cord Injury (T7)	11	-	-	-	-	-	■	-	■	-	-	-	-	2
P ₉ (44 yrs., male)	Spinal Cord Injury (C5)	21	-	■	■	-	-	■	■	■	■	■	■	■	8
P ₁₀ (52 yrs., male)	Multiple Sclerosis	16	■	-	■	-	■	-	■	■	-	-	-	■	6
P ₁₁ (56 yrs., female)	Parkinson's	16	-	■	■	■	■	■	■	■	-	■	-	-	8
Summary			3	3	7	1	5	7	7	9	2	5	6		

[†]The code in the parentheses denotes the affected vertebra(e), e.g., “Spinal Cord Injury (C5)” refers to a traumatic injury at the 5th cervical vertebra.

[‡]From [19]: Mo = Slow movements; Sp = Spasm; St = Low strength; Tr = Tremor; Co = Poor coordination; Fa = Rapid fatigue; Gr = Difficulty gripping; Ho = Difficulty holding; Se = Lack of sensation; Dir = Difficulty controlling direction; Dis = Difficulty controlling distance.

3.4 Measures

3.4.1 Motor impairments. Self-reported motor symptoms and impairments were collected using the eleven categories from Findlater et al. [19], such as slow movements (Mo), rapid fatigue (Fa), spasm (Sp), or tremor (Tr); see Table 1.

3.4.2 Device and gesture characteristics. The following information was manually extracted from the recorded videos:

- **DEVICE-CONCEPT**, nominal variable, indicates the specific conceptualization of the imagined input device. By adopting a body-centered interaction design perspective for on-body [26] and around-body [13] interfaces, we identified four categories for this variable, defined according to the increasing proximity of the imagined device to the participant’s body: (i) *embodied*, a body part serves directly as the device, e.g., the left hand in an open-palm pose represents a smartphone; (ii) *body-supported*, the imagined device is held, mounted on, or supported by a body part, e.g., the right hand holds an imagined remote control; (iii) *wheelchair-supported*, the device is mounted on the wheelchair, e.g., an imagined push button on the left armrest; and (iv) *mid-air*, the device is operated in free space, e.g., pushing a joystick forward with the hand forming a grasping fist.
- **DEVICE-ARCHETYPE**, nominal variable, specifies the archetype of the imagined input device, with the following categories identified during the analysis of participants’ videos: *joystick*, *keyboard*, *photo camera*, *push button*, *remote control*, *selfie stick*, *smartphone*, *smartwatch*, *smartglasses*, and *tablet*.
- **SUPPORTER**, nominal variable, refers to the body part used to mimic, hold, or support the imagined device, such as the *right hand* holding a smartphone, drawing on categorizations previously used for on-body input [6,27], which frame the body as an interaction surface or support. By analogy, SUPPORTER

captures this role in imagined devices. However, when the input device is conceptualized in free space, SUPPORTER is labeled as *mid-air*.

- **EFFECTOR**, nominal variable, indicates the specific body part used to effect the gesture to operate the imagined device, such as the *index finger* of the right hand touching the left open palm conceptualizing a smartphone. This measure was informed by Vatavu and Gheran’s [70] concept of the implementer in intermanual gesture input, referring to the moving body part that enacts a gesture on a supporting surface. By analogy, EFFECTOR captures which body part actively executes the gesture on the imagined device and, together with SUPPORTER, specifies the roles of different body parts in interactions involving non-physical devices.
- **HANDEDNESS**, nominal variable adopted from McNeill’s [48] gesture coding system, specifies the hand(s) involved in articulating a gesture, with four categories: *right hand* (RH), *left hand* (LH), *two same hands* (2SH), and *two different hands* (2DH).¹ The last two categories describe bimanual gestures, distinguishing whether both hands perform the same (2SH) or different (2DH) poses and movements. For example, tapping a mid-air button with the right index finger is coded as RH, whereas tapping on the left hand as 2DH.
- **GESTURE-TYPE**, nominal variable, for which the following four common categories in gesture-based interaction with handheld devices were used, adopted from prior elicitation studies [7,20,60]: *touch* and *swipe* (gestures involving light contact with a touch-sensitive surface, such as a smartphone, and directional movements across it), *press* (interactions involving buttons that require greater applied force than a simple touch), and *mid-air* (gestures involving movement

¹Terminology and abbreviations defined by McNeill [48, p. 379] for gesture coding, which we adopt here exactly for consistency.

Table 2: The list of referents used in the end-user elicitation study, drawing on prior work. For each referent, an imaged input device and a corresponding gesture to operate it were elicited.

Referent category/Referent	Description provided to participants	References [†]
Devices		
1 Turn on/off the TV	Turn on/off the TV (the TV turns on if it is off and vice versa)	[7,18,38]
2 Turn on/off lights	Turn on/off the lights (lights turn on if they are off and vice versa)	[7,38]
3 Place/answer call	Open the phone application to answer an incoming phone call or place a call	[7,60]
4 End call	End the current phone call	[60]
5 Take photo	Take a photo of what is in front of you	[11,80]
Content		
6 Photo/video	Get direct access to photos/videos; the first photo is displayed on a screen	[7,10,38]
7 Music	Get direct access to music; the first file starts playing	[7,10]
8 Email	Get direct access to email; the most recent email is displayed on a screen	[7,10,38]
9 Agenda/calendar	Get direct access to the agenda/calendar, displayed on a screen	[7]
10 Social media/notifications	Get direct access to the most recent notifications, displayed on a screen	[7,10,18,45]
Actions		
11 Accept	Answer positively to a system question, confirm selection, “OK”	[33,45,56,76]
12 Reject	Answer negatively to a system question, reject action, “Cancel”	[33,45,56,76]
13 Undo	Cancel or reverse the effect of the most recently executed command	[7,18,33,56,76]
14 Menu access	Open the menu of the current application, e.g., show the TV menu	[7,18,33,52,56,76]
15 Home screen	Go to the home screen of the current application	[18,39,45,52,60]
Navigation		
16 Next [‡]	Advance to the next element in a list, e.g., show the next photo, next TV channel	[33,38,39,56,60,76]
17 Previous [‡]	Go back to the previous element in a list	[33,38,39,56,60,76]
18 Increase [§]	Increase the value of a parameter, e.g., audio volume, light intensity, etc.	[7,52,56,76,80]
19 Decrease [§]	Decrease the value of a parameter, e.g., audio volume, light intensity, etc.	[7,52,56,76,80]
20 Task/tab switch	Switch to another task or tab in the current application	[18,33,52,60,76,80]

[†]Papers from the scientific literature on end-user gesture elicitation, from which referents were selected, included: the most influential gesture elicitation studies, according to [72], elicitation studies with people with motor impairments [7,18,45,80], and studies focused on content type [10]. [‡]Also referred as “next horizontal” and “previous horizontal” in prior work. [§]Also referred as “next vertical” and “previous vertical” in prior work.

of the device in space or holding it in a specific position and orientation). The distinction between *touch* and *press*, beyond differences in duration and pressure, also reflects differing motor demands, such as precision, applied force, and stable contact. The distinction between the first three gesture types and *mid-air* further reflects differing abilities to control movement direction in free space.

Figure 1, on the first page, presents examples of gestures coded using these measures. Two raters independently extracted information from the video recordings, with Cohen’s κ inter-rater agreement coefficients ranging from .748 to .968 ($p < .001$), with an average of .830 (SD=.082). Three coefficients fell within the “almost perfect” range—DEVICE-ARCHETYPE (.964), EFFECTOR (.879), and GESTURE-TYPE (.839)—and the rest revealed “substantial” agreement—DEVICE-CONCEPT (.779), SUPPORTER (.748), and HANDEDNESS (.770). Any disagreements were resolved by revisiting the video recordings.

