Impact of Situational Impairment on Interaction with Wearable Displays

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ABSTRACT

The number of wearable devices that we carry increases, with smaller companion devices like smartwatches providing quick access for simple tasks. These devices are, however, not necessarily in direct sight of the user and during everyday activities, it is unlikely, even undesirable, that the user constantly focuses on or interacts with these screens. Furthermore, interaction is often limited because our hands are occupied carrying or holding items such as bags, papers, boxes, or tools. In this paper, we evaluate how encumbrance affects, among others, the time it takes to perceive and react to a notification depending on the placement of the companion device. Our experimental results can assist designers in choosing the right device for the task.

CCS CONCEPTS

• **Human-centered computing** → *Mobile devices*; Empirical studies in ubiquitous and mobile computing.

KEYWORDS

Wearable computing; Encumbered interaction; Smartwatch; Smart Glasses.

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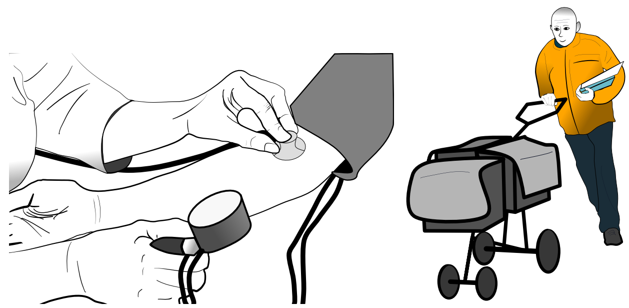

Figure 1: Example use cases where people handle objects restraining the user in viewing and interacting with on-body wearable devices.

1 INTRODUCTION

Smartwatches and smartphones have become ubiquitous companions that present a broad range of information, from notifications to navigation instructions. On top of that, these devices frequently require input during micro-interactions. All this information and input demands a lot of our attention, but in real-world settings, our mobile devices often have to share our attention with other tasks. We might be walking or driving, for instance, or carrying items in one or both hands while interacting with our smartphone [9], situations which are referred to as situationally-induced impairments and disabilities [13].

There is a wide variation of tasks that require us to carry items or hold tools while still being able to view and interact with a mobile or wearable device (Fig. 1). A nurse might want to access a patient's records or current status while treating the patient [6], an assembly worker needs to access assembly instructions while putting pieces together, and in the near future, mail carriers will not only deliver mail and parcels, but also collect information as mobile crowdworkers [1]. Those mail carriers have to get an overview of their assigned data collection tasks and potentially the means to enter some data. The data collection should not interfere with their main task, but repeatedly grabbing a smartphone or looking at a smartwatch can be impeding, as their hands are already carrying mail or parcels.

Someone's working environment or task sometimes imposes additional requirements or restrictions. Workers might need to read or acknowledge notifications immediately, for instance, while there is usually no time pressure in a personal context. Wearing a smartwatch while handling certain machinery might be disallowed for safety reasons in an industrial context, and in a medical setting the device might need to be positioned away from the hands to avoid contamination, or simply because it would be covered by the nurse's gloves. With regard to on-body location, tradition also plays a role: a smartwatch is worn on one's wrist, not necessarily because that location makes the most sense for the task at hand, but because it is customary. It is worthwhile to rethink this, as moving the device up the arm next to the elbow has some advantages. The arm provides a larger support surface that can be used for larger screens and the arm rotates less compared to the wrist, which can result in a more constant visibility of the screen.

Many factors affect the suitability of a particular mobile or wearable device as a supporting tool for a secondary task while performing a primary task. Depending on the placement of the device, it might be easy to view but hard to reach, and vice versa. In this paper, we evaluate how various types of encumbrances affect the time it takes to read and acknowledge notifications on a wearable companion device. Our results show that some device placements are very suitable for simple input, as they are not affected by any type of encumbrance, while others are easy to read, but hard to reach for input when carrying larger items.

2 RELATED WORK

Using mobile devices on the go results in technology being handled in a much more demanding environment than a desktop setting. Reading a notification, for instance, is a matter of a quick glance in a desktop setting, but requires the user to access the device first when using a smartphone on the go. Ashbrook et al. [2] investigated the effect of mobility and placement on access times of on-body interfaces. The smartphone attached to the wrist was fastest to access. There was no effect of mobility on access times, meaning that participants were not significantly faster or slower while walking compared to standing still.

