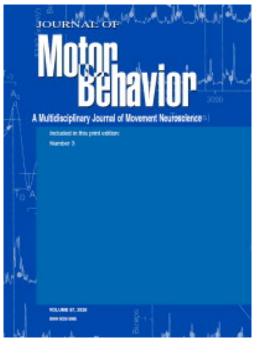

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RESEARCH ARTICLE

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Guiding the Hand to an Invisible Target

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ABSTRACT. Numerous devices are being developed to assist visually impaired and blind individuals in performing everyday tasks such as reaching out to grasp objects. Considering that the size, weight, and cost of assistive devices significantly impact their acceptance, it would be useful to know how effective various types of guiding information can be. As an initial exploration of this issue, we conducted four studies in which participants with normal vision were visually guided toward targets. They were guided by information about the direction to the target, and either about the distance to the target or about the time required to reach the target. We compared participants' performance when provided with different amounts of each of these kinds of information. We found that restricting information about the distance from the target or the time it would take to reach the target to only a few possible values does not affect performance substantially. Restricting information about the direction to the target to only a few possible values appears to be more detrimental, but the disadvantage of having few possible directions can be mitigated by combining values in multiple directions. These findings can help optimize haptic presentations in assistive technology.

Keywords: low vision, motor control, arm movements, pointing, visual guidance

Introduction

Reaching out for objects is an activity that everyone performs many times every day (Bock & Züll, 2013). Whether grasping a coffee mug or a pen, or reaching for a doorknob, most people move effortlessly and automatically (Schneiberg et al., 2002; von Hofsten, 1989). Being able to perform reaching movements is of great importance for one's quality of life. But there are people for whom reaching is not effortless, such as people with severe visual impairments. This is quite a large group of people: more than 300 million worldwide in 2023 according to the World Health Organization. While physically capable of conducting reaching movements, many visually impaired people find it difficult or even impossible to reach out and grasp objects (Pardhan et al., 2011).

To help address this problem, feelSpace is currently developing a tactile bracelet aimed at helping guide the reaching and grasping movements of the visually impaired. The bracelet design is based on feelSpace's naviBelt (Kärcher et al., 2012) which assists the visually impaired with wayfinding by using motor vibrations. The current version of the bracelet provides haptic information in four general directions (up, down, left, and right). Powell et al. (2024) investigated the viability of the bracelet and showed that tactile commands—sent manually by the experimenter based on live feedback from the helmet-mounted camera worn by the participant—provide a feasible alternative to the auditory commands that are usually used in assistive devices, with the advantage that the user can rely on auditory information for other purposes, such as social interactions or processing auditory information from the surrounding environment. Currently, an automated solution that does not require human assistance is being developed. The ultimate goal is to improve the bracelet so that it can become part of an AI-assisted system to guide the hand of visually impaired persons toward objects selected by the user based on a smartphone camera feed, giving its users more autonomy in their daily lives.

One key question in the ongoing development of the bracelet is how much information is required for effective assistance of hand navigation. As the device is supposed to serve as an everyday aid, it is important to find the best compromise between precision and ease of use. Providing too little information might prevent people from achieving the full potential benefit of such a device (Kristjánsson et al., 2016). But providing too much information might create confusion and make it difficult to learn to use the device (Elli et al., 2014). Moreover, if providing a bit more information makes the bracelet larger, heavier, or more expensive, the benefits might not outweigh the costs. The current version of the bracelet provides binary guiding information in four general directions. It provides information about the dominant direction of the hand movement that will bring the hand to the target, but no information about the distance of the hand from the object as it only uses one intensity of vibration, and one of the four directions is indicated by vibration at each instant. There is reason to believe that people could distinguish between at least 4 levels of vibration (Consigny et al., 2023; Sagastegui Alva et al., 2020), as long as the vibration frequencies are within the range that is detectable by dedicated pressure mechanoreceptors (Roudaut et al., 2012)—from 5 to

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150 Hz for Meissner corpuscles (located more peripherally) or from 20 to 1000 Hz for Pacinian corpuscles (present deeper in the skin). If using many levels of vibration is beneficial, the frequency could be optimized, or even varied, to achieve as high a resolution in the level of vibration as possible. To plan how to best try to improve the bracelet by adding (or removing) information, it would be useful to have a coarse estimate of the number of directions and of levels of intensity that are likely to be beneficial for guiding the hand.