3.4.3 Consensus among elicited interactions. Consensus among proposed input devices and gestures was evaluated with the agreement rate measure, computed automatically from the gesture descriptions following the “computer” model [71]:

$$AR_{\epsilon}(R) = \frac{\sum_p \sum_{q \neq p} [\delta(p, q) \leq \epsilon]}{N(N-1)} \quad (1)$$

where N is the number of device-gesture proposals elicited for referent R , δ is the dissimilarity function used to compare two individual proposals p and q , ϵ is a positive value representing the tolerance at or below which two proposal descriptions are sufficiently similar to be considered equivalent, and $[\cdot]$ is Kronecker’s function that evaluates to 1 when the inner expression is true and 0 when false. With this definition, AR takes values between 0 (no agreement) and 1 (all proposals are equivalent). We represent proposals with the six measures described previously, e.g., p may be (*embodied, tablet, forearm, index finger, 2DH, touch*). Since these variables are categorical, we followed recommendations in [71] and implemented δ with Lin’s [42] probabilistic information theoretic approach, one of the best performing distances for categorical data [8]:

$$\delta(p, q) = 1 - \sum_{k=1}^6 w_k S_k(p_k, q_k) \quad (2)$$

where $S_k(p_k, q_k)$ is the per-attribute similarity between any two values of the k -th categorical attribute, and w_k is the weight assigned to the k -th attribute, as follows:

$$S_k(p_k, q_k) = \begin{cases} 2 \log(\pi_k(p_k)) & p_k = q_k \\ 2 \log(\pi_k(p_k) + \pi_k(q_k)) & \text{otherwise} \end{cases} \quad (3)$$

$$w_k = \frac{1}{\sum_{k=1}^d \log(\pi_k(p_k)) + \log(\pi_k(q_k))} \quad (4)$$

$\pi_k(x)$ is the sample probability of the k -th attribute to take value x , which we estimated from our collected data, e.g., $\pi_1(\text{embodied})=.800$, $\pi_2(\text{tablet})=.136$, $\pi_3(\text{forearm})=.045$, $\pi_4(\text{index finger})=.409$, $\pi_5(2DH)=.536$, and $\pi_6(\text{touch})=.382$ for the previous example; see Section 4 that presents these results. According to Eq. 3, Lin’s [42] measure assigns higher weights to matches on frequent values and lower weights to mismatches on infrequent values [8].

3.5 Statistical Analysis

Repeated measurements extracted from the videos were aggregated and Wilcoxon tests were performed to compare observed percentages against expected ones, e.g., a 25% a priori theoretical chance of observing an *embodied* device in the four-category DEVICE-CONCEPT dependent variable. To examine the effects of REFERENT and REFERENT-CATEGORY on the categorical variables, such as DEVICE-ARCHETYPE or HANDEDNESS, generalized linear mixed-effects models were employed with the Poisson distribution and Powell’s BOBYQA optimizer [4]. For agreement rate analysis, we used interpretation recommendations from the most recent formalization of the end-user elicitation method [71].

4 Results

We present results on participants’ conceptualizations of imagined devices and corresponding gestures, and the relationships with their specific motor impairments. We are also interested in any consensus forming among participants’ proposed interactions.

4.1 Conceptualizations of Imagined Input Devices

We found that the vast majority of the imagined input devices were conceptualized as *embodied* (80.0%), a percentage significantly higher than the 25.0% theoretical chance level for this four-category variable ($V=66.0$, $p=.004$); see Figure 2, left. This was followed, at a considerable distance, by devices imagined as floating in *mid-air* (13.2%) with a percentage significantly lower than chance ($V=0.0$, $p=.013$). The *embodied* conceptualization was the only one consistently present across all referents and, even more, in a substantial proportion with at least 45.5%. A Friedman rank sum test revealed a statistically significant difference among the four conceptualizations ($\chi^2_{(3)}=22.697$, $p<.001$), with pairwise Wilcoxon signed-rank tests (FDR-adjusted p -values) showing significant differences between *embodied* and all other DEVICE-CONCEPT categories ($p=.010$) as well as between *mid-air* and *wheelchair-supported* ($p=.035$) imagined devices. We did not find significant effects of REFERENT-CATEGORY ($\chi^2_{(3)}=1.817$, $p=.611$) or REFERENT ($\chi^2_{(19)}=13.213$, $p=.828$) on DEVICE-CONCEPT, indicating a relatively similar distribution of the four conceptualizations across the twenty referents in our study—either as the pair *embodied* and *mid-air* devices (e.g., the case of *Navigation* referents, such as “increase” or “next”), or as *embodied* (e.g., most of the *Actions*, such as “accept” or “reject”); see Figure 2, left.

The most frequently observed device archetype was that of a *smartphone* (36.4%), a percentage significantly higher than the 10% theoretical chance level for this ten-category variable ($V=66.0$,

$p=.004$), followed by *remote control* (27.3%, $V=52.0$, $p=.014$), *joystick* (14.5%, $V=45.0$, $p=.074$, *n.s.*), and *tablet* (13.6%, $V=51.0$, $p=.110$, *n.s.*), cumulatively accounting for 91.8% of the imagined devices; see Figure 2, middle. The *smartphone* was the only archetype consistently observed across all referents, whereas *photo camera*, *selfie stick*, *push button*, and *smartglasses* each occurred for only one referent. A Friedman rank sum test revealed a statistically significant difference among the DEVICE-ARCHETYPE categories ($\chi^2_{(9)}=56.975$, $p<.001$), with pairwise Wilcoxon signed-rank tests (FDR-adjusted p -values) showing significant differences between *smartphone* and all other categories ($p<.05$) except *remote control* ($p=.738$, *n.s.*), and between *remote control* and all categories ($p<.05$) except *tablet* ($p=.103$, *n.s.*) and *joystick* ($p=.221$, *n.s.*). We also found statistically significant effects of REFERENT-CATEGORY ($\chi^2_{(3)}=27.890$, $p<.001$) and REFERENT ($\chi^2_{(19)}=131.91$, $p<.001$) on DEVICE-ARCHETYPE, indicating that specific devices were imagined in response to different referents. For example, effecting referents in the *Actions* category was divided between *remote control* (54.5%) and *smartphone* (36.4%) use, whereas *Content* referents were associated more frequently with *smartphone* (40.0%) and *tablet* (45.5%) devices, with a negligible percentage of *remote controls* (3.6%).

The analysis of the SUPPORTER body part involved in giving shape to these conceptualizations revealed a high prevalence for the *hands* (66.8%), observed either in an open palm or a fist; see Figure 2, right. These poses indicate actions related to mimicking, supporting, or holding the imagined input device for representation, stabilization, and operation/interaction. At a considerable distance, the *thigh*, *wrist*, and *forearm* followed, amounted to 17.2%. The observed difference among the SUPPORTER categories was statistically significant ($\chi^2_{(5)}=38.819$, $p<.001$), with the percentage of using the hands being significantly higher than all other body parts ($p<.015$).

4.2 Gestures for Imagined Input Devices

Gesture types varied between *touch* (38.2%, significantly higher than chance, $V=48.0$, $p=.041$) and *press* (28.2%, $V=37.5$, $p=.719$, *n.s.*), followed by *mid-air* (24.1%, $V=13.0$, $p=.932$, *n.s.*), and *swipe* (9.5%, $V=0.0$, $p=.004$); see Figure 3, left. A Friedman rank sum test revealed a statistically significant difference among the GESTURE-TYPE categories ($\chi^2_{(4)}=10.029$, $p=.018$), with pairwise Wilcoxon signed-rank tests (FDR-adjusted p -values) showing significant differences between *swipe* and all other gesture types ($p<.05$). We detected a marginally significant effect of REFERENT-CATEGORY ($\chi^2_{(3)}=7.630$, $p=.054$) and a significant effect of REFERENT ($\chi^2_{(19)}=48.977$, $p<.001$) on GESTURE-TYPE, indicating that different gesture types were found suitable for different referents. For example, the referents in the *Content* category received more *touch* gestures, such as “social media/notifications” (63.6%) and “photo/video” (72.7%), whereas *Actions* involved a relatively equal number of *touch* and *press* input, such as “menu” (45.5% and 45.5%) or “accept” (45.5% and 40.0%).