With regard to different on-body placements, Thomas et al. [12] analyzed how gesture input on a touchpad is affected by pose for a series of locations. Participants preferred placing the touchpad on the thigh or arm. However, visual output was given through a head-mounted display, and not on the location of the input. Results might be different if input and output are co-located. Harrison et al. [4] investigated which on-body locations are suitable for minimal visual feedback. Wrist and upper arm performed best in terms of average reaction times, but participants were mostly sitting at a desk. Ng et al. [9–11] observed what kind of items people carry while walking through public space and classified them according to size and how they were held. Representative items of these categories were used in a study where participants were precisely tracked while interacting with a smartphone, both standing still and walking. In this case, mobility and encumbrance both had an effect on the user's input accuracy and speed [9].

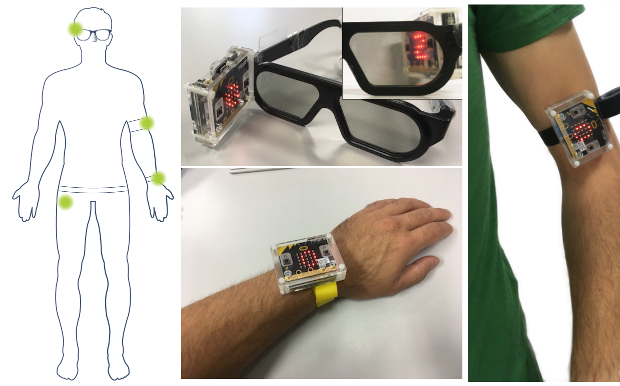

Figure 2: We placed the wearable device at the outside of the wrist, like a watch, on the upper arm facing forward, in the pocket like a phone, and on the frame of a pair of glasses.

In subsequent experiments, Ng et al. investigated if encumbrance affects one- and two-handed interaction differently [10] and whether gesture input alleviates the problem [11]. Generally, touch accuracy and selection time drop significantly, whether one or two hands were used, but the thumb is more precise for input than the index finger. Two-finger gestures like pinching are also more robust against encumbrance than single-finger gestures such as tap and drag. Dobbelstein et al. [3] evaluated how people interact with a smartwatch while carrying items and came to the conclusion that the swipe gesture was least affected by mobility or encumbrance.

To summarize, related work shows how encumbrance affects interaction with a touchscreen, as well as how touch input and visibility are affected by on-body location. We extend this body of knowledge by evaluating how encumbrance affects visibility and accessibility of on-body devices.

3 ENCUMBRANCE VS VISIBILITY AND INTERACTION

In our study, we evaluate the following hypotheses:

- **H1-P×Acc**: the device *placement* has a significant effect on *device access time.*
- **H1-P×Read**: the device *placement* has a significant effect on *reading time.*
- **H2-E×Acc**: the *type of encumbrance* has a significant effect on *device access time.*
- **H2-E×Read**: the *type of encumbrance* has a significant effect on *reading time.*

With regard to on-body *placement*, we evaluate four different device locations: (1) on the outer side of the wrist, like a *watch*, (2) on the front of the upper *arm* as an arm strap, (3) attached to a pair of *glasses* to simulate smart glasses, and (4) placed where the participant indicates (s)he would usually carry a mobile *phone* (Fig. 2).

To evaluate the effect of encumbrance, we simulate four different *types of encumbrance*: (1) *none* as baseline measurement, (2) the non-dominant hand occupied by carrying a *stack* of papers, (3) both