In the current studies we try to determine the minimal amount of information that is required to efficiently guide the hand to a target. We use visual information because it is much easier to manipulate (by the experimenter) and interpret (by normally sighted participants) than haptic information. It does not require extensive training to be used (by normally sighted people), because vision normally contributes to planning reaching movements and provides constant feedback about the ongoing movement (Brenner & Smeets, 2023; Sarlegna & Sainburg, 2009; Saunders & Knill, 2005). There is no guarantee that the resolution that we find for visual information will also apply to haptic information, as the discrimination of haptic stimuli is highly dependent on parameters of the stimulation (Oroszi et al., 2020) and on the exact location of the stimulation due to differences in sensitivity even within the hand (Lakshminarayanan et al., 2015; Wheat & Goodwin, 2009). However, the upper limit of helpful information (the resolution beyond which guidance of the hand hardly improves) is unlikely to be higher for haptic than for visual information (Richardson et al., 2019). On the contrary, it may be lower if the haptic information cannot be distinguished as quickly and reliably due to the more limited bandwidth of tactile information processing (Cohen et al., 2016; Kokjer, 1987; Mao et al., 2009). Knowing beyond what resolution guidance hardly improves under ideal circumstances will provide an upper limit to the resolution that it would make sense to try to achieve with the bracelet. This can guide the choices that are made when developing new prototypes of haptic devices to test.

We present results from four studies investigating how limited information can help guide one's finger to a target. Our measure of performance is the median time it takes for the finger to reach the target. The aim of Study 1 was to examine how the number of different levels of information about the distance between the finger and the target affects performance. Information about the distance was represented in two ways: as a distance from the target and as the time required to reach the target at the current velocity (time to contact; Hecht & Savelsbergh, 2004; Oberfeld & Hecht, 2008). While the former is probably easier to learn, the latter is more flexible in that the useful scale of times to contact is probably more consistent across different kinds of reaching movements in daily life than is the distance to the object of interest. Study 2 was designed as a validation of the parameters used to represent time in Study 1. Study 3 focused on how the number of different directions that can be indicated influences performance. Finally, Study 4 examined whether using multiple guiding signals at the same time to indicate the direction, rather than the current single signal, can benefit performance. If presenting multiple signals simultaneously is better than only presenting the largest signal, it is worth considering activating multiple bracelet motors to different extents at the same time rather than increasing the number of motors to achieve a higher resolution in indicating the direction.

Materials and Methods

Participants

All participants were young adults who volunteered to take part in the experiment after being informed about what they would be required to do and signing a consent form (in accordance with our ethical approval). They all had normal or corrected-to-normal vision and could move their arm normally. Twelve participants took part in each of the four studies (7 women in Study 1; 5 in the other studies). Several participants took part in multiple studies.

Experimental Procedure

The studies were conducted in a quiet room with participants seated approximately 60 cm from a 24.5 inch monitor (54.5×30.3 cm, 1920×1080 pixels, 60 Hz) placed on a large desk. An infrared diode was attached to the nail of their dominant index finger to allow an Optotrak 3020 motion capture system to track its position (at 500 Hz). Another diode that was attached to the edge of the desk briefly stopped emitting light when a sensor detected that a flash was presented in the top left corner of the screen. Such a flash was presented whenever the first guiding image of a new trial appeared, which we consider to be the moment that the new trial started, allowing us to synchronize the movement recordings with the image presentation to within 2 ms. Each study started with a thorough explanation of the task followed by a short training session. Including this, Study 1, Study 4, and Studies 2 and 3 together, each took approximately 30 min. At the beginning of each session, the motion tracking system was calibrated by participants placing and holding their index fingers briefly at four positions marked on the desk.

