Sensory stimulation for human guidance in robot walkers: a comparison between haptic and acoustic solutions

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Abstract— **We compare two different solutions to guide an older adult along a safe path using a robotic walking assistant (the *c-Walker*). The two solutions are based on tactile or acoustic stimuli, respectively, and suggest a direction of motion that the user is supposed to take on her own will. We describe the technological basis for the hardware components, and show specialised path following algorithms for each of the two solutions. The paper reports an extensive user validation activity, with a quantitative and qualitative analysis.**

I. Introduction

Ageing is often associated with reduced mobility, consequence of a combination of physical, sensory and cognitive degrading. Reduced mobility may weaken older adults' confidence in getting out alone and traveling autonomously in large spaces. Reduced mobility has several serious consequences including an increase in the probability of falls and other physical problems, such as diabetes or articular diseases. Staying at home, people lose essential opportunities for socialisation and may worsen the quality of their nutrition. The result is a self-reinforcing loop that exacerbates the problems of ageing and accelerates physical and cognitive decline [1].

In the context of different research initiatives (the *DALi* project[1] and the *ACANTO* project[2]) we have developed a robotic walking assistant that compensates for sensory and cognitive impairments and supports the user's navigation across complex spaces. The device, called *c-Walker* (Fig. 1), is equipped with different types of low level sensors (encoders, inertial measurement unit) and advanced sensors (cameras) that collect information on the device and its environment. Such measurements are used by the *c-Walker* to localise itself and to detect potential risks in the surrounding environment. By using this information, the *c-Walker* is able to produce a motion plan that prevents accidents and drives the user to her destination with a small effort and satisfying her preferences. The projects follow an inclusive design approach which requires older users involvement and participation at appropriate moments in the process, once the evaluation protocols have been validated.

In this work we describe two different mechanisms for guidance available in the *c-Walker*: the haptic and the acoustic guidance. The haptic guidance is a passive system based on the use of a pair of bracelets that vibrate in the direction the user is suggested to take. The acoustic guidance is based on simulating a sound in space that the user should follow in order to move in the right direction. The user is in charge of the final decision on whether to accept or refuse the suggestions. In the paper, we describe the technological foundations of the different mechanisms and algorithms and offer some details and insight on how they can be integrated in the *c-Walker*. In addition, we present the results of two evaluation studies involving a population of students, which sets the basis for the definition of a protocol for the evaluation of the performance of the guidance systems and on the quality of the users' experience. The results of the evaluation disclose important design directions for future guidance systems definition.

The paper is organised as follows. In Sec. II, we review the scientific literature related to our work. In Sec. III, we describe the haptic and the acoustic guidance mechanisms available in the *c-Walker*. In Sec. IV we describe the guidance algorithms in which the different mechanisms can be used. We report our testing and validation activities on all of the systems in Sec. V, and finally we conclude with Sec. VI.

II. Related Work

The robot wheelchair proposed in [2] offers guidance assistance such that decisions come from the contribution of both the user and the machine. The shared control, instead of a conventional switch from robot to user mode, is a collaborative control. For each situation, the commands from robot and user are weighted according to the respective experience and ability leading to a combined action.

Other projects make use of walkers to provide the user with services such as physical support and obstacle avoidance. In [3], the walker can work in *manual mode* where the control of the robot is left to the user and only voice messages are used to provide instructions. A shared control operates in *automatic mode* when obstacle avoidance is needed and user intention is overridden acting on the front wheels. Other solutions rely on a passive braking system to mechanically steer the walker towards the desired direction [4], [5]. Key to any guidance system of this kind is the ability to detect and possibly anticipate the user intent. A valuable help in

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[1]http://www.ict-dali.eu

[2]http://www.ict-acanto.eu

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this direction can be offered by the use of force sensors [6] or of omnidirectional mobile basis [7]. These solutions are very expensive, whereas the *c-Walker* is proposed as a low cost device. Another relevant solution is the *JAIST active robotic walker* (JaRoW), proposed by [8], which uses infrared sensors to detect lower limb movement of the user and adapt direction and velocity to her behaviour.

