Users with Motor Impairments' Preferences for Smart Wearables to Access and Interact with Ambient Intelligence Applications and Services

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Abstract We report insights into the preferences of people with motor impairments to use smart wearables to access applications and services of ambient intelligence environments. We highlight preferences for smartglasses and the delivery of notifications, smartwatches and health applications, smartwatches and control of smart homes, and for smart rings and bracelets for making payments and using public interactive systems. We also report results from a correlation analysis indicating that people with higher disability levels prefer smart earbuds and rings to smartwatches, smartglasses, and smart bracelets. Our findings are useful to inform applications at the intersection of ambient intelligence and wearable computing to increase access to smart environments for users with motor impairments and limited mobility.

1 Introduction

Smart wearables, such as smartwatches, fitness trackers, and smart earbuds, are becoming mainstream, enabling new interactive experiences and access to new applications and services for mobile users [19, 21]. According to the vision of Ambient Intelligence (AmI), wearables implement several principles of smart environments—they are responsive, adaptive, transparent, ubiquitous, and intelligent [3]—at the personal level of the user's body [4]. Also, with their small form factors, intuitive interactions based on voice and gestures, subtle feedback mechanisms, and capacity for operating in networks of connected devices, wearables facilitate the disappearance of technology from perception by tight integration on and with the human body [20].

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Fig. 1 A person with upper body motor impairments, caused by spinal cord injury, interacting with a computer mouse, smartphone, and smartwatch, respectively.

Sensors and devices that are worn or affixed to the body are always on and always available, unlike other mobile devices, such as smartphones and tablets, that need to be retrieved from pockets or bags, activated from idle states, and stored away when no longer needed. From this perspective, wearables provide unique opportunities for users with motor disabilities, for which reaching to the smartphone, grasping, and keeping it in a steady position during interaction represent accessibility challenges [10, 16, 18]. Nevertheless, wearables bring accessibility challenges of their own caused by tiny screens, small form factors, and input based on motion and gestures not always easy to articulate by users with motor impairments or in line with their motor abilities [12, 13, 22]. For example, Figure 1 shows a person with spinal cord injury interacting with a mouse, a smartphone, and a smartwatch—three input devices representative for the desktop, mobile, and wearable computing paradigms. The figure reveals accessibility challenges and corresponding coping strategies to use these devices, reflected in how the devices are positioned, oriented, and held.

In the context where wearable devices play an important part in implementing the vision of AmI [4], it is important to understand the perceptions and preferences of users with various motor abilities for such devices. To this end, we report in this paper results from a study conducted with twenty one people with motor impairments to document their desirability regarding wearables to access services and applications in various AmI contexts of use, from the control of appliances in a smart home [9] to public interactive systems [27]. Our findings are useful to inform future work at the intersection of wearable computing and AmI [4] for users with motor disabilities.

2 Related Work

A large body of work exists on documenting accessibility challenges experienced by people with motor impairments using interactive computing systems and on designing assistive technology [7, 11]. Examples include mouse input [6, 31], interaction with mobile devices [10, 16, 18], gesture input on touchscreens [17, 24, 25, 29], using remote controls [14, 23], and, to a less extent, interactions with wearables, such as fitness trackers [2], smart rings [8], smartwatches [12], and Augmented and Virtual Reality (AR/VR) glasses and head-mounted displays [13, 15]. For example, Malu and Findlater [13] evaluated the accessibility of Google Glass for users with upper body motor impairments, and proposed an alternative input modality for interacting with content displayed on the glasses via switch-based wearable touchpads affixed to the body or the wheelchair. Mott *et al.* [15] conducted interviews to examine the accessibility of VR, including head-mounted displays for VR, and identified seven barriers regarding the physical accessibility of VR devices for people with limited mobility. Malu *et al.* [12] examined accessible smartwatch interactions for users with motor impairments and elicited new gestures for common smartwatch actions. Carrington *et al.* [2] reported insights into the accessibility of fitness trackers from interviews with wheelchair athletes and physical and occupational therapists. And Gheran *et al.* [8] discussed the opportunities of smart rings as assistive devices for users with motor impairments, including one-button input and gesture interactions.