Participants were asked to reach invisible targets by sliding their fingers across the desk (Figure 1). Each such invisible target was 15.6 cm from the previous

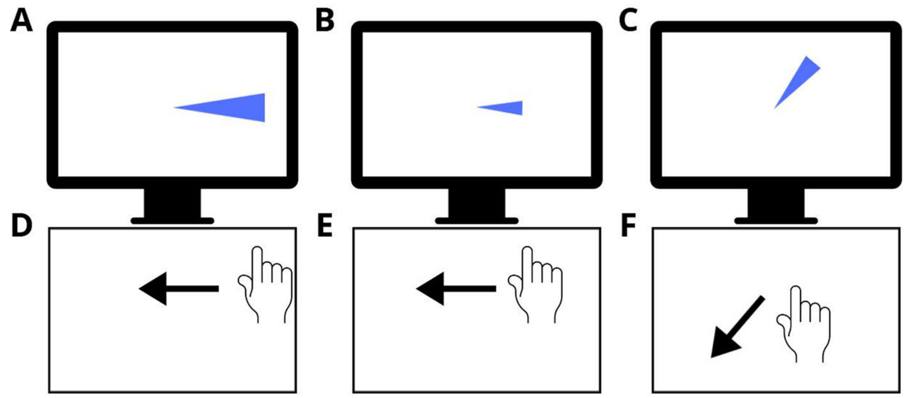

FIGURE 1. The arrow on the screen (A-C) indicates the direction that the hand has to move across the desk (D-F) to reach the target. When the hand moves in the indicated direction (D to E) the length of the arrow decreases (A to B) until the hand reaches the target. When the hand reaches the target, the trial ends, and the next trial starts with a new target being selected and the arrow indicating the direction in which the hand has to move to reach that target (C and F).

target in a random direction, ensuring that it remained within 19.5 cm of a central position on the desk. Participants were guided toward the target by a blue arrow on the screen pointing in the direction in which they were supposed to move their finger (with the intuitive mapping of 'up' on the screen corresponding with the finger moving away from the body; Brenner et al., 2020). There were two kinds of guidance: distance and time. For distance guidance, the length of the arrow was proportional to the finger's distance from the target. For time guidance, the length of the arrow was proportional to the time it would take to reach the target if one were to continue moving at the current velocity (time to contact). Only the component of the motion in the direction of the target was considered in determining the time to contact. Thus, for time guidance, whenever the finger was static or was moving away from the target the length of the arrow was at its maximum. This maximal length corresponded with a time to contact of 2000 ms. In both cases the maximum length of the arrow was 12.1 cm on the screen, corresponding with the initial target distance of 15.6 cm on the desk for distance guidance. A possible advantage of time guidance is that it might easily generalize to different distances without requiring additional resolution, but of course this would have to be tested if it turns out to work well for the current single distance.

When the finger successfully reached a target, for which the diode attached to the finger had to be less than 0.3 cm from the selected target position in the horizontal plane, participants heard a tone and a new target appeared on the screen. The participants' goal was to reach as many targets as possible within each 90 s session. Thus, the number of targets that was presented depended on the participant's performance, while the duration of the sessions was always the same. We considered the time from when a new target appeared until it was reached to be the trial time. In each study, we started from the easiest session, the one with the maximum amount of available information, and increased difficulty in each subsequent session by reducing the amount of information. This design guarantees that participants had more practice before more difficult sessions, so we can be sure that if performance is poorer with less information this is due to a reduction in the amount of information rather than to participants having difficulty understanding the task (which could be trained).

Study 1

In the first study, the number of directions that the arrow could point to was unrestricted. There were 5 sessions for each type of guidance, with each session lasting for 90 s. The number of trials per session depended on how quickly participants moved, but it was in the order of 60 trials. For each type of guidance, participants started with the maximal resolution of the arrow that could be provided on the screen, and the resolution of the arrow (the number of possible arrow lengths) was reduced in each subsequent session. The resolution can be interpreted as the amount of information about the distance from the target that is provided to the participant. Thus, for example, for a resolution of 2, the arrow length decreased by half when the finger was halfway to the target center (if guided by position) or when the velocity reached a value that would get the finger to the target center in 1000 ms or less (if guided by time), so the possible lengths of the arrow were its full length and half its length (two options). The arrow's length would have been zero when the finger reached the target center, but this was never shown because as soon as the finger reached the target a new target appeared, so arrow length was determined relative to the new target. The five sessions for each type of guidance had resolutions set at the maximum, 8, 4, 2, and 1. For a resolution of 1, the arrow had a constant length throughout the trial (Figure 2). The order of the kinds of guidance was counterbalanced across participants, with the second kind of guidance starting after all five sessions of the first kind of guidance had been completed.