More than half (58.6%) of the proposed gestures were bimanual, with the two hands more frequently involved in different poses or motions (53.6% for 2DH, $V=63.0$, $p=.009$) than in symmetric ones (5.0% for 2SH, $V=0.0$, $p=.005$); see Figure 3, middle. Although bimanual gestures typically require more physical effort than unimanual ones, this outcome emerged because one hand often mimicked or

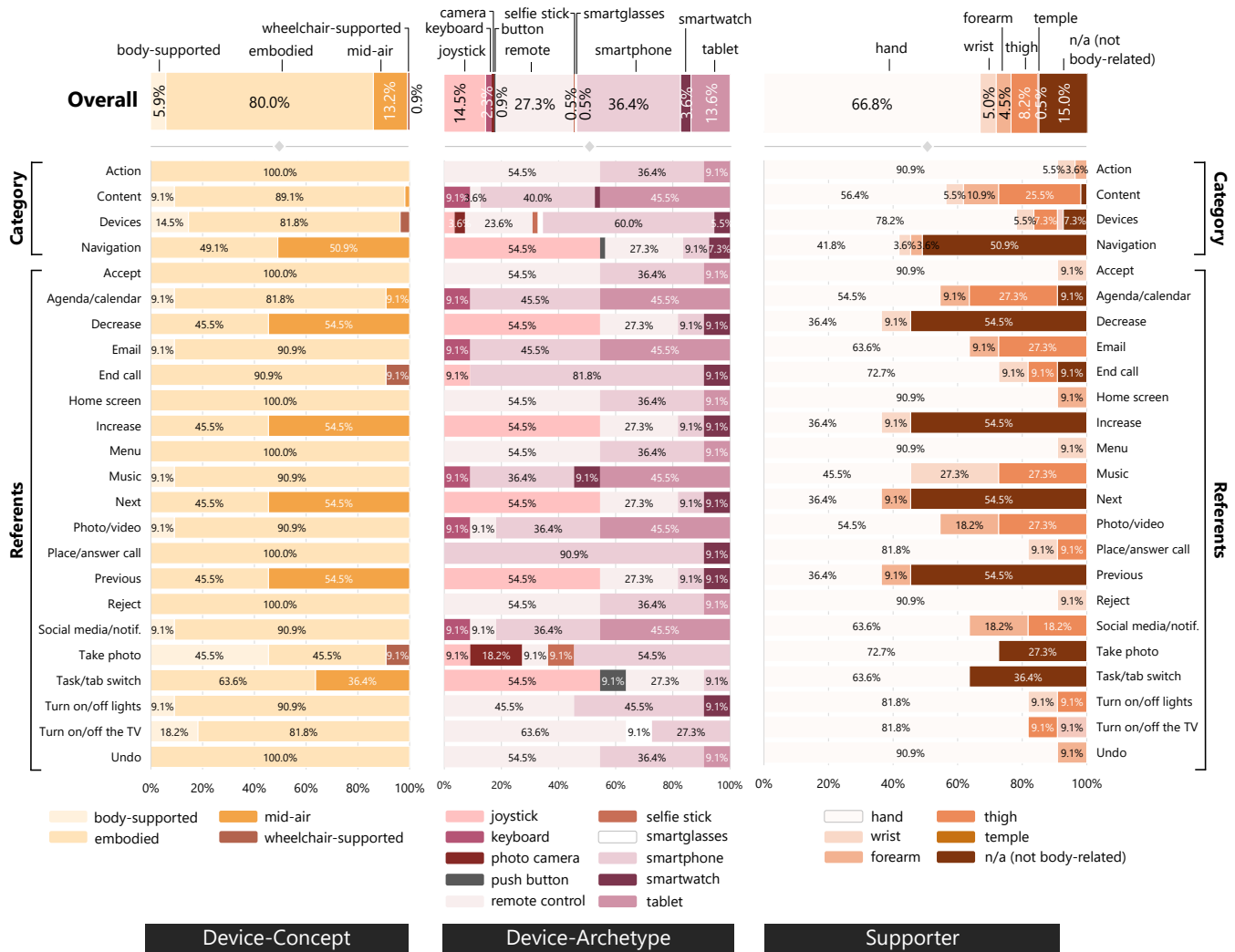


Figure 2: Conceptualization categories (left), device archetypes (middle), and support body parts (right) for the imagined devices, shown per referent, referent category, and across all referents. Note the high prevalence of *embodied* conceptualizations (left), frequent references to *smartphones* and *remote controls* (middle), and large use of the *hands* to embody or support devices.

supported the imagined device while the other performed input on it, such as touching the center of the open palm with a finger of the opposite hand. A Friedman rank sum test revealed a statistically significant difference among the HANDEDNESS categories ($\chi^2_{(3)}=18.35, p<.001$), with pairwise Wilcoxon signed-rank tests (FDR-adjusted p -values) showing significant differences between 2DH and both 2SH ($p=.020$) and LH ($p=.020$). We also found statistically significant effects of REFERENT-CATEGORY ($\chi^2_{(3)}=11.010, p=.012$) and REFERENT ($\chi^2_{(19)}=63.759, p<.001$) on HANDEDNESS, indicating that the use of one or both hands was determined by the specific nature of the referents. For example, *Navigation* referents, such as “next” and “previous,” received more unimanual gestures (63.6%), whereas bimanual gestures reflecting conceptualizations of devices requiring two-handed operation were more common for *Actions*, such as “reject,” “menu access,” and “home screen” (72.7%).

The EFFECTOR measure revealed that the *index finger* and *thumb* were frequently used (40.9% and 39.1%); see Figure 3, right. These results complement those of the SUPPORTER body part, reported in Figure 2, right, where the imagined device was conceptualized or held with one hand, which favored input with the opposite fingers. A Friedman rank sum test revealed a statistically significant difference among the EFFECTOR categories ($\chi^2_{(4)}=24.081, p<.001$). A notable effector, occurring only for one participant and one referent, was *eye gaze*, with the participant proposing gazing at the left wrist to effect “turn on/off lights.” There was no significant effect of REFERENT-CATEGORY ($\chi^2_{(3)}=1.340, p=.720, n.s.$) or REFERENT ($\chi^2_{(19)}=6.069, p=.998, n.s.$) on EFFECTOR, indicating a relatively uniform distribution of the body parts used to implement gestures for imagined input devices across the referents used in our study.

