Many Cues, Few Clues: Identifying Design Opportunities for Digital Cues in Physical Rehabilitation Processes

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Abstract

Cueing is defined as the use of external temporal or spatial stimuli to facilitate the initiation and continuation of movement. For gait rehabilitation, cues can take the form of multimodal stimuli, providing metrics and instructions for patients to correct their movements, and can be used in multiple contexts and objectives. Therefore, the design space of interactive systems for rehabilitation is quite broad and there is a lack of systematic guidance for designers who are interested in creating and evaluating novel assistive tools. We performed a systematic literature review on the usage of cues in gait rehabilitation. In this paper, we present the preliminary results of this review, focusing on the use of digital and non-digital cues combined with mobility aid such as crutches. We discuss some considerations for future studies evaluating the design of assistive devices in physical rehabilitation and provide initial recommendations for context-adaptive digital cues, opening new perspectives for tailored and personalised gait training and rehabilitation.

Keywords

cues, rehabilitation, assistive technologies, accessibility, gait, mobility aid

1. Introduction

Cueing is defined as using external temporal or spatial stimuli to facilitate the initiation and continuation of movement, providing the necessary trigger to switch from one movement to another in a sequence of movements [2]. The ability to walk is the result of a fine coordination of sensori-motor control, with voluntary movements automatically regulated. Walking skills can be affected by injuries, diseases or cognitive decline. Gait rehabilitation provide patients with means to re-acquire the necessary skills to maintain their mobility. Patients with Parkinson's Disease (PD), for example, have been shown to significantly improve the speed and execution of their movements through the use of cues in their rehabilitation processes [2, 33].

In recent years, interactive systems have been developed to help patients going through rehabilitation. These systems can bring awareness to inexperienced users about the correct usage of mobility aids during earlier stage of rehabilitation [23]. Additionally, measuring instruments connected to mobility aids like crutches can provide gait analysis of patients with the goal of helping them perform necessary corrections, for example, recognize the level of weight-bearing in the lower limbs to ensure that the patient is putting the prescribed amount of weight in the injured leg during walking with crutches [3]. This opens new perspectives for personalized care, monitoring progress throughout the rehabilitation process.

Cues are of paramount importance when it comes to helping patients going through rehabilitation

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processes of all kinds. Cues can take the form of auditory, visual or multimodal stimuli, and can be used in multiple contexts and objectives. Therefore, the design space of interactive systems for rehabilitation is quite broad. Consequently, there is a lack of systematic guidance for designers who are interested in creating and evaluating novel assistive tools. We believe there are more design opportunities for creating assistive systems providing real-time feedback and support during rehabilitation processes. The main contribution of this paper is an overview of the use and perception of cues by users in the need of acquiring new sensori-motor skills and inform the creation of novel assistive tools exploiting digital cues for physical rehabilitation processes.

2. Methods

A systematic review of the literature was conducted in January-February 2019 to assess how multimodal digital and non-digital cues are being designed or evaluated to monitor, train and provide feedback regarding rehabilitation processes with a special focus on gait training and movement, as well as to better guide future developments in the area.

2.1. Search process

The following scientific databases and repositories were searched: Science Direct, ResearchGate, Wiley Online Library - Movement Disorders, Semantic Scholar, Archive of Physical Medicine Rehabilitation. Search used the following key word combination: Crutches [crutches, forearm crutch], Rehabilitation [Walking rehabilitation, Physical rehabilitation, Gait rehabilitation], Gait [Walking, Gait improvement, Gait training], Cues [Cueing, Cue Projection, Visual Cues]. Search was conducted independently by the primary author, and all authors were involved in the analysis and discussion.

2.2. Inclusion and Exclusion criteria

Inclusion criteria consisted of the following: (1) studies that evaluate the effect of cueing in gait; (2) studies that report measurement parameters in gait; (3) studies that focus on the impact of cueing in gait rehabilitation, (4) studies that focus on the impact of visual cues or auditory cues at home environments for gait training; (5) studies about content-adaptive visual and auditory cues; (6) studies that were published in English. All five criteria had to be present in order to be considered eligible for inclusion.

Exclusion criteria consisted of the following: (1) studies of crutches related with weight-bearing only because this was out of scope for this literature review, since our focus on gait training/ rehabilitation processes; (2) studies that are focused on virtual reality technical aspects-only; (3) studies that are not focused on the use of cueing.