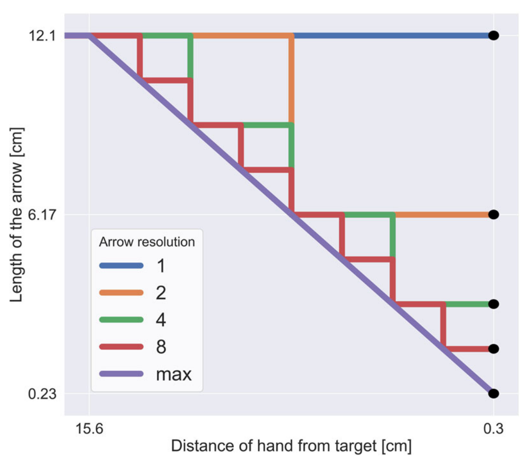

FIGURE 2. Representation of the arrow's length in relation to the finger's distance from the target. For a distance larger than 15.6 cm the length of the arrow was 12.1 cm. Upon reaching a distance of 0.3 cm from the target (position marked with black dot), the trial ended and the next trial started.

Study 2

Study 2 was conducted to check whether the rather arbitrary choice of a maximal time to contact of 2000 ms when guided by time in Study 1 was a good choice, and whether the choice matters at all. The general design of Study 2 was identical to that of the sessions in which the hand was guided by time in Study 1. There were 5 sessions that were presented in a fixed order. In subsequent sessions, the maximal time to contact was set to 4000 ms, 2000 ms (the same value as in Study 1), 1000, 500, and 250 ms. The resolution of the arrow was maximal in all sessions.

Study 3

In Study 1 we varied the resolution of the information about the amplitude of the required movement. In Study 3 we did the same for the direction of the required movement. The general design was similar to that of Study 1, but now the resolution with which the distance was indicated was always maximal, while the resolution with which the direction was presented was varied, i.e. instead of varying the number of possible lengths of the arrow, we varied the number of directions in which it could point. For example, if the number of directions was set to 4, the arrow could point up, down, left, or right. The direction to the target was obviously not always precisely one of these four. The arrow always pointed in the direction of the longest component of the total distance to the target. So, with four directions, if the finger had to move 1 cm to the left and 10 cm away from the body to reach the target, the arrow pointed up (Figure 3A). If some time later the finger had moved 9 cm away and 0.1 cm to the right, so that it now had to move 1.1 cm to the left and 1 cm further away, the (by now shorter) arrow would point to the left. During 5 subsequent sessions, the number of possible arrow directions

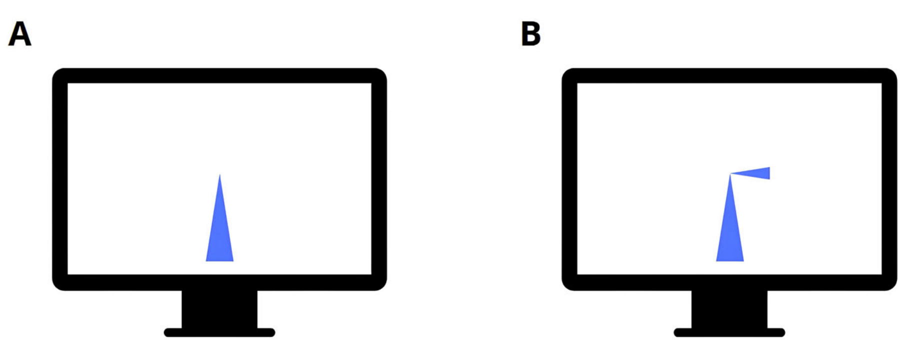

FIGURE 3. Representation of guiding information for a target further away (upwards on the screen) and slightly to the left. The display on the screen either shows a single arrow (Study 3; A) or multiple arrows (Study 4; B). In this example there are 4 possible directions: up, down, left, and right. In A, only the largest component of the required finger displacement is shown. In B, multiple arrows show all positive components (both up and to the left).

was first unrestricted and then limited to 9, 6, 4, and finally 3. Since restricting the number of directions influenced performance more than restricting the number of lengths of the arrow, there were fewer trials in this study (a median of about 35 trials per session).