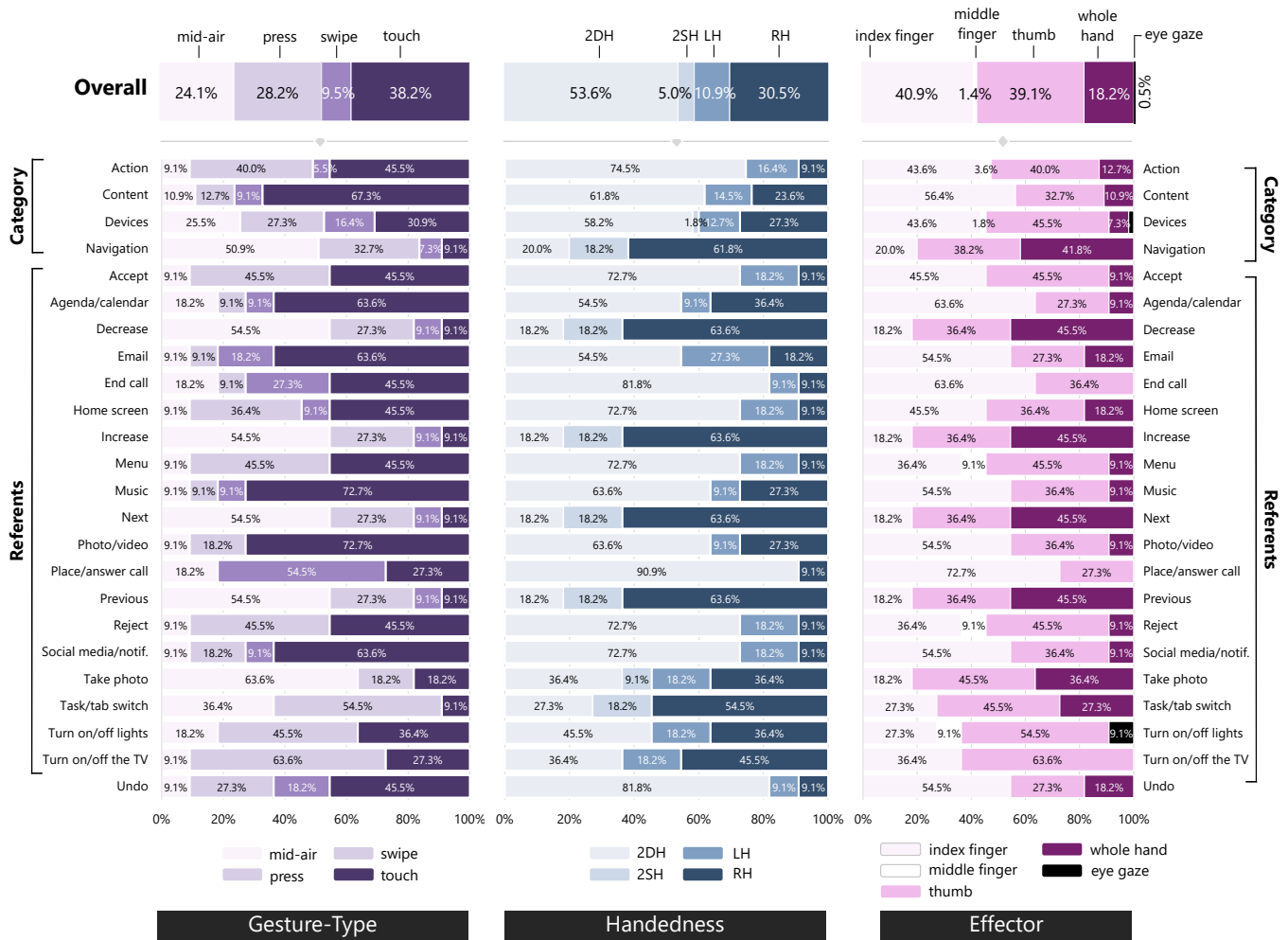


Figure 3: Gesture type (left), handedness (middle), and effector (right) for the proposed gestures, shown per referent, referent category, and across all referents. Note the relative uniform distribution of *mid-air*, *press*, and *touch* input (left), similar preference for both *bimanual* and *unimanual* operation (middle), and frequent use of the *index* and *thumb* fingers (right).

4.3 Consensus Formation for Imagined Input Devices and Corresponding Gestures

We found a relatively large consensus with respect to how the devices were conceptualized, measured in terms of DEVICE-CONCEPT and DEVICE-ARCHETYPE. The agreement rate values, computed with $\epsilon=0$, ranged between .145 for “take photo” and .818 for “place/answer call” with a mean of .345 (SD=.156); see Figure 4. This value is higher than the average of .250 (SD=.200) found in previous gesture elicitation studies [72, p. 27] on a corpus of 267 papers. Moreover, it is not significantly different ($V=138, p=.224, n.s.$) from .300, the threshold for medium agreement [71, p. 41]. However, when we also considered the gestures in the analysis through the additional EFFECTOR, SUPPORTER, GESTURE-TYPE, and HANDEDNESS measures, the average AR dropped to a mere .069 (SD=.053), with a minimum of .000 (no consensus at all) for “email” and a maximum of .164 for “increase,” “decrease,” “next,” and “previous,” being significantly smaller ($V=54.0, p=.029$) than .100, the threshold for low

agreement [71, p. 41]. Instead of revealing a consensus set of interactions, as typical in gesture elicitation studies [71,72], our findings show that, while input devices are more consistently conceptualized across participants, the way in which they are implemented and operated through gestures induce user-specific articulation aspects, which indicates the need for personalized and ability-based design. To this end, we look in the following at the relationships between imagined devices, gestures, and participants’ motor impairments.

4.4 Relationship to Motor Impairments

Figure 5 presents each participant’s preferences for both imagined input devices and gestures to operate them, visualized as heatmaps based on the measures discussed in Subsections 4.1 and 4.2. The first eleven columns represent the motor impairments self-reported by participants, according to the categories from [19]. The remaining columns represent the specific categories of the device and gesture measures, with darker tones indicating stronger participant

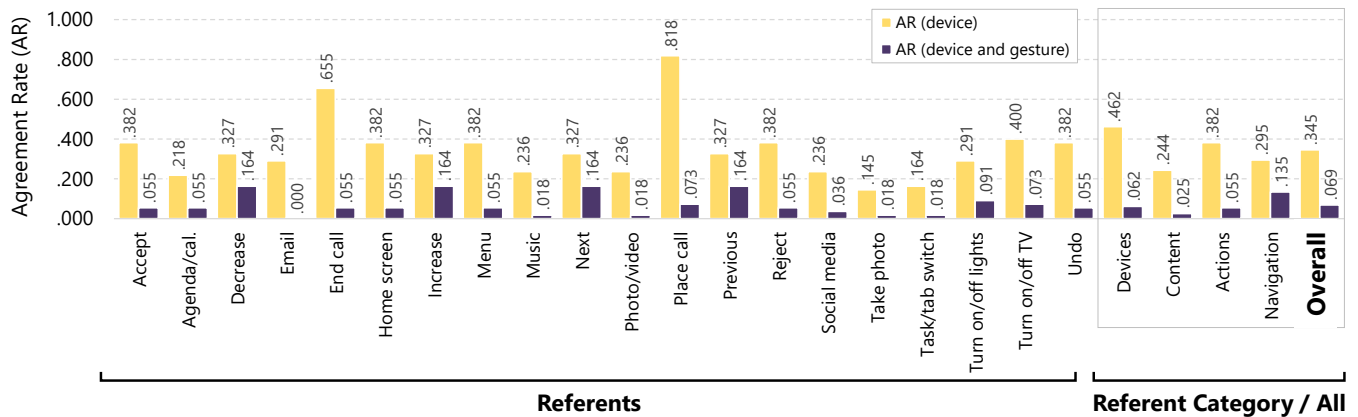


Figure 4: Consensus among participants’ preferences for imagined input devices and for operating them with gestures. Note the considerably higher agreement in conceptualizing devices (.345), five times greater than in the gestures to operate them (.069).