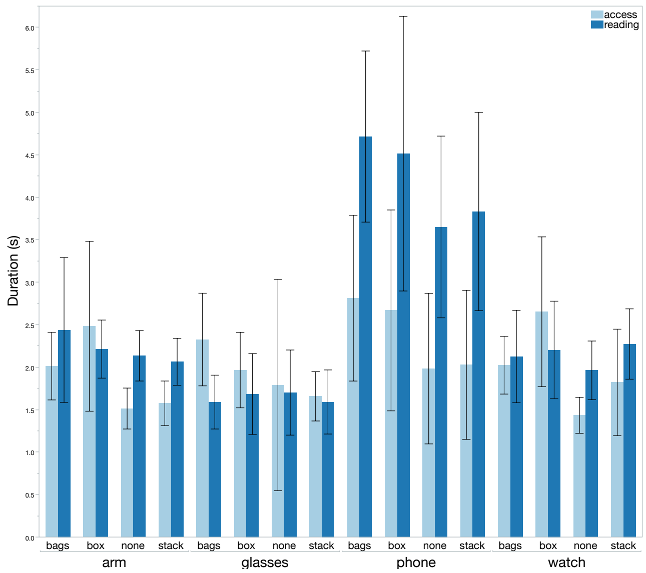

Figure 3: Response times by placement and encumbrance. Error bars denote one standard deviation from the mean.

hands occupied by carrying two *bags* of approx. 1kg, and (4) both hands occupied by carrying a cardboard *box* of 66×35×35 cm. The paper stack simulates what is described as *complex objects* which "require more careful and intricate finger action and grip" [9].

For each of the possible combinations of *encumbrances* and *placements*, participants either press a button on the device after an audio cue (*access*), or say out loud the number visible on the device's display (*reading*). The former is interesting for notifications that require interaction, and the latter for notifications that only need to be perceived.

3.1 Apparatus: a generic wearable device

We used a micro:bit [8], which is easily placed on the body to simulate various wearable devices with its 5×4cm size. It provides two hardware buttons and a 5×5 LED matrix, and is connected to a host application via Bluetooth. While this is obviously a very low resolution, it is sufficient to show single-digit numbers. The buttons are easy to find using tactile feedback as they are recessed in the casing, which also prevents accidental input. The host application, running on an iPad Pro, was used to keep track of button presses.

3.2 Procedure

At the start, we measured a participant's preferred walking speed while interacting with a smartphone as a baseline (PWS&I [10]). During the trials, participants walked back and forth along a predefined trajectory of about twelve meters around a meeting room table. The space was large enough to walk while carrying a large object, yet it also required a certain amount of attention to avoid collisions.

In each condition, participants had to react to five notifications, with a random delay of up to ten seconds between subsequent trials. We measured the time between a notification's audio cue

Table 1: Average response times in seconds.

		Phone	Watch	Arm	Glasses
Reading	None	*M* = 3.65	*M* = 1.96	*M* = 2.13	*M* = 1.70
		SD = 1.07	*SD* = 0.34	*SD* = 0.3	*SD* = 0.5
	Stack	*M* = 3.83	*M* = 2.27	*M* = 2.06	*M* = 1.59
		SD = 1.17	*SD* = 0.41	*SD* = 0.28	*SD* = 0.38
	Bags	*M* = 4.71	*M* = 2.12	*M* = 2.44	*M* = 1.59
		SD = 1.01	*SD* = 0.54	*SD* = 0.85	*SD* = 0.32
	Box	*M* = 4.41	*M* = 2.20	*M* = 2.21	*M* = 1.68
		SD = 1.40	*SD* = 0.57	*SD* = 0.34	*SD* = 0.48
Access	None	*M* = 1.98	*M* = 1.43	*M* = 1.51	*M* = 1.63
		SD = 0.89	*SD* = 0.21	*SD* = 0.24	*SD* = 0.30
	Stack	*M* = 2.03	*M* = 1.82	*M* = 1.57	*M* = 1.65
		SD = 0.88	*SD* = 0.63	*SD* = 0.26	*SD* = 0.29
	Bags	*M* = 2.81	*M* = 2.02	*M* = 2.01	*M* = 2.33
		SD = 0.98	*SD* = 0.34	*SD* = 0.39	*SD* = 0.55
	Box	*M* = 2.67	*M* = 2.65	*M* = 2.48	*M* = 1.97
		SD = 1.18	*SD* = 0.88	*SD* = 1.00	*SD* = 0.44

and the participant pressing a button on the device (*access*), or saying out loud the number shown on the device's display (*reading*). This resulted in 2 measurem.×4 placements×4 encumbr.×5 rep.=160 trials per participant. We ran our repeated measures factorial experiment with the order of access time and reading time measurements balanced across participants, and *encumbrance* and *placement* randomized using Latin squares.