Study 4

Following up on Study 3, we investigated the effect of limiting the number of possible arrow directions but using multiple components at the same time to indicate the direction. Using the example presented for Study 3, with 4 directions, both components of the distance to the left and up are presented at the same time, with the lengths of the two arrows corresponding with the distances in those directions (Figure 3B). We used both conditions of distance and time, with the same maximum arrow lengths as in Study 1 (12.1 cm, corresponding with 15.6 cm of finger movement or a time to contact of 2000 ms). For each type of guidance, in the first session, there was a single arrow pointing precisely toward the target (as in the first sessions in the previous studies). In subsequent sessions, arrows could be pointing in one or more of 9, 6, 4, and 3 directions (the same directions as we used in Study 3, but now not only the dominant direction was shown). At each moment only positive components, i.e., arrows pointing in the general direction of the target were presented. In general, for sessions with an odd $(2n+1)$ number of directions, the number of positive components is equal to $n+1$, while for sessions with an even $(2n)$ number of directions, the number of positive components is equal to n. The order of the types of guidance was counterbalanced across participants.

Data Analysis

We did not exclude any data from the analysis. Our measure of performance was the median trial time for each session and participant. We plotted the median and intra-quartile range (of these median trial times) across participants to illustrate how performance varied across the sessions of each study. For each study, we used a repeated measures ANOVA (rmANOVA) to ascertain whether the type of guidance (distance or time) or the resolution affected performance systematically. If the resolution affected performance, we also compared performance across all resolutions with post-hoc tests with Bonferroni correction.

Results

Figure 4 shows the performance in all sessions of all studies. The rightmost blue dots for studies 1, 3, and 4 are all at very similar values (median ± IQR of 1.2 ± 0.3s for study 1; 1.3 ± 0.3s for study 3; 1.1 ± 0.2s for study 4), as they were expected to be because they represent the same conditions. The same is true for the rightmost orange dots for studies 1 and 4, and the dot for a maximal time to contact of 2000 ms for study 2 (respectively 1.4 ± 0.2s, 1.4 ± 0.7s, and 1.4 ± 0.2s). This makes us confident that the results that we find are reproducible. Comparing the global performance across the four studies, the most obvious observation is that reducing the resolution with which the direction is presented is much more detrimental than reducing the resolution with which the distance is presented. Moreover, if few directions are

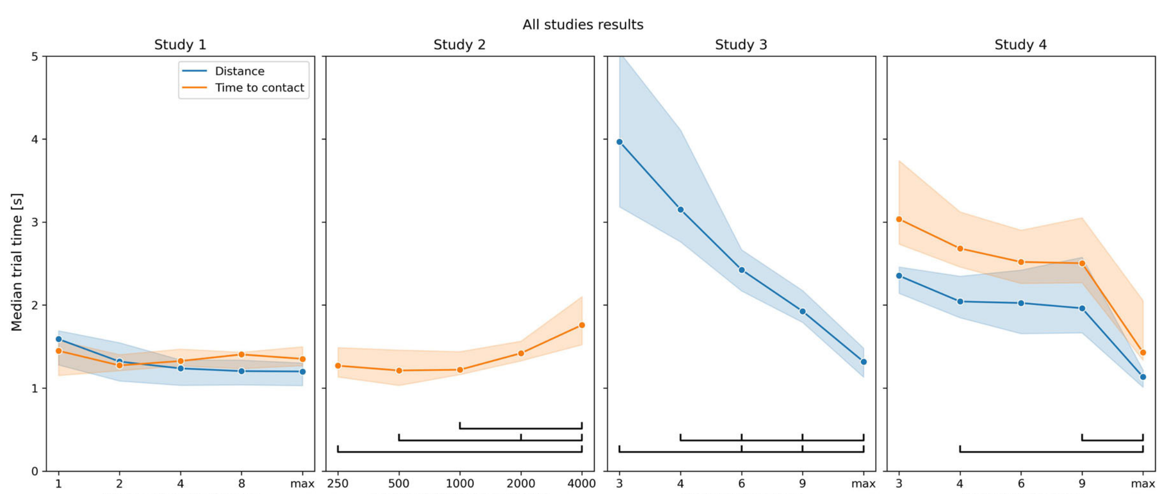

FIGURE 4. Plots of the results of all four studies. The dots show the medians across participants of the median time taken per trial by each participant. The shaded areas indicate the corresponding intra-quartile range. Distance guidance data are shown in blue; time guidance data are shown in orange. The lines at the bottom of the panels indicate for which combinations of conditions performance differed significantly in post-hoc tests (marked with ticks).

presented, performance is better if multiple arrows indicate the precise direction rather than if a single arrow indicates the dominant direction.