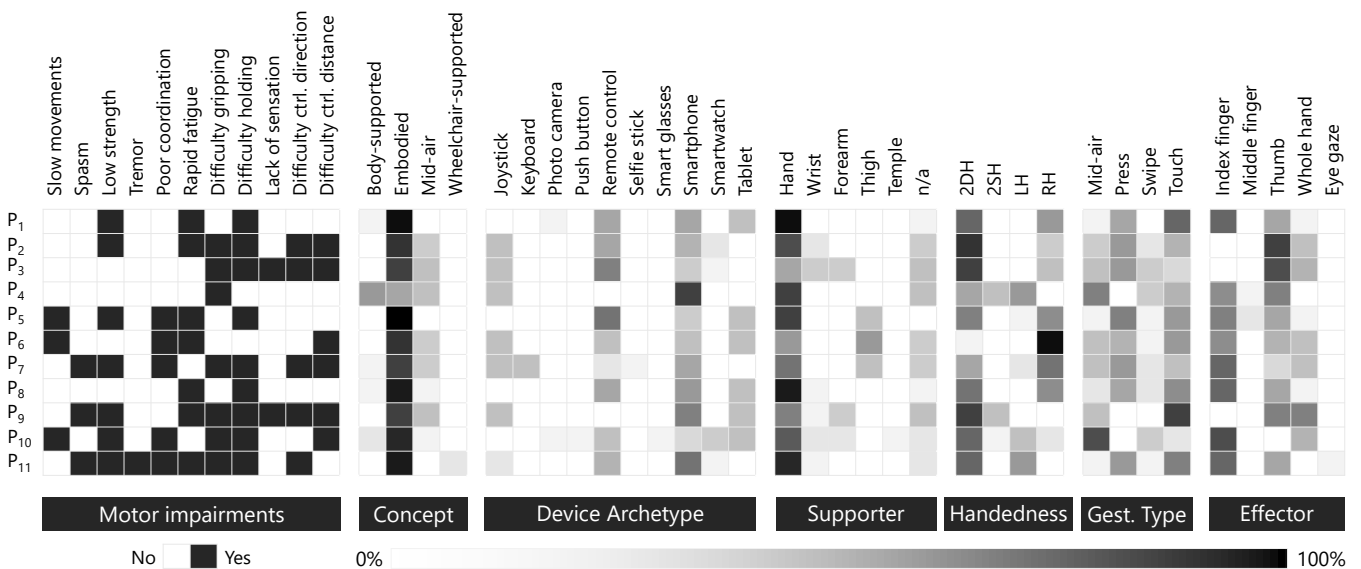


Figure 5: Individual preferences for imagined devices and corresponding gestures, shown next to participants’ self-reported motor impairments. Note similarities in device conceptualization and archetype, yet differences in gesture articulation.

preference. For example, participant P₁, shown on the first row, expressed a strong preference for embodied conceptualizations involving 2DH and RH configurations as well as for touch gestures effected with the index finger on the support offered by the opposite hand. Participants’ preferences appear visually aligned in terms of DEVICE-CONCEPT and DEVICE-ARCHETYPE, with consistent shadings across rows, which confirms the higher agreement rate for imagined devices (Figure 4). However, their preferences diverge across the gesture articulation measures. In the following, we look at individual interaction preferences through the lens of participants’ specific motor impairments.

Participants P₅, P₆, and P₁₀, who reported slow movements, generally favored remote controls, smartphones, and tablets—all devices that afford button presses or touch input rather than operation

through large-amplitude movements. These preferences align with small-scale, low effort interactions, given that these participants also reported rapid fatigue or low strength. Furthermore, P₅ and P₆ were two of the three participants in our sample that proposed using the thighs, where the arms naturally rest, to support their conceptualizations of imagined devices. P₆ said: “I always keep my phone on my right leg, in a special holster. It’s the same type of holster athletes use, except they wear it on their arms.” Figure 6c shows P₆ using the index finger to swipe across the right thigh, embodying an imagined smartphone, to effect the “place/answer call” referent. These preferences indicate a strategy to mediate physical effort by appropriating a stationary body part for interaction purposes.

Another three participants, P₇, P₉, and P₁₁, who reported hand spasticity among other motor impairments, proposed unique device

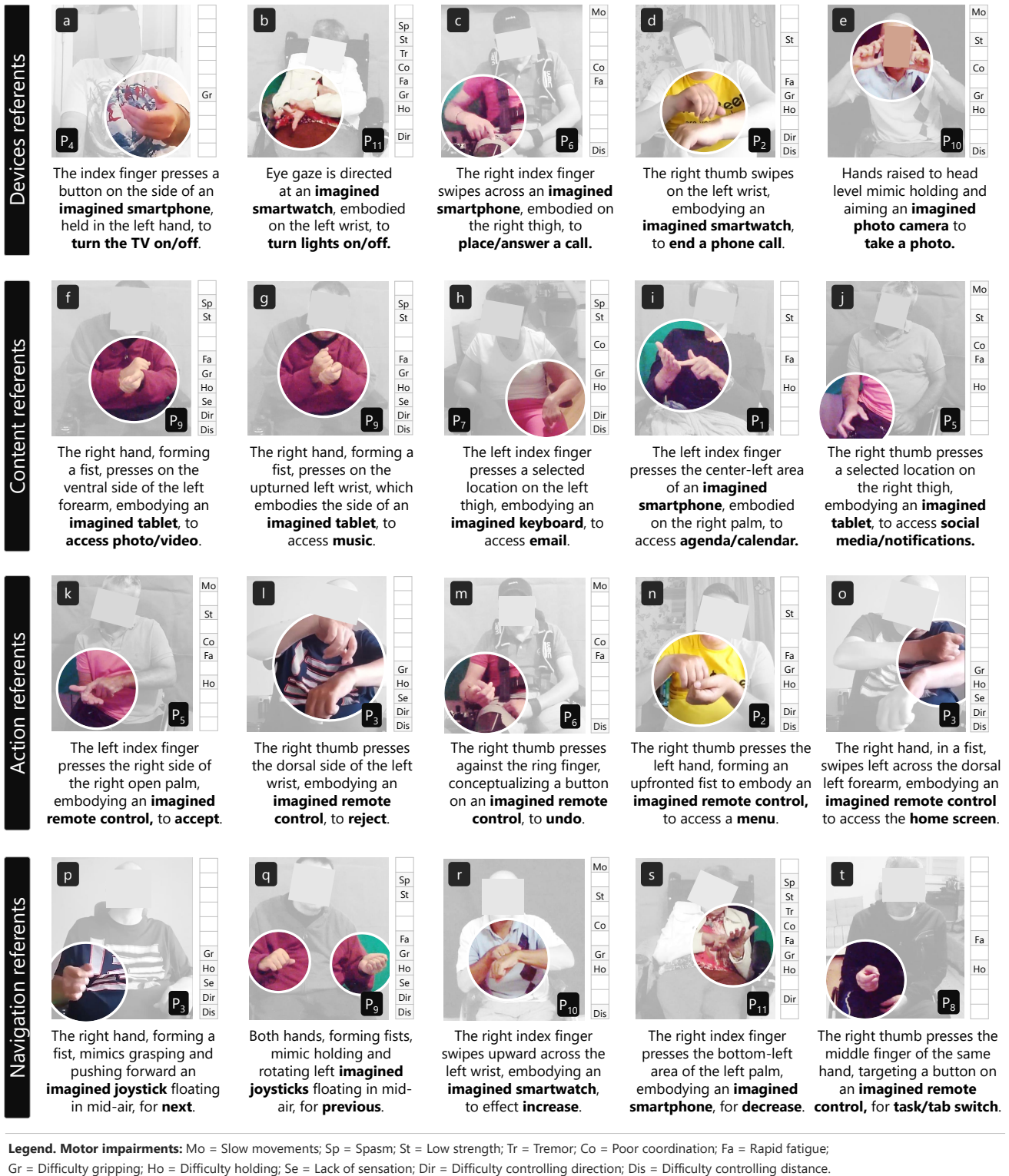


Figure 6: Examples of imagined input devices and corresponding gestures proposed by our participants. All twenty referents are illustrated, grouped into the *Devices*, *Content*, *Actions*, and *Navigation* categories (correspondence with Table 2). Each photograph is accompanied by the participant’s self-reported motor impairments (correspondences with Table 1 and Figure 5).

conceptualizations and input modalities adapted to this condition. For example, P₁₁ suggested a wheelchair-supported joystick to effect the “end call” and “take photo” referents; P₇ imagined and demonstrated holding a selfie stick for “take photo” and a custom keyboard, materialized with the thighs and featuring different keys at various locations for each of the five referents in the *Content* category; and P₁₁ proposed eye gaze directed at the wrist as a shortcut for “turn on/off lights”—preferences that were all unique to them; see Figures 6b, 6h, and 6s for a few of their gestures. These participants showed among the lowest preferences for remote controls, which typically require stable motor control for gripping, holding, and operating. In fact, P₉ and P₄, the latter reporting difficulty gripping, were the only who did not propose remote controls, one of the most preferred device archetype in our study; see the *DEVICE-ARCHETYPE* columns in Figure 5. P₄ remarked a similarity between smartphones and remote controls that makes them interchangeable in certain contexts, ultimately favoring the former as being more technologically advanced: “*I wish that when I’m sitting in front of the TV and it’s turned on, the smartphone could be used as a remote control.*” Figure 6a shows the index finger of the left hand pressing an imaginary button on the side of an imagined smartphone held in the same hand to effect “turn TV on/off.” Guided by this reasoning, P₄ proposed only two devices, imagined smartphone and joystick, compared to a median number of four devices across all participants and a maximum of seven devices for P₁₀; see Figure 5.