The mentioned solutions can be considered as "active" guidance systems, meaning that the system actively operates to steer the user toward the desired direction by mechanical actions. A possible idea to reduce intrusiveness, which is the main objective of the systems analysed in this paper, is to use passive devices, where suggestions on the direction of motion take the form of visual, auditory or tactile stimuli, and the user remains totally in charge of the final decision. Haptic interfaces are used to provide feedback on sense of motion and the feeling of presence, as in [9]. Guidance assistance can be provided by giving feedback on the matching between the trajectory followed by the user and the planned trajectory. In [10], a bracelet provides a warning signal when a large deviation with respect to the planned trajectory is detected. In [11] a belt with eight actors is used to provide direction information to the user in order to complete a way-point navigation plan. As shown below, haptic bracelets are one of the possible guidance methods offered by the *c-Walker*.

A different "passive" guidance system is based on acoustic signalling. Our acoustic guidance solution is based on synthesising a sound from a virtual point towards the desired direction. The main method to render sound signals from a specified point is based on the Head Related Transfer Function (HRTF), which represent the ear response for a given direction of the incoming sound. As such, they need to be determined for each individual [12]. Other approaches are based on sound propagation modeling. The sound attenuation is taken into account using the Interaural Level Difference (ILD), which accounts for the presence of the listener head. Similarly, Interaural Time Difference (ITD) accounts for the distance between ears and sound source [13]. These filtering processes are computationally demanding. The acoustic guidance mechanism implemented in the *c-Walker* is based on the adoption of lightweight algorithms amenable to an embedded implementation [14].

III. Guidance mechanisms

In this section, we describe the two main mechanisms that we use as "actuators" to suggest changes in the direction of motion.

A. Haptic Bracelets

A "vibrotactile" device is able to transmit tactile stimulation in the form of vibrations. Vibration is best transmitted on hairy skin because of skin thickness and nerve depth, and it is best detected in bony areas. Wrists and spine are generally the preferred choice for detecting vibrations, with arms immediately following. A haptic guidance uses vibrotactile devices to guide users inside the environment. Considering older adults as users and the fact that the signal is transmitted while the user moves (indeed, movements is known to adversely affect the detection rate and the response time of lower body sites [15]) makes the problem very challenging.

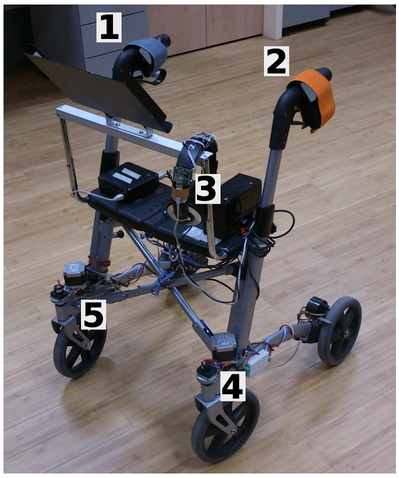

Fig. 1. The *c-Walker* with the guidance mechanisms: 1. Right bracelet, 2. Left bracelet, 3. Headphone, 4. Left motor, 5. Right motor.

To implement the haptic guidance, we designed a wearable haptic bracelet in which two cylindrical vibro–motors generate vibratory signals to warn the user (Fig. 1). On each bracelet the distance between the two motors is about 80 mm, which is conservatively greater than the minimal distance of 35 mm between two stimuli to be differentiated on the forearms. Notice that there is no evidence for differences among the left and right sides of the body [16]. The subject wears one vibrotactile bracelet on each arm to maximize the stimuli separation while keeping the discrimination process as intuitive as possible. Vibration of the left wristband suggests the participant to turn left, and vice versa. In order to reduce the *aftereffect* problem typical of continuous stimuli (which reduces the sensibility to vibrations) and to preserve users' ability to localize vibration, we selected a pulsed vibrational signal with frequency 280 Hz and amplitude of 0.6 g, instead of a continuous one. When a bracelet is engaged, its two vibrating motors alternatively vibrates for 0.2 s. The choice of frequency and amplitude of the vibrations, as well as the choice of two vibrating motors instead of one, was an outcome of a study with a group of older adults [17].