In Study 1, there was no significant effect of the type of guidance ($F_{1,11}$=1.11, $p = 0.31$, η_p^2=0.092), but a significant effect of resolution ($F_{4,44}$=3.07, $p = 0.026$, η_p^2=0.22) and a significant interaction between type of guidance and resolution ($F_{4,44}$=3.74, $p = 0.011$, η_p^2=0.25). Looking at Figure 4 (Study 1) we see that performance was better when there were many steps, but mainly for distance guidance. Altogether the differences are quite modest. In Study 2 there was a significant effect of the selected maximal time ($F_{4,11}$=14.2, $p < 0.001$, η_p^2=0.56). Performance was especially poor for the longest time (4000 ms). From Figure 4 (Study 2) it would appear that a shorter maximal time than the 2000 ms that we originally chose is somewhat better. In Study 3 there was a significant effect of the number of directions on performance ($F_{4,11}$=51.4, $p < 0.001$, η_p^2=0.82). There was a steep decline in performance when the number of directions was reduced (Figure 4, Study 3). In Study 4 there was a significant effect of both the type of guidance ($F_{1,11}$=5.37, $p = 0.041$, η_p^2=0.33) and of the resolution ($F_{4,44}$=5.67, $p < 0.001$, η_p^2=0.34). The interaction between the type of guidance and resolution was not significant ($F_{4,44}$=1.33, $p = 0.27$, η_p^2=0.11). Performance was better with distance guidance than with time guidance (Figure 4, Study 4). Importantly, presenting many directions rather than only the dominant direction appears to mitigate the effect of reducing the number of directions. With 9 directions, performance was quite similar to that in Study 3, but with fewer directions, the decline in performance was clearly smaller.

Discussion

In four studies, we explored how quickly participants reached targets when provided with different kinds (distance to or time to contact) and amounts (number of steps in amplitude or direction) of visual information. Our goal was to examine the general ability of participants to reach the target and the relationship between their performance and the varying informational content of the guiding signal. What can we conclude from the results and what implications do they have for improving the bracelet?

Study 1 shows that indicating the magnitude of the required movement in the direction of the target does not make much difference. Increasing the number of steps from 1 to 2 might be slightly beneficial, but beyond that the resolution does not seem to matter. That the number of amplitude steps is not important suggests that performance relies on guiding the finger in the correct direction, more than on guiding it to move the correct distance. In accordance with primarily relying on the direction, whether the distance is presented directly or as a time to contact hardly matters: the pattern of results was similar for guidance based on distance and time. Moreover, the scaling of the time to contact in Study 2 hardly affects performance. Thus, presenting vibration with more than two levels in the bracelet to indicate how far to move is probably not very useful.

But a limitation of this study in terms of using distance information to guide the hand is that the next target was always at the same distance from the previous one. This was necessary to ensure that we could use the time taken to make each movement (and therefore the median trial time) as a reliable measure of performance. However, it gives participants some information about the total distance that they have to move, so maybe providing a larger number of steps is a bit more useful than our results suggest. Thus, considering that the current version of the bracelet does not include any information about the distance from the target, it might be worth testing using 2 (or maybe even 3) amplitude steps. This could be done with either type of guidance. Distance guidance seems to be slightly better, at least when there are many amplitude steps, and is slightly more intuitive, but relying on time to contact might transfer better to movements that differ widely in distance. Another reason to consider multiple steps is discussed below.