Despite this prior work, wearables have been little examined for enabling access to AmI services for users with motor disabilities; see Şiean and Vatavu for a recent survey on accessible wearable interactions [22]. However, in the context of enabling universal access to AmI environments, "a proactive design-for-all approach acts as a catalyst, facilitating the introduction of accessibility into the new technological environment" [5], of which smart wearables have been specifically identified to play an important role. Moreover, Cook and Song [4] highlighted the role played by wearable sensors and computing systems for AmI use case scenarios and discussed how the integration of AmI and wearable computing can bring added value to both areas. For instance, information collected by the environment could be used to predict users' physiological responses and be validated by wearable sensors, while data provided by wearables could trigger corresponding responses and changes in the smart environment [4]. However, despite the opportunities of using wearables in smart environments, little is known about the preferences of people with limited mobility and motor disabilities to use such devices to access AmI services and applications, such as interacting with public services and systems or controlling the appliances of a smart home. In this paper, we present results in this direction.

3 Study

We interviewed a number of twenty-one people with various motor impairments (seventeen were male). Participants' age varied between 28 and 59 years (M=43.3, SD=8.2 years, normally distributed values according to a Shapiro-Wilk test W=.971, p=.758). At the moment of the study, participants had been living with the motor impairment for 3 to 47 years (M=23.1, SD=10.7 years, normally distributed W=.946, p=.281). The main cause of motor disability in our sample was spinal cord injury

(SCI) most frequently at vertebrae C_5-C_6 and C_6-C_7, reported by sixteen participants (76.2%). Other causes included traumatic brain injury, spina bifida, osteogenesis imperfecta, and multiple sclerosis. All of the participants were wheelchair users, of which twelve (57.2%) were using manual wheelchairs, seven (33.3%) power wheelchairs, and two (9.5%) had their power wheelchairs customized. The WHODAS 2.0 health and disability scores varied between 22.9 and 85.4 on a scale of 100 (M=52.4, SD=17.3, values normally distributed according to a Shapiro-Wilk test W=.974, p=.825).[1] The interviews focused on the following aspects:

1. Assessment of the participant's health and disability with the 12-item version of the WHODAS 2.0 instrument [26]. WHODAS is a generic tool that produces standardized disability levels and profiles covering aspects of cognition, mobility, self-care, getting along, life activities, and participation to community activities.
2. Evaluation of the perceived difficulty to use the following conventional computing and input devices: *keyboard*, *mouse*, *smartphone*, *tablet*, *TV remote control*, and of the *wheelchair,* representing the conditions of the independent variable Device and collected using 5-point Likert scales with items ranging from 1 (not difficult to use at all) to 2 (little difficult), 3 (moderately difficult), 4 (difficult), and 5 (very difficult or impossible for me to use this device). For the participants that were using wearable devices at the time of the study or had used wearables before, we asked about the perceived difficulty of using those particular devices.
3. Elicitation of preferences for using wearables for various AmI applications and in various contexts of use. We considered five categories of wearables, *smartwatch*, *smart bracelet*, *smartglasses*, *smart earbuds*, and *smart ring*, and nine categories of applications, *health and fitness*, *control of home appliances*, *music*, *delivery of notifications*, *making payments*, *interacting with public systems*, *playing video games*, and *applications for the work place.* The categories of wearable devices were informed by market statistics regarding end-user spending on smart wearables worldwide,[2] and we also included emerging wearables, such as smart rings.[3] These categories constitute the independent variable Wearable (nominal, five conditions) in our study. The AmI applications that we considered in the evaluation were chosen to cover a wide palette of functionalities and services, user needs, and contexts of use: indoor and outdoor, private and public, and home and office scenarios, representative of AmI environments. These categories constitute the Application independent variable (nominal, nine conditions) in our study.