B. Audio interface

The acoustic interface has the role of transmitting to the user directional information by means of acoustic signals reproduced over the headphones (Fig. 1). To encode the directional information in audio signals, we took advantage of the humans ability of recognizing the position in space where natural sounds originate. The human beings ability to interpret the position of sound sources depend on the shape of the human external ears, which depend on the direction of arrival of impinging sound waves. The sound spectral changes at the basis of this process can be synthesized to reproduce the same sensation on artificial sounds played

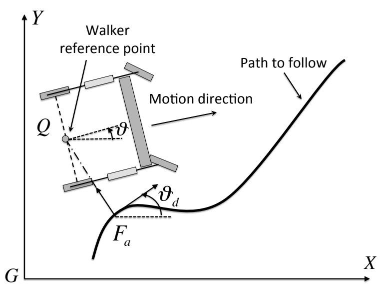

Fig. 2. Graphic representation of the Frenet-Serret reference of the *c-Walker* with respect to the path.

back over headphone. To suggest to the user to turn left, the interface reproduces a sound that is perceived from the listener as coming from a location on his/her left side, hence generating an illusion of coming from the direction he/she is supposed to follow. The synthesis of positional sound is made possible thanks to the binaural synthesis algorithm implemented within the `Audio Slave` software module.

The Audio Slave component receives as input the spatial coordinates of the virtual sound source $(S_x,\ S_y)$ and generates the corresponding positional sound. To this end, the Audio Slave module converts Cartesian coordinates into polar coordinates (r, θ), in which r represents the distance between the center of the listener's head and the virtual sound source position, and θ identifies the angle on the horizontal plane subtended between the user frontal plane and segment joining the virtual sound source position with the center of the user head. We chose to use as a guidance signal a white noise since it better conveys the spectral cue useful for sound localization. The guidance stimulus lasts for 50 ms and it is repeated every 150 ms. The binaural processing algorithm can simulate virtual sounds in any location of the horizontal plane, contrary to the haptic interface which in turn gives just a left/right indication. To compensate head movements, an Inertial Measurement Unit (IMU) is mounted on top of the headphone arches using an approach similar to [18]. The Audio Slave synthesize a sound taking into account attenuation and delays according to the physics of sound wave propagation and applies filtering to reproduce the low–pass effect introduced by the presence of the listener's head.

IV. Guidance algorithms

The guidance algorithms rely on an accurate estimate of the position of the *c-Walker* with respect to the planned path. Since the latter is generated internally by a module of the *c-Walker* (see [19]), only the knowledge on the position $Q = [x\ y]^T$ and of the orientation θ expressed in some known reference frame is needed. This problem, known in the literature as *localisation problem*, is solved in the *c-Walker* using the solutions proposed in [20].

With this information it is possible to determine the Frenet-Serret point F_a, that is the closest point to the path. The segment joining the vehicle with such a point is then perpendicular to the path tangent in F_a, as in Fig. 2 (a). We define as y_d and θ_d respectively the distance along the projection of the vehicle to F_a and the difference between the orientation of the *c-Walker* and the orientation of the tangent to the path in the projection point. The two proposed guidance algorithms use this information to compute the specific "actuation".

We observe that the objective of the guidance algorithms is not the perfect path following of the planned trajectory. This would be very restrictive for the user and perceived as too authoritative and intrusive. To give the user the feeling of being in control of the platform, she is allowed an error (in both position and orientation) that is kept lower than a desired performance threshold throughout the execution of the path. Therefore, the path can be considered as the centre line of a virtual corridor in which the user can move freely.

A. Haptic guidance algorithm

The haptic guidance algorithm generates a control action that suggests to the user the desired approach direction to the path. The intent is to make the user performing the same action of an autonomous vehicle that executes a path following control algorithm. To this end, we consider the kinematic model of the *c-Walker* (unicycle–like vehicle)

$$\dot{x}_d = \cos(\theta_d)v, \quad \dot{y}_d = \sin(\theta_d)v, \quad \dot{\theta}_d = \omega, \tag{1}$$

where y_d and θ_d are the quantities defined in the previous section, and x_d is the longitudinal coordinate of the vehicle that, in the Frenet-Serret reference frame is identically zero by definition. The inputs of the model are the forward velocity $v \neq 0$ and the angular velocity ω.

A compromise between accuracy and cognitive load for the interpretation of signals is the definition of a simple alphabet of quantised control symbols: a) turn right; b) turn left; c) go straight. Therefore, the user has free choice of forward velocity, while the haptic bracelets signal the sign of the angular velocity. We have therefore designed a very simple control Lyapunov function which ensures a controlled solution to the path following in the case of straight lines acting only on the vehicle angular velocity and irrespective of the forward velocity of the vehicle. Such a controller works also for curved paths if we are only interested on the sign of the desired angular velocity.