Other participants, such as P₁, P₃, and P₅, who reported difficulty holding objects, expressed a strong preference for remote controls despite associated accessibility challenges. For example, Figure 6l shows P₃ using the thumb to press the dorsal side of the left wrist, conceptualizing an imagined remote control, for “reject,” and Figure 6k shows P₅ using the index finger to press the right side of the right open palm for “accept.” We found that this preference was supported by the participants’ routine use of such devices, which posed challenges for carrying around that the imagined counterpart could alleviate: “*I have a small bag full of remote controls. I have to carry all of them with me: the garage remote, the remote for the house door, the remote for the gate to the apartment courtyard, and the car remote*” (P₁). A similar reasoning was given by P₆: “*I use a lot of remote controls for the car, for opening doors. You can see the keychain hanging from the joystick on my wheelchair.*” Figure 6m shows P₆ using the thumb to press against the ring finger of the same hand, conceptualizing an imaginary button on an imagined remote control, to execute the “undo” referent.

Participants experiencing poor coordination—P₅, P₆, P₇, P₁₀, and P₁₁—generally showed little preference for body-supported devices, instead favoring the use of the hands to embody remote controls and smartphones. This finding reflects deliberate disengagement from gripping, holding, and maneuvering actions that body-supported devices typically require. For example, Figure 6r shows P₁₀ using the index finger to swipe across the left wrist, embodying an imagined smartwatch, to “increase,” and Figure 6s shows P₁₁ using the index finger to press the bottom-left area of the left open palm, conceptualized as a smartphone, to execute the “decrease” referent. Rapid fatigue, reported by seven participants (see Figure 5, left), often resulted in conceptualizing devices as embodied rather than body-supported or floating in mid-air, with the participants favoring touch over more fatigue-inducing forms of input. For example,

this pattern stands out in P₁, P₅, and P₈’s preferences; see Figure 6i for P₁ using the index finger to press the right open palm, embodying an imagined smartphone, for “agenda/calendar”; Figure 6j for P₅ using the thumb to press on the right thigh, embodying an imagined tablet, for “social media/notifications”; and Figure 6t for P₈ pressing the thumb against the fist to conceptualize an imagined remote control, in order to effect the “task/tab switch” referent.

Lack of sensation, reported by P₃ and P₉, was associated with the highest observed preference for mid-air floating devices as well as for embodying devices across the hand, wrist, and forearm. Both participants showed absolutely no intent for devices that required being held, and P₉’s reflection reveals a mixture of embodiment and mid-air floating devices determined by a practical necessity: “*Because of my motor disability, I prefer to always have my phone within reach, so I wear it hanging around my neck at all times.*” Figure 6p shows P₃ using the the right hand, forming a fist, to mimic grasping and pushing an imagined joystick forward to effect “next” and Figure 6q illustrates P₉ with both hands, forming fists, holding and rotating two imagined joysticks to the left to effect “previous.” Neither of the two imagined joysticks is physically supported, but instead they float in mid-air, ready to be used when needed.

Difficulty in controlling the direction or distance of movement, each reported by five participants, was related to a tendency of using the wrist and forearm, alongside the hands, for embodying imagined input devices, typically involving smartphones, remote controls, and smartwatches. For example, the preference for the forearm was presented by P₃ with specific details: “*I saw that YouTubers use a control panel with multiple buttons that can be customized. I’d love to have something like that too, but with a ball to move the cursor, and I could always wear it on my arm, on the forearm.*” Figure 6n shows P₂ pressing with the right thumb on the left hand, forming an upfront fist to embody an imagined remote control, to effect “menu,” and Figure 6o shows P₃ swiping the right hand across the dorsal side of the left forearm, conceptualizing an imagined remote control, to effect “home screen.” Other examples are “ending a phone call” with the thumb swiping on the left wrist, mimicking an imagined smartwatch (Figure 6d) and pressing with the right hand on the upturned left wrist, embodying an imagined tablet, to access “music” (Figure 6g), and raising the hands to head level to mimic holding a photo camera to “take a photo” (Figure 6e).

These results reveal a spectrum of preferences for interacting with imagined input devices, from participants who rely on fine motor input and minimal movement to those who perform larger mid-air gestures. In the next section, we interpret these findings through the lens of two ability-centered accessibility frameworks.

5 Discussion

Our findings indicate that preferences for imagined input devices converge around a few archetypes, likely reflecting participants’ prior experience with physical counterparts, yet the gestures to implement and operate them are diverse. Mapping these gestures to participants’ individual motor abilities suggests that imagined devices can inspire more accessible interaction techniques, thanks to the flexibility and adaptability afforded by their non-physical nature. Translating these concepts into practical systems, however, represents an open challenge. For example, technical aspects such

as recognizing such gestures need to be addressed in future research, and practical methods for integrating them into design workflows require development. To pave this path, we begin by interpreting our findings in Subsection 5.1 from the perspective offered by ability-based design [74], a framework that emphasizes a distinctive designer stance focused on users' abilities before committing to any technology. We also highlight how imagined devices can act as mediators between users' abilities and interactive systems, for which we adopt in Subsection 5.2 the lens of ability-mediating design [69], a framework that we use to explain how interactions are shaped by users' imagination of non-physical devices. Building on this, we propose in Subsection 5.3 a roadmap toward imagination-powered accessible computing, where users' imagination plays a central role.

5.1 Imagined Input Devices and Ability-Based Design

According to ability-based design [74,75], designers focus on users' abilities, not disabilities, and systems should adapt to those abilities through user sensing and modeling in context. This stance and approach are relevant for imagined input devices since the focus is on imagination that surfaces interaction concepts grounded in users' abilities, without technological constraints. From this perspective, imagined input devices offer a highly adaptable design strategy, where both form factor and input modalities originate from users themselves, resulting in interactions inherently personalized to individual motor abilities, i.e., a "design for one" approach [25, 54]. In the following, we walk through the principles of ability-based design to discuss accessible interactions involving imagined input devices by connecting empirical evidence from our study to practical examples of potential applications. Designers can use this discussion as probes and exemplars in the context of ability-based design, while Subsection 5.3 proposes a roadmap for researchers.

In ability-based design [74,75], designers adopt a stance grounded in three core principles: *ability*, *accountability*, *availability*.

5.1.1 Ability. According to this principle, designers focus on what users can do, not on their disabilities [75]. Although imagined devices are not formalized input techniques, they surface unconstrained mental models of interaction that arise directly from users' imagination, prior experience, preferences, and motor abilities. By emerging through interactions revealed naturally from a user's gestures, imagined devices embody ability-based input strategies not limited by existing technologies or physical form factors, which might otherwise remain hidden. In this sense, imagination functions as a generative probe for identifying how people intuitively structure interaction around their actual abilities. **Example:** P₁₁, with Parkinson's-related tremor, spasm, and poor coordination, proposed using her left thumb to press against the same hand, forming a fist, to effect the "home screen" action. This gesture did not originate from any design assumptions about what Parkinson's permits. Both the device conceptualization (the fist is the remote control) and input modality (button press) arose directly from what P₁₁ could perform reliably, not from being instructed, trained, or guided in any way about this interaction. This example illustrates how imagined devices provide direct insight into users' perception, knowledge, and practical use of their abilities before any implementation exists. **Recommendation for designers:** Use imagined input

devices as early-stage probes into users' individual motor abilities. Let users initiate movement, allowing their abilities to reveal the interaction space, and use the observations for subsequent interaction design. Designing with imagined devices thus requires adopting a second-place position—observing first, adapting second—before any technological assumptions enter the design process.