At the end of the session, we asked participants to rate the different placements according to their suitability for reading and access. Ratings were given on a 5-point Likert scale. A complete session took about 45 minutes.

4 RESULTS

Twelve participants (nine male) completed our study: 2 aged 18-23, 4 aged 24-29, 3 aged 30-35, and 3 aged 36-41. Ten participants (would) wear their wristwatch on the non-dominant hand. Ten participants carry their smartphone in the pocket of their trousers on the side of their dominant hand and two participants the other side. Eight use the front pocket and four the back pocket.

4.1 Reading time

We ran a mixed-effects RM ANOVA with log-transformed *duration* as continuous response and *encumbrance*, *placement*, and their interaction as fixed effects. Participant was modeled as random effect. Fig. 3 and Table 1 provide an overview of the results. *Encumbrance* has a sign. effect on *reading* time ($F_{3,940} = 9.80, p < .0001$), as does the *placement* ($F_{3,940} = 676.61, p < .0001$) and their interaction effect *placement* * *encumbrance* ($F_{9,940} = 5.64, p < .0001$). We can therefore accept hypotheses H1-P×Read and H2-E×Read. A *post hoc* Tukey HSD test shows that the glasses are sign. faster and the phone slower than all other device placements ($p < .0001$). There is no sign. difference in reading times between the arm and watch placement ($p = .342$), but there is a sign. difference in reading times between carrying the bags or box compared to carrying nothing

Table 2: Lap time differences with the preferred walking speed while interacting (PWS&I). Negative values indicate a faster walking pace.

		Phone	Watch	Arm	Glasses
Reading	None	*M* = -4.74	*M* = -3.89	*M* = -4.01	*M* = -3.31
		SD = 5.06	*SD* = 4.22	*SD* = 4.68	*SD* = 6.33
	Stack	*M* = -2.87	*M* = -2.19	*M* = -3.63	*M* = -3.88
		SD = 7.24	*SD* = 4.22	*SD* = 6.26	*SD* = 3.50
	Bags	*M* = -0.21	*M* = -2.24	*M* = -3.23	*M* = -3.48
		SD = 8.96	*SD* = 5.43	*SD* = 4.08	*SD* = 3.62
	Box	*M* = 2.36	*M* = 1.37	*M* = 2.58	*M* = 1.29
		SD = 5.46	*SD* = 4.28	*SD* = 6.37	*SD* = 7.51
Access	None	*M* = 0.17	*M* = -3.21	*M* = -3.42	*M* = -2.79
		SD = 8.34	*SD* = 5.39	*SD* = 4.59	*SD* = 8.44
	Stack	*M* = -0.44	*M* = -2.71	*M* = -4.39	*M* = -4.52
		SD = 7.87	*SD* = 6.19	*SD* = 5.05	*SD* = 8.66
	Bags	*M* = 0.77	*M* = -4.39	*M* = -2.33	*M* = -4.07
		SD = 6.38	*SD* = 3.82	*SD* = 4.55	*SD* = 4.32
	Box	*M* = 2.96	*M* = -3.07	*M* = -3.13	*M* = -1.41
		SD = 5.08	*SD* = 4.89	*SD* = 5.92	*SD* = 7.96

($p < 0.001$), and carrying the bags compared to the stack of papers ($p = .002$).

Looking at the results of the *post hoc* Tukey HSD test regarding the interaction effect *placement * encumbrance*, reading time for the glasses is, to no surprise, not significantly affected by encumbrance. For the phone, the two-handed encumbrances (bags and box) result in significantly slower reading than the stack of papers or no encumbrance ($p < .0085$). Reading from a device placed on the upper arm is not significantly influenced by encumbrance ($p > .0755$), while the watch is significantly slower to read while carrying the stack of papers ($p = .0246$).