In contrast with the modest influence of varying the number of amplitude steps, varying the number of directions clearly influenced performance substantially. As shown in Study 3, when there were only 3 directions it took participants about twice as long to reach the target as with 9 directions, and about three times as long as with unrestricted directions. Each reduction of the resolution resulted in a further decrease in performance. With 4 directions, as in the current version of the bracelet, the median times needed for the successful execution of the task were more than twice as long as with an unrestricted number of directions, and at least 20% longer than with 6 directions. Although this suggests that increasing the number of directions could improve performance substantially, an issue that needs to be considered is that in the case of the bracelet, limitations in people's ability to localize signals presented on the wrist (Chen et al., 2008; Cody et al., 2010; Hong et al., 2017; Matscheko et al., 2010) might reduce the benefit of increasing the number of directions.

A potential strategy for dealing with the limited number of directions that people can distinguish between is by using multiple channels at the same time. As shown by Study 4, such a strategy works. Performance is not as good as with a single arrow indicating the precise direction ('max' in Figure 4, Study 4), but decreasing the resolution from 9 to 4 directions does not affect performance in the way that it does for the same change in resolution when only a single direction is shown (Figure 4, Study 3). For this to work, one must obviously be able to present various levels of stimulation at the four positions. If people can distinguish between enough intensities of the vibration of the bracelet, and readily combine levels across positions (as they apparently do for the visually presented arrows), relying on this method might help guide the hand by the bracelet without having to increase the number of positions at which the hand is stimulated. Whether this is so obviously needs to be tested with the bracelet itself, preferably with blind participants. It might also be useful to examine whether more information is useful with more practice. Notwithstanding such limitations, our findings provide novel insights into the benefits of various ways of guiding the hand to a target, which could serve as a basis for improving technical solutions aimed at enhancing the quality of life of the visually impaired.

It is important to note several additional limitations of the current study. The most important limitation is that we used visual guidance. We cannot be sure that our findings will also apply to tactile guidance, because details of the way in which movements are guided and executed may be different for tactile stimulation to the arm than for visual stimulation of the eye (Sarlegna & Sainburg, 2009). Moreover, our assumption that a higher resolution of information is likely to be more helpful for visual guidance than for haptic guidance might not hold, as there are several accounts of rapid processing of haptic signals such as vibrations (Satpute et al., 2020), thermal changes (Peiris et al., 2019), robotic 'force field' (Reinkensmeyer & Patton, 2009), and pneumatic pressure (Kim et al., 2008). However, as there is reason to believe that the general principles are similar for guidance by vision and touch (Darling et al., 2018; Nelson et al., 2019), the results identify the adjustments to the bracelet that are most likely to benefit performance.

Another limitation of the current study is the employment of fully sighted participants, who might naturally guide their movements differently than the visually impaired. The target population of bracelet users differs from our participants in terms of how they process and perceive their environment (Amedi et al., 2001; Cattaneo et al., 2008, Dormal et al., 2018), so they might guide their movements quite differently. On the other hand, after training, blind participants might guide their movements on the basis of haptic information more like sighted people do with vision. Ultimately, obviously, studies with tactile guidance and blind participants are needed to determine the best design of the bracelet for haptic guidance. The current results can be used to guide the choice of how to present the information in such studies. In such studies it is probably also a good idea to consider effects of (prolonged) training, because the most intuitive method of presentation may not be the best after training. This might not only help design the bracelet, but also provide interesting insights about the ability to learn to make better use of whatever information is available. In the current study, several participants took part in multiple studies, potentially enhancing their performance in the later tasks. However, we saw no improvement in performance across studies for the identical conditions. Moreover, our conclusions are not based on comparing performance between the studies.

Notwithstanding all these limitations, our findings provide novel insights into the benefits of various ways of guiding the hand to a target, which could serve as a basis for improving technical solutions aimed at enhancing the quality of life of the visually impaired. Additionally, the findings more generally suggest that providing continuous information about the direction to the target is more important than providing continuous information about the distance to the target.

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Authors' Contributions

Conceptualization, M.F. and E.B.; methodology, M.F., and E.B.; software, E.B.; validation, M.F., and E.B.; formal analysis, M.F.; investigation, M.F.; resources, E.B.; data curation, M.F.; writing-original draft preparation, M.F.; writing-review and editing, M.F. and E.B.; visualization, M.F.; supervision, E.B.; project administration, M.F., and E.B. All authors have read and agreed to the published version of the manuscript.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Data Availability Statements

The data presented in this study are openly available at osf.io/zmu2b.

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