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[1] According to the general population norms for polytomous scoring of the WHODAS 2.0 short version [26, p. 44], the minimum score from our sample (22.9) corresponds to the 93rd percentile (i.e., 93% of the general population score better), the mean score (52.4) corresponds to the 98th percentile, and the maximum score (85.4) positions between the 99.7th and 100th percentiles (i.e., 99.7% of the population score better on the WHODAS 2.0 test). Moreover, according to the normative data report of Andrews *et al.* [1] based on 8,841 respondents of the 12-item WHODAS 2.0 instrument, individuals scoring between 20 and 100 are in the top 10% of the population distribution likely to have clinically significant disabilities.

[2] `https://www.statista.com/statistics/1065271/wearable-devices-worldwide-spending`

[3] `https://www.statista.com/statistics/1080078/use-of-wearable-technology-for-pos-payments-in-europe-by-country`

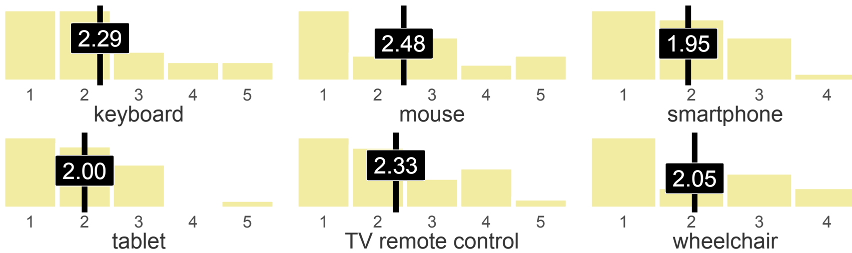

Fig. 2 Perceived difficulty ratings to use various devices (1 denotes "no difficulty to use at all" and 5 denotes "very difficult or impossible for me to use this device"); mean ratings are highlighted.

4 Results

Figure 2 illustrates difficulty ratings for using conventional input devices (mouse and keyboard), computing devices (smartphone and tablet), the TV remote control, and the wheelchair, respectively. A Friedman test did not find a significant effect of Device on perceived difficulty ($\chi^2_{(N=21,5)}$=6.651, p=.248>.05, $n.s.$). A number of twelve participants (12/21=57.1%) reported having used smart wearables before the study, as follows: smartwatches (three participants), smart earbuds (seven participants), and smart bracelets (two participants). The average perceived difficulty for those devices was 2.1 on a scale of 5, corresponding to the "little difficulty to use" label. These results suggest that, just like in the case of conventional computing and input devices (difficulty ratings shown in Figure 2), people with motor impairments develop coping strategies to use smart wearables, a process that is not effortless, but not perceived as too difficult either, according to our participants' responses.

We collected a total number of 308 preferences from the 21 participants regarding suitable associations between Wearable devices and Application categories; see Figures 3 and 4. On average, each participant provided 14.7 associations (SD=6.6) from the total number of 5 (devices) × 9 (application categories) = 45 possibilities, representing 32.7% of the available associations. Smartwatches were chosen for 31.5% of the associations with applications, followed by smartglasses (19.8%), smart bracelets (18.5%), smart rings (18.2%) and, in the last place, smart earbuds (12.0%). Regarding application types, the fitness and health category received the most associations (18.8%), followed by notifications delivery (15.9%), interaction with public systems (14.0%), music (12.7%), and control of home appliances (12.0%). Figure 4 details the relationships between the five categories of Wearable and the nine categories of the Application variable. Both smartwatches and smartglasses were perceived useful for displaying notifications (the thick pink and magenta ribbons from Figure 4), while rings were associated more with health applications, making payments, and interacting with public systems. Also, smart bracelets shared the largest proportion with fitness and health applications, but were also perceived useful for making payments and for delivering notifications, respectively (the light blue ribbons from Figure 4). Together, Figures 3 and 4 illustrate a comprehensive picture of our participants' preferences for suitable Wearable × Application associations.