The pair $(x_d,\ y_d)$ represents the Cartesian coordinates, in the Frenet-Serret reference frame, of the midpoint of the rear wheels axle. In light of model (1) and recalling that x_d does not play any role for path following, we can set up the following control Lyapunov function

$$V_1 = \frac{k_y y_d^2 + k_\theta \theta_d^2}{2}, \tag{2}$$

which is positive definite in the space of interest, i.e., $(y_d,\ \theta_d)$, and has as time derivative

$$\dot{V}_1 = k_y y_d \sin(\theta) v + k_\theta \theta \omega, \tag{3}$$

where $k_y > 0$ and $k_\theta > 0$ are tuning constants. Imposing ω equals to the following desired angular velocity

$$\omega_d = -q_\theta \theta_d - \frac{k_y}{k_\theta} y_d \frac{\sin(\theta_d)}{\theta_d} v, \tag{4}$$

with $q_\theta > 0$ additional degree of freedom, the time derivative in (3) is negative semidefinite; using La Salle invariant principle, asymptotic stability of the equilibrium point $(y_d,\, \theta_d) = (0,\, 0)$ can therefore be established, with the *c-Walker* steadily moving toward the path.

Together with the virtual corridor of width $2y_h$, we also define a cone of amplitude $2\theta_h$. The cone, centered on the corridor, defines the allowed heading of the *c-Walker*. When V_1 in (2) is greater than a certain V_1^{max}, which is defined as in (2) when $y_d = y_h$ and $\theta_d = \theta_h$, the actuation takes place. For the haptic and acoustic algorithms, the parameters that define the corridor are the same, that are $y_h = 0.3$ m and $\theta_h = 0.52$ rad. The constants q_θ, k_y and k_θ are also the same for both haptic guidance and acoustic guidance, but change according to the actual position of the *c-Walker* with respect to the corridor. When the *c-Walker* is outside the corridor $y_d > y_h$, we want the controller to be more active to steer the vehicle inside, therefore we select $k_y = 1$ and $k_\theta = 0.1$. On the contrary, when the *c-Walker* is inside $y_d \leq y_h$, to mantain the current orientation tangent to the path we select $k_y = 0.1$ and $k_\theta = 1$.

We define the parameter α to represent the magnitude of the error with respect to the desired position, but also considering the dimension of the selected virtual corridor:

$$\alpha = \min\left(1, \frac{V_1}{V_1^{max}}\right). \tag{5}$$

After the computation of ω_d as in (4), we can determine the final control direction with $\omega = \alpha\omega_d$. The sign of ω rules the direction of switching: a) if $\omega > t_\omega$ then the user has to turn left; b) if $\omega < -t_\omega$ then the user has to turn right; c) if $\omega \in [-t_\omega,\, t_\omega]$ then the user has to go straight. t_ω is a design threshold used to be traded between the user comfort and the authority of the control action.

B. Binaural acoustic guidance algorithm

To identify the position in space of the virtual guidance sound source, we adopted the following approach. First, we define a circle of radius ds centered in the vehicle position Q (ds is set equal to 1.2 m during our experiments). The segment connecting the origin of the Frenet-Serret reference frame (F_a) and P – that is the intersection between the circle and the tangent to the circle in the origin of F_a – is labeled as dp. If multiple intersections exist, the algorithm selects the one that lies close to the forward direction of the *c-Walker*. In case only one solution exists, this corresponds to $|y_d| = ds$, meaning that the point P coincides with the origin of the reference frame F_a. If $|y_d| \geq ds$, then no solution exists, and P lies on the segment joining Q and F_a.

We define the desired sound source position with respect to a fixed reference system as S. Generally, S is computed as the projection of P onto the planned path. However, if the *c-Walker* is near to a straight path component, or it is farther than ds from the path, then S coincides with P. The location of S is then transformed into the *c-Walker* reference coordinate frame by:

$$S_{cw} = \begin{bmatrix} s_{x_{cw}} \\ s_{y_{cw}} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} (S - Q). \tag{6}$$

As said previously, in case $|y_d| \geq ds$, the target is pushed toward the planned path along the shortest direction.

C. Actuation

Haptic: The bracelets are actuated according to the direction to follow. There are two choices of actuation: the first considers the value of ω as discussed above, while the second considers the value of $s_{y_{cw}}$ defined in (6). In both cases, the sign determines the direction of turning.
Binaural: The binaural algorithm fully exploits the reference coordinates S_{cw} in (6) using a finer granularity of positions than the Left/Right haptic guidance.