5.1.2 Accountability. Following this principle, designers are responsible for changing systems, rather than expecting users to adapt themselves to system requirements [75]. Because imagined devices have no physical instantiation other than the gestures to operate them, the absence of physical constraints reveals what ideal accountability could look like in practice: systems that conform entirely to users, rather than the reverse. Without any a priori constraints to change, imagined devices embody interactions in which adaptation has already taken place, defined by users in terms of form, operation, and movement. This flexibility aligns strongly with the accountability principle, and positions imagined devices as a lens through which to understand how future interactive technologies could better adapt to users with various motor abilities. **Example:** P₁, a participant with spina bifida, who experiences low strength and difficulty holding objects, seamlessly switched between imagining a remote control and a smartphone, both embodied through her hands, to perform tasks from the *Devices* category. The ease of this transition did not require P₁ to adjust to weight, grip, or form factors; instead, the devices adapted instantly to her preferences. **Recommendation for designers:** Use imagined devices to explore an expanded space of design opportunities freed from physical constraints such as mass, shape, or size. Treat these user-defined conceptualizations as guides for how real devices could look like and, more importantly, how they should behave by shifting the burden of adaptation from the user to the system. Such a stance ultimately pushes designs toward the ideal of accountability, where systems have full responsibility for the adaptation.

5.1.3 Availability. This principle asserts that systems should be affordable and easily acquirable [75]. Imagined devices, being conceptual rather than physical, inherently reduce barriers of cost, maintenance, and procurement, whereas their implementation relies on gesture sensing and recognition algorithms, typically using off-the-shelf video or depth sensors [16,21,22,28]. In this context, availability is primarily determined by leveraging recognition algorithms to support flexible operation, a software challenge rather than a hardware one. **Example:** Most gestures elicited in our study require only a front-facing camera, such as those integrated in a PC [61] or a smartphone mounted on the wheelchair tray or armrest [18,37]. Alternative setups may include wearable cameras [21] or smartwatches with inertial sensors [36] for mid-air motion gesture sensing. **Recommendation for designers:** Design interactions for imagined input devices to minimize reliance on specialized hardware and, instead, leverage commodity sensors already available in users' environments, such as smartphone cameras and integrated radars, along with zero-shot learning techniques [44] to recognize spontaneous gesture articulations. With this approach, designers can maximize availability by enabling technical solutions that are primarily software-based and, thus, more easily distributed and updated than hardware-dependent ones.

Two additional principles, optional in the framing of ability-based design [74,75], pertain to the behavior of adaptive and adaptable interfaces and are highly relevant for imagined input devices.

5.1.4 Adaptability. According to this principle, interfaces should be adaptive or adaptable to provide the best possible match to user's abilities [75]. By their very nature, imagined devices exist solely in a user's imagination and, as such, their form factor and operation are intrinsically aligned with the user's mental models of the interaction and precise knowledge of their own motor abilities. This makes imagined devices uniquely flexible, interchangeable, and capable of being summoned or dismissed instantly based on current needs and context. **Example:** P₈, a participant with a spinal cord injury, who experiences rapid fatigue and difficulty holding objects, used different hand configurations for different interactive tasks: they conceptualized a remote control with a closed fist to effect "turn on/off TV," and used an open palm for "turn on/off lights;" also, they imagined a smartphone as an open palm for "place/answer call," while switching to a raised hand in front of the body to "take photo," all meaningful variations in their context. **Recommendation for designers:** Leverage imagined input devices to shift design focus from purely physical and material interfaces to include non-physical and conceptual elements, where adaptability can manifest in new ways across non-physical form factors. For instance, interactions with imagined devices may vary naturally according to task demands, user fatigue, or situational context.

5.1.5 Transparency. This principle holds that interfaces should provide users with awareness of their adaptive behaviors, including the possibility to override, preview, or revert changes [75]. Because imagined devices are first conceptualized as mental models before being enacted through gesture articulations, they should offer a strong sense of agency with control over both the interaction model and its execution. However, imaginary interfaces have traditionally been implemented without feedback [21], which poses a technical challenge for usability and accessibility. **Example:** Continuing the previous example, auditory feedback could assist P₈ when switching among different device conceptualizations, e.g., "Entering imagined remote control mode" when first recognized, and "Remote control mode continued" when switching to a different pose of holding the imagined device. **Recommendation for designers:** Treat transparency as a core design challenge in non-physical device spaces, where users cannot rely on implicit physical cues. Shift the design mindset toward discovering novel methods to communicate system behavior by translating conceptual interactions into perceivable and actionable feedback. As a practical guideline, support users' sense of control with feedback about what the system has recognized, which enables the opportunity to correct input if needed.

Two final principles of ability-based design [74,75] regard user and context sensing and modeling, as follows.

5.1.6 Performance. This principle asserts that systems should sense, model, monitor, and predict user performance to achieve optimal alignment with users' abilities [75]. **Example:** More than half of the participants reported experiencing rapid fatigue due to various health conditions, which could be inferred from changes in gesture articulation measures, such as consistency, accuracy, or speed. In such cases, systems could suggest switching to less fatiguing

gestures. **Recommendation for designers:** Repurpose the sensing technologies already used to detect gesture-based interactions, such as video cameras, to monitor user performance over time. This approach responds directly to each user's abilities by embracing an initially open-ended space of possible imagined devices and corresponding gestures, allowing adaptation to performance variability within each user's own gesture space [48].

5.1.7 Context. Systems should also sense, model, monitor, and anticipate the interaction context to adjust accordingly [75]. **Example:** Mid-air gestures, observed in a percentage of 24.1% in our study, while effective in private or unconstrained settings, may also draw attention or feel socially inappropriate when performed in public [58]. **Recommendation for designers:** Detect situational context, such as social settings and the presence of others, which may influence users' gesture behavior. For example, context-aware systems can improve gesture recognition by adjusting expectations, e.g., increase the a priori probability of observing more subtle movements in social situations vs. larger mid-air gestures and pointing in private ones. More generally, integrating the knowns of context can potentially illuminate the unknowns of unconstrained gesture articulation, an approach to accessible design where systems adapt their expectation of user behavior based on the environment.

5.2 Imagined Input Devices and Ability-Mediating Design

Since users' motor abilities are mediated through the devices they imagine, the lens of ability-mediating design [69] is equally useful for framing such interactions. Whereas ability-based design emphasizes abilities and system adaptation, ability-mediating design centers on how abilities evolve as influenced by the interactive systems with which users engage. Three principles are core to this approach: *mediation*, *world coverage*, and *instrumentation*.

5.2.1 Mediation. According to this principle, systems are designed to mediate perception and action to empower users with enhanced skills and enriched experiences [69]. **Example:** All but two participants reported experiencing difficulty holding objects, and most described gripping as difficult. While the involved abilities for gripping and holding physical devices are impacted by device mass, shape, and size, imagined input devices open the possibility of bypassing these limitations through novel abilities, such as interacting with a weightless conceptual remote control or smartphone with flexible form factors, determined by imagination alone. **Recommendation for designers:** Focus on the novel abilities that users can acquire through interactions with non-physical devices, and explore possibilities that go beyond the constraints of physical devices and existing motor abilities. While enhancing system accessibility, this approach can simultaneously incorporate complementary design goals, such as motor rehabilitation and related cognitive skills development, including improved memory and spatial reasoning, and turn mediation into a multipurpose design element.

5.2.2 World coverage. Following this principle, systems should embrace and operate across diverse modes of world existence: physical, virtual, imaginary, and hybrid combinations thereof [69]. **Example:** By integrating spatial augmented reality technologies, such as smartglasses [46] or projector-based systems in the environment

or wheelchairs [3], imagined input devices could become visible, aiding their operation by stabilizing mental models, scaffolding interactions, and improving gesture articulation consistency. **Recommendation for designers:** Embrace the non-physical dimension offered by imagined input devices to explore interactions spanning across different reality boundaries, and extend design across the physical-virtual continuum [49], where physical gestures control virtual devices. As a practical guideline, support users with optional, mixed-reality-like visualizations of imagined input devices.