	Fitness & health	Control home appliances	Music	Notification delivery	Make payments	Control the PC	Interact with public systems	Control video games	Apps for the work place	ALL APPLICATIONS	%
smartwatch	18	15	9	16	15	3	15	1	5	97	31.5%
smart bracelet	14	2	4	10	12	0	13	0	2	57	18.5%
smartglasses	4	9	8	18	0	11	0	6	5	61	19.8%
smart earbuds	7	7	14	4	0	0	0	0	5	37	12.0%
smart ring	15	4	4	1	15	1	15	0	1	56	18.2%
ALL DEVICES	58	37	39	49	42	15	43	7	18	308	100%
%	18.8%	12.0%	12.7%	15.9%	13.6%	4.9%	14.0%	2.3%	5.8%	100%	

Fig. 3 Participants' preferences, shown as frequencies, for using smart wearables for various applications and services, e.g., 18 participants associated smartglasses with notifications delivery.

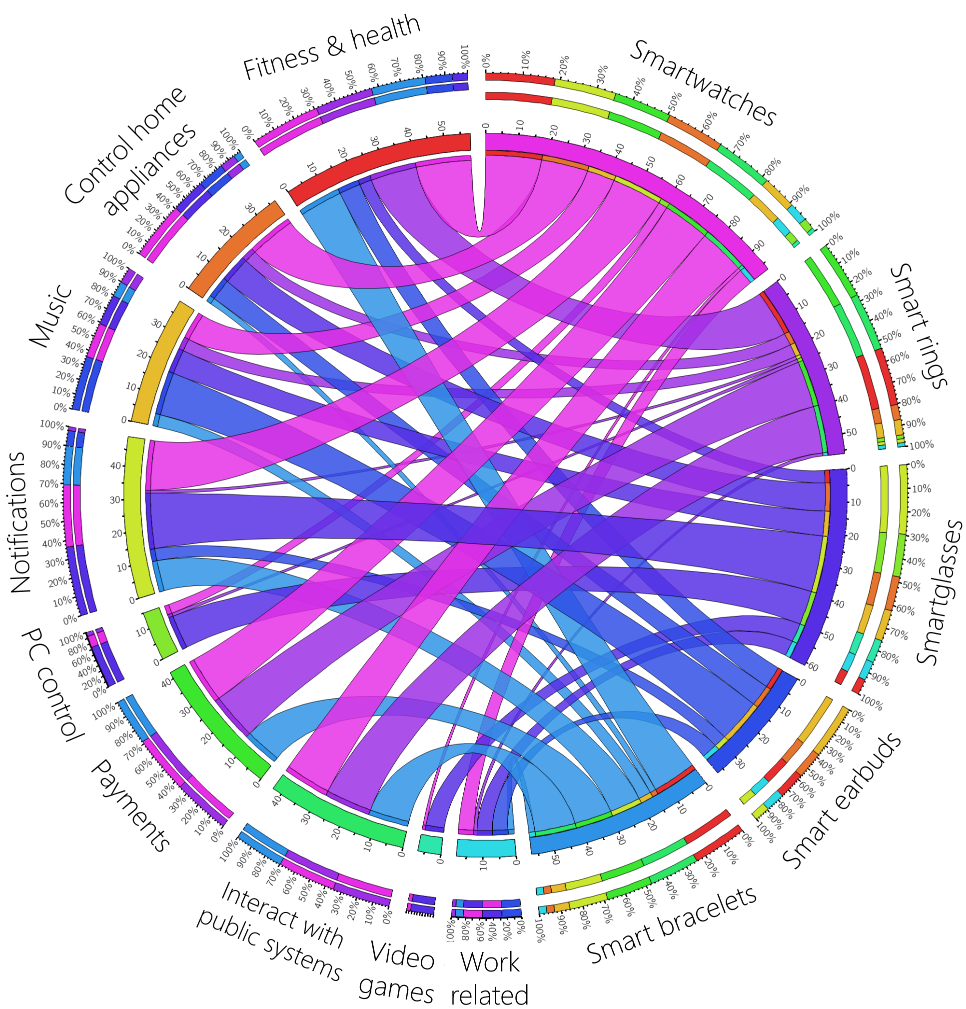

Fig. 4 Association map highlighting preferences for wearables and applications. Notes: the thicker the ribbon, the stronger the association; graphical layout produced using Circos (http://circos.ca).

	smart watch	smart bracelet	smart glasses	smart earbuds	smart ring
smartwatch		.698**	.488*	.402	.241
smart bracelet	.698**		.329	.700**	.225
smartglasses	.488*	.329		.235	.277
smart earbuds	.402	.700**	.235		.454*
smart ring	.241	.225	.277	.454*	
WHODAS 2.0	-.464*	-.172	-.249	.156	.168

Fig. 5 Pearson correlation coefficients (N=21) between participants' preferences for smart wearables; statistical significance is indicated with symbols * (p=.05) and ** (p=.01). See Figure 6 for correlations between preferences for AmI applications.