The sound processing algorithm can synthesize sound signals generated by a virtual sound source located in any position on the horizontal plane. However, the front horizontal half–plane has been discretized into a set of seven equally spaced cones. In this manner, the direction of the virtual sound source has been discretized into 7 possible locations. As result of the discretization, the new position of the virtual sound source is S_s. By defining with θ_i the actual azimuthal angle of the user head – measured by means of the IMU – the final sound source position S_p is calculated as

$$S_p = \begin{bmatrix} \cos(\theta_i) & \sin(\theta_i) \\ -\sin(\theta_i) & \cos(\theta_i) \end{bmatrix} S_s.$$

V. Experimental results

A formative evaluation was designed to compare and contrast the performance of the two different guidance systems. Since the preliminary state of user research in this field [21], [22], the main focus of the evaluation was on system performance, rather than on the user experience. The study had two concurrent objectives: to develop a controlled experimental methodology to support system comparisons and to provide practical information to re-design. In line with an ethical application of the inclusive design process [23], at this early stage of the methodological verification process of an evaluation protocol, we involved a sample of University students.

1) Participants: Thirteen participants (6 females, mean age 30 years old, ranging from 26 to 39) took part in the evaluation. They were all students or employees of the University of Trento and gave informed consent prior to inclusion in the study.

2) Design: The study applied a within-subjects design with Guidance (4) and Path (3) as experimental factors. All participants used both the guidance systems (haptic and binaural) in three different paths: straight (I), C shaped (C) and S shaped (S). The order of the system conditions was counterbalanced across participants.

3) Apparatus: The experimental apparatus used in the experiment is a prototype of the *c-Walker* shown in Figure 1. An exhaustive description of the device and of its different functionalities can be found in [4]. A distinctive mark of the *c-Walker* is its modularity: the modules implementing the different functionalities can be easily plugged on or off based on the specific requirement of the application. The specific configuration adopted in this paper consisted of: 1.

a `Localisation` module [20] (which provides the walker position with an error that is less than 1% of the travelled path), 2. a short term `Planner` [19] (which plans safe routes inside the selected environment), 3. a `Path Follower` (which implements the guidance systems reported in this paper).

A. Procedure

The evaluation was run in a large empty room of the University building by two experimenters: a psychologist who interacted with the participants and a computer scientist who controlled the equipment. At the beginning of the study, participants were provided with the instructions in relation to each guidance system, mainly that the haptic vibration (either on the left or right arm) would have indicated the side of the correction necessary to regain the path, while for binaural guidance would have provided a sound indicating the direction and the amount of the correction needed. In this latter case, the participants were given a brief training to make them experience the spatial information of the sounds, which is not trivial as a haptic vibration.

The starting position of each trial varied among the four corners of a rectangular virtual area (about 12 x 4 meters). The *c-Walker* was positioned by the experimenter with a variable orientation. At the end of each system evaluation, which lasts around 90 minutes, participants were invited to answer 4 questions, addressing ease of use, self-confidence in route keeping, acceptability of the interface in public spaces and an overall evaluation on a 10 points scale. Participants were also invited to provide comments or suggestions.

B. Data analysis

Performance was analysed considering four dependent variables. A measure of error was operationalised as deviation from the optimal trajectory and calculated using the distance of the orthogonal projection between the actual and the optimal trajectory. We collected a sample of 100 measurement (about one value every 10 centimetres along the curvilinear abscissa of the path) that were then averaged. Due to the limited length of the paths (10 m each), the trajectories are measured using on-board incremental encoders, which provides acceptable accuracy with an accumulated error below 1% of the travelled path [20]. *Time* was measured between the start of participant's movement and the moment the participant reached the intended end of the path. *Length* measured the distance walked by the participant. For each participant and guidance system, we averaged an index scores for the four 'S', the four 'C' and the two 'I' paths. Data analysis was performed employing the analysis of variance (ANOVA) with repeated measures on the factors 'Guidance' and 'Path'. Post-hoc pairwise comparisons corrected with Bonferroni for multiple comparisons (two tails) were also computed.