5.2.3 Instrumentation. Achieving effective ability mediation requires instrumenting the user’s body and/or surrounding environment with computing technologies [69]. **Example:** Wearables, such as smartwatches, can detect mid-air motion gestures through integrated inertial sensing [36], such as for pointing with an imagined remote control, while instrumentation of the environment, such as with video projectors [3], can materialize imagined devices for richer user experience. **Recommendation for designers:** Beyond the focus on availability in ability-based design, the principle of instrumentation emphasizes the mediating role of technology in translating user intentions into effective commands. Designing for instrumentation means ensuring that these translations are robust in addition to implementable with available resources. Designers should leverage and integrate existing, readily available technologies within users’ environments to support the use of imagined devices, while considering the mutual influence between instrumentation and design decisions. In this bidirectional relationship, readily available technology simultaneously enables and constrains, yet can be reconfigured for the purpose of mediating new user abilities that involve operation of imagined devices.

5.3 Future Work: A Research Roadmap for Imagination-Powered Accessible Computing

Imagined input devices offer conceptual flexibility and invite users to act naturally, according to their abilities in context. This sets the stage for a new approach to accessible interaction design, which can maximize the potential of ability-based design principles while emphasizing the mediation of existing abilities and user-defined input as central design elements. In this approach, otherwise impalpable mental models become materialized through physical gestures to be sensed and interpreted by the computer system. However, translating such interactions into practical systems remains a technical challenge requiring gesture recognition and interpretation at an unprecedented level of flexibility. Based on our empirical findings and discussion, we outline in the following several directions for *imagination-powered accessible computing*, a novel design approach to accessibility in which imagination is acknowledged as a key driver for enabling accessible interactions. We envision future research along three core directions, as follows.

5.3.1 Sensing and recognition technology. The study reported in this work centered on understanding users’ conceptualizations of imagined devices. However, reliably recognizing the corresponding gestures to operate these devices remains a technical challenge, and future work is needed to advance gesture recognition techniques when input is performed under various motor impairments.

Possible approaches may draw from vision-based techniques, as pioneered in imaginary interfaces [21,63], and wearable sensing [36], while addressing gesture segmentation in free-form movement [68] and explicitly accounting for the greater variability in gesture execution among users with motor impairments [51,57]. We envision practical solutions integrating multiple strategies, from user-controlled [40,59,68] and automated [35,64] gestured segmentation to advanced machine learning techniques capable of identifying gesture classes not present in the training set [44]. For example, Steins et al. [63] implemented gesture detection for imaginary devices when hands remained above waist height and stationary for 500 ms. Combining explicit or automated segmentation with zero-shot learning techniques [44], which can recognize gesture classes unseen during training, represents interesting future work for tackling both input with imagined devices and the variability in gesture input among users with motor impairments.

5.3.2 Expanding knowledge about imagined input devices across user groups, applications, and interaction modalities. Our findings revealed ten device archetypes for tasks involving content access and smart home control. However, other imagined input devices may emerge in different contexts, such as public displays [23] or healthcare environments [41]. Future studies on interactions mediated by imagined input devices should also involve a broader range of user groups, from children to older adults, whose imagination and interaction preferences may substantially differ [15]. Such investigations will consolidate a knowledge base on the mental models that people use to conceptualize and operate imagined devices through gestures, reflective of their natural behavior and existing motor abilities, similar to user-defined gesture sets [72]. Extending this research to other input modalities, such as voice or eye gaze, will further broaden design insights for other abilities. This direction aligns with the trajectory of emerging technologies, such as smartglasses, which will expose users to new interaction modalities, likely to expand the repertoire of input devices they can imagine. As our study is replicated across different user demographics and emerging devices, we expect new discoveries to expand the space of possible interactions mediated by imagined input devices.

5.3.3 Integrating imagination into accessibility design frameworks. Existing accessibility frameworks, such as ability-based [74,75] and ability-mediating [69] design, highlight key dimensions of abilities, technology, and context, yet place less emphasis on users’ mental models. Furthermore, they do not explicitly account for *imagination*, whereas integrating users’ imaginative capacities into design practice could unlock novel opportunities in interactive systems, which call for dedicated design principles. For example, an imagination-oriented principle could complement ability-based design as follows: “Designers create systems that provide the best possible alignment with users’ mental models of interactions and actual system capabilities to support them.” Likewise, an imagination-centered principle could complement ability-mediating design as follows: “Systems are designed to give physical form to users’ imagined interaction models.” Despite the challenging transition from users’ mental models to actionable design principles for imagined devices, future research on how imagination can function as a design element, and how it can be systematically elicited and operationalized in practice, may open new areas of scientific inquiry. Furthermore, combining

physical and imagined devices may lead to new design opportunities, where hybrid devices, including both physical and imaginary components, can offer both tangible feedback, e.g., to stabilize the hand and fingers, and flexibility in form. These exciting possibilities can be explored by integrating imagination as a novel dimension in accessible interaction design through a redefinition of input devices across the physical-virtual continuum [49], a richer understanding of users' mental models [76], and more robust techniques for recognizing and interpreting user-defined gestures [72].

6 Limitations

There are several limitations to our study, which we present in the following along with opportunities to address them in future work.

Our sample included only $N=11$ participants, just over half the commonly reported $N=20$ in end-user gesture elicitation studies [72], but matches sample sizes in elicitation studies conducted with participants with motor impairments [7,45] and aligns with the median $N=10$ in CHI and ASSETS papers involving motor or physical disabilities [43, p. 8]. Still, a larger sample could allow for deeper analysis, an aspect included in our future work directions.

Since gesture development and interpretation vary across cultures [48] and influence outcomes in gesture elicitation studies [17, 47], a multicultural sample would provide richer insights into imagined input device use. Similarly, repeating the study as emerging devices such as smartglasses become more widely adopted might lead to different interaction preferences, with design implications for how skeuomorphism can be aligned with human perceptuo-motor processes [34] in evolving technological landscapes and how physical effort can be managed in gesture-based input [31] vs. alternative modalities offered by emerging devices. For example, eye-gaze control might be favored over gestures in contexts where minimal effort or discreet input is desired for imagined devices, while combining gaze and gesture is known to outperform systems that rely solely on either [12], with opportunities for multimodal operation of imagined devices that draw on different physical analogs than those observed in our study.

Lastly, we focused on users with upper-body motor impairments and no reported cognitive disabilities. However, future work could consider individuals for whom motor impairments may co-occur with intellectual challenges, as the latter may affect the ability to form mental models of input devices as well as to enact those models into gesture-based interactions for systems to recognize.

Our proposed research directions in Subsection 5.3 address these limitations as promising opportunities for future work.

7 Conclusion

We examined conceptualizations of imagined input devices and corresponding gestures to operate them as proposed by users with upper-body motor impairments. Our findings revealed a strong preference for embodying devices rather than holding them, and surfaced ten device archetypes, among which smartphones and remote controls were frequently observed. We also uncovered a diversity of gesture articulations with little consensus across participants, which we analyzed in relation to their self-reported motor impairments. Based on these findings, we proposed design recommendations for interactions involving imagined input devices

through the lenses of ability-based and ability-mediating design, and glimpsed toward future research on imagination-powered accessible computing. As our study has barely scratched a vast space of possible innovations in accessibility, we look forward to more investigations into imagined input devices for more accessible, flexible, and ability-centered interactions with computer systems.

Open Data

We are releasing our dataset, consisting of the device and gesture measures extracted from video recordings, as a .csv file along with R code that reads the data and runs agreement analysis. The dataset is freely available for research purposes at <https://raduvatavu.usv.ro>. By releasing this dataset, we aim to foster further discoveries, as discussed in Subsection 5.3, enable replication studies, and provide a baseline for future empirical work in this space.

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