Figures 5 and 6 present Pearson correlation coefficients for these associations. We found high correlations (statistically significant at p=.01) between smartwatches and bracelets ($r_{(N=21)}$=.698) and between bracelets and earbuds (.700), respectively; see Figure 5. Also, we found high correlations (p=.01) between participants' preferences for using wearables to make payments and interact with public systems (.940), and between fitness and health and interacting with public systems (.636), respectively; see Figure 6 for other correlations. Most correlations with the WHODAS 2.0 scores were negative, but except for the smartwatch ($r_{(N=21)} = -.464$, p=.05), none were statistically significant. The few positive correlations with WHODAS 2.0 (Figures 5 and 6, bottom) are interesting: participants with higher disability preferred more interactions with smart earbuds and rings compared to smartwatches, smartglasses, and smart bracelets, and were also more interested in health applications.

Some participants also provided several interesting comments during the interviews, which are useful to understand in more depth their perceptions of smart wearables and preferences for associations between wearables and AmI applications. For instance, participant P_5 (SCI at vertebrae C_6-C_7) was using a fitness tracker at the moment of the study, but was not wearing it on the wrist; instead, he preferred to attach the fitness tracker to his handbike to see incoming calls and to check the time. P_{18} (SCI, C_4-C_5) commented that health and fitness applications, common on wearable devices, are generically designed to encourage walking, running, climbing stairs, and other similar activities, which he found not appropriate for his disability, while the related notifications were perceived irritating. And P_{10} (spina bifida) said that when other people wear earbuds on the street, they pay less attention to their surroundings, making her navigation in crowded places more challenging.

5 Conclusion and Future Work

We reported insights from interviews conducted with people with motor impairments and limited mobility to understand their preferences for smart wearables in re-

	Fitness & health	Control home appliances	Music	Notifica tion delivery	Make paymen ts	Control the PC	Interact with public systems	Control video games	Apps for the work place
Fitness & health		.198	.140	.348	.636**	-.120	.631**	.240	.189
Control home appliances	.198		.480*	.235	.421	.087	.357	-.024	.109
Music	.140	.480*		.061	.577**	.171	.570**	.145	.343
Notification delivery	.348	.235	.061		.553**	.000	.452*	.060	.312
Make payments	.636**	.421	.577**	.553**		.071	.940**	.378	.460*
Control the PC	-.120	.087	.171	.000	.071		.020	.322	.288
Interact with public systems	.631**	.357	.570**	.452*	.940**	.020		.432*	.424
Control video games	.240	-.024	.145	.060	.378	.322	.432*		.373
Apps for the work place	.189	.109	.343	.312	.460*	.288	.424	.373	
WHODAS 2.0	.228	-.064	-.272	-.101	-.192	-.410	-.222	-.266	-.232

Fig. 6 Pearson correlation coefficients (N=21) between participants' preferences for AmI applications; statistical significance is indicated with symbols * (p=.05) and ** (p=.01), respectively. See Figure 5 for correlations between preferences for smart wearables.

lation to specific applications and services representative of AmI use case scenarios. We found large preferences for applications involving the delivery of notifications, health, making payments, and using public interactive systems. Our results indicate opportunities for employing smart wearables to enable access to public systems (e.g., interaction with public displays) and services (e.g., POS payments), but also for controlling smart homes. Future work will exploit the associations revealed by our study between specific wearables and applications, e.g., smartwatches to control home appliances and smart rings to interact with public systems, including elicitation of preferred interactions with various types of wearables [30], in the context of increasing access to AmI environments [5] and the accessibility of interactive media experiences [28] for such smart environments.

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