4.2 Device access time

We ran a mixed-effects RM ANOVA with log-transformed *duration* as continuous response and *encumbrance*, *placement*, and their interaction as fixed effects. *Encumbrance* has a sign. effect on device *access* time ($F_{3,941} = 91.14, p < .0001$), as does the *placement* ($F_{3,941} = 13.59, p < .0001$) and their interaction effect *placement * encumbrance* ($F_{9,941} = 5.36, p < .0001$). We can therefore accept our hypotheses H1-P×Acc and H2-E×Acc. A *post hoc* Tukey HSD test shows that both two-hand encumbrances (bags and box) cause access times to be sign. higher ($p < .0001$) than carrying the stack of papers. Not surprisingly, carrying nothing results in sign. shorter access times than carrying the stack of papers ($p = .0383$). In contrast to reading time, the glasses do not have an advantage when it comes to access time, where only the phone is significantly slower than all other device placements ($p < .0001$). We observed that participants developed various strategies to cope with the box to access the device in their pocket: some moved the box underneath their non-dominant arm, for instance, while others simply put the box down. The large difference between reading and access times for the phone is a result of some participants leaving the device in their pocket when they had to press the button.

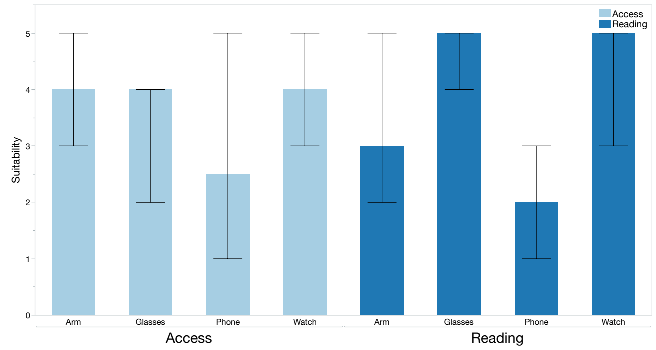

Figure 4: Median overall suitability ratings of the various placements to react to notifications. Answers were given on a 5-point Likert scale, with a higher rating being better. Error bars denote range.

4.3 Walking speed

We ran a mixed-effects RM ANOVA with log-transformed *lap time* as continuous response and *encumbrance*, *placement*, and their interaction as fixed effects. For device access time, only *encumbrance* has a sign. effect ($F_{3,192} = 8.1684, p < .0001$), while for reading time, only the *placement* has a sign. effect ($F_{3,219} = 9.2689, p < .0001$). A *post hoc* Tukey HSD shows that reading notifications on the phone results in a significantly slower walking speed ($p < 0.0016$), and that the box significantly slows down walking when having to press a button ($p < .0160$). When comparing the walking speed during the trials with the preferred walking speed while interacting (PWS&I), participants walked faster on average. For reading time, participants were only slower in the phone condition, and for access time only when carrying the box (Table 2).

4.4 Qualitative ratings

Fig. 4 summarizes the ratings with regard to suitability for reading and access. For reading, participants rated the phone the lowest (*M*=1.8, *SD*=.7), the upper arm somewhat positive (*M*=3.4, *SD*=1), and the watch (*M*=4.6, *SD*=.7) and glasses (*M*=4.7, *SD*=.5) the highest. For access, all placements received positive scores: phone (*M*=3.0, *SD*=1.4), glasses (*M*=3.5, *SD*=.7), upper arm (*M*=3.8, *SD*=.7), and watch (*M*=3.9, *SD*=.8). When asked for their favorite device to read notifications, 7 participants opted for the glasses, 4 for the watch and 1 for the upper arm. For the task of pressing a button, 4 participants preferred the watch, 3 the phone, 3 the upper arm, and only 2 the glasses.

5 DESIGN FOR ENCUMBERED INTERACTION

Smart glasses always present information directly in the user's field of view (FOV). In our study, this was clearly an advantage, but can be distracting in other settings. In an industrial context notifications that pop up in the FOV can cause safety issues as the information might cover crucial parts of machinery. In other contexts, smart glasses might not be socially acceptable, e.g., when a nurse is treating a patient. Wearing comfort and ergonomics of smart glasses are also still an issue [7], and interacting can be challenging if users are uncomfortable using gesture input and voice commands [5]. One possibility is to use glasses for output only and provide a separate device for input, e.g., touch input as part of smart garments. If a particular task makes it difficult to view or reach a watch, the device can be placed on the upper arm without significant drawbacks. The smartwatch has the advantage that users are accustomed to watches and commercial products are readily available but the screen and interaction space are limited. Using the upper arm instead of the wrist has the advantage that the display is out of the hands' interaction zone. This can be of interest for reasons of safety and comfort. The arm also provides a stronger support enabling larger screens.

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