C. Results

Regarding the path following accuracy, the post-hoc pairwise comparisons with ANOVA highlighted the binaural turns to be the most effective for 'I' and 'S' shaped paths, while the haptic guidance suffers particularly the 'S' shaped paths, while it is still a viable solution in the other two cases. For the time needed to travel along the paths, the ANOVA analysis showed that the 'I' path differed significantly from the 'S' path. However, walking time was independent of Path for the binaural guidance. Conversely, the 'S' path was performed significantly slower than the 'I' path for the haptic guidance. On average, the binaural solutions takes 2,5 sec less than the haptic interface. Finally, when analysing the travelled path length, the post-hoc comparisons indicated that the haptic guidance differed significantly from the binaural and that the 'I' path differed significantly from the 'C' and 'S' paths. The haptic guidance showed the worst result in the 'S' path. Furthermore, for the binaural condition there was no effect of Path.

	P	**E**	**C**	**A**	**Total**
Haptic	++	++	++	+++	9
Binaural	+	+	++	+	5

TABLE I

SUMMARY OF THE RESULTS: PERFORMANCE **P**, EASINESS **E**, CONFIDENCE **C** AND ACCEPTABILITY **A**.

D. Questionnaire

Participants scores to the four questionnaire items were normalised for each participant in relation to the highest score provided among all the answers. The ANOVA indicates that the haptic guidance is perceived as easier to use, while for the confidence to maintain the correct trajectory the two systems are in practice equivalent. Concerning the acceptability to use the guidance systems in public spaces, the haptic solution was again the preferred one. Finally, participants liked the haptic systems with respect to the binaural, and have suggested its integration with other, possibly active, mechanical guidance systems.

Participants spontaneously reported a general dislike about wearing headphones mostly because they might miss important environmental sounds and because of the look. Most of the participants agreed that the binaural condition required more attention than the other system, still appreciating its novelty and the capacity to provide a constant feedback on the position. Most of them appreciated the amount of information the binaural system can provide, yet some reported a difficulty in discriminating the direction of the sound.

Most of the participants reported to prefer the haptic guidance system to the binaural, as easier and less intrusive. However, they complained about the poverty of the left and right instructions and the lack of a modulation. Some participants suggested possible ways to increase communication richness, such as, modulating the frequency of the vibration in relation to the magnitude of the correction. Some participants reported a kind of annoyance for the haptic stimulation but only for the first minutes of use.

The summary of these results can be found in Table I, which also collects a ranking of the two guidance systems.

E. Discussion

The aim of this study was to gather quantitative and qualitative information for the evaluation of two different guidance systems. To this aim participants had the opportunity to navigate non-visible paths (i.e., virtual corridors). To maintain the correct trajectory, participants could only rely on the instructions provided by the *c-Walker* and, after using each system, they were asked to provide feedback.

Although informative, in terms of quantifying the angle of the suggested trajectory, the binaural guidance system emerged to be poorly performant the 'C' path. However, it is likely that with adequate training the performance with the binaural system could improve a lot. The results of the questionnaire suggest that a system using headphones were not very acceptable because of the possibility to miss environmental sounds and because of the look. Moreover, the binaural system was reported to require more attention than the haptic one. Overall, the binaural guidance was appreciated because it was something new and provided detailed information. Indeed, most of the participants' suggestions related to the haptic guidance systems were addressed at codifying the instructions in terms of the angle of the correction. Significant performance differences emerged between the haptic and the binaural guidance, which could in part be explained by the natural tendency to respond faster to auditory stimuli rather than to tactile stimuli. One participant explicitly mentioned that the left-right stimulation tended to generate a zigzagging trajectory. In terms of user experience, the haptic guidance was perceived as more acceptable than the binaural system, since the haptic bracelets could be hidden and did not interfere with the environmental acoustic information.

To summarise, according to Table I, the best guidance for the user experience was no doubt the haptic, even though the binaural turned to be more effective in the technical evaluation reported previously. The participants' evaluations highlighted new challenges for the socio-technical design of future guidance system, e.g. user acceptability.

VI. Conclusions

In this paper we have presented two different solutions for guiding a user along a safe path using a robotic walking assistant. We have described the technological and scientific foundations for the two different guidance systems, and their implementation in a device called *c-Walker*. The systems has been thoroughly evaluated with a group of volunteers. This paper contributed a novel evaluation protocol for comparing the different guidance systems, and opens new challenges for interaction designers. Future research will repeat this study in more ecological contexts, enlarging the cohort of users and of guidance systems to be compared. Moreover, quantitative results will be produced.

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