2.3. Article selection

The initial titles search resulted in 43000 titles out of which 32499 were identified as duplicates, remaining 10501 records screened articles. The title and abstract for each paper were screened using the inclusion and exclusion criteria to determine applicability to the research objective obtaining first the final list of full-text papers to be reviewed. We excluded 10466 of the search results, as they did not fit the aim of this review. Full-text articles assessed for eligibility were 35 papers. After analyze, to ensure that the studies addressed the impact of cueing in gait training, 7 were excluded resulting in a final number of 28 papers included for the full review. The breakdown of years of publication for the 28 papers is: five papers published in 1996-2000, four papers in 2001-2005, ten papers in 2006-2010, nine papers in 2011-2015. Regarding where the analyzed papers were published, 25 were in a journal, two in a conference and one in a congress.

3. Results

3.1. Participants

In this section, we describe the characteristics of the participants included in the reviewed studies

3.1.1. Age

Most studies do not specify the age span of participants, only their mean age. In twenty-five studies, participants were 60 years old or older [1, 4–10, 13, 14, 16–22, 24–30, 33]. Three studies do not report the age of participants.

3.1.2. Walking skills

Waking skills were assessed before the experiment by means of self-report or evaluation methods. For participants diagnosed with PD, gait parameters were defined according to motor component (Part III) of Unified Parkinson's Disease Rating Scale (UPDRS) [4–6, 8–10, 13–15, 17, 18, 22, 31]. Three studies describe overall UPDRS scale [26, 28, 33], and five others detail the walking condition of participants [20, 25, 27, 29, 30]. The freezing of gait was measured through Freezing of Gait Questionnaire (FOGQ score) [4–6, 13, 15, 17, 22, 25, 30] and UPDRS item 14 (Freezing when walking). More specifically, a score of two refers to occasional freezing when walking, or a score of three refers to frequent freezing when walking, and occasionally falls from freezing [19]. Three studies only report the freezing as an inclusion criteria or exclusion criteria [10, 28, 31].

Finally, some studies do not report how they measure participants' walking skills or impairment, only inclusion criteria [16, 21, 24]. Three studies do not refer to the walking skills of participants [1, 7, 11].

In some studies, inclusion criteria required participants to walk independently [4, 8, 9, 18, 21], to walk without assistive device or assistance [19, 24], ability to stand independently and to walk on a treadmill [26], no gait impairment [16]. In other studies, gait impairment or being user of assistive device was an inclusion criteria. Three studies included only participants with gait impairment [11, 14, 31], one participant with mild to severe gait disturbance [22]. In regards of assistive devices, one study required participants to walk with an assistive device [6], participants walk with assistive device if necessary [27] and participants could walk with or without assistive device [28]. Some studies do not report the inclusion criteria regarding walking skills [1, 5, 7, 10, 13, 17, 20, 25, 29, 30, 33], however participants' walking skills have been reported [7, 10, 13, 20, 25, 29, 30, 33]. Only one study report the exclusion criteria of participants [15].

3.1.3. Cognitive skills

Cognitive skills of participants were assessed before the experiment using different tools or scales. Twelve studies used the Mini Mental State Exam (MMSE) score [4–6, 9, 13, 14, 22, 25, 26, 31, 33], other twelve used the Hoehn Yahr Scale [2, 7, 8, 10, 13, 16, 18, 20, 24, 27–29], one used the Short Test of Mental Status Dementia Score (STMSDS) [21] and one used the Montreal Cognitive Assessment (MoCA) score [17]. Three studies do not report cognitive assessment of participants [11, 19, 30].

Cognitive assessment was used to determine inclusion or exclusion criteria for participants. Inclusion criteria for participants without cognitive impairment were: MMSE scores higher than 23 [5], MMSE> 24 [9], ability to understand and follow simple directions [28]. Exclusion criteria for participants with a potential cognitive impairment were: MMSE scores lower than 24 [4, 15, 22, 26], participants with a mini-mental status exam score of less than 22 [6], participants with PD were also excluded if they were scored <24 out of 38 on the STMSDS [21], score of less than 27 on the MMSE [14] and cognitive impairment [25]. In one study, participants were excluded if had a diagnosis of peripheral neuropathy in lower limbs, and dementia or a score of less than 24 on the MoCA [17]. Eleven studies do not report the inclusion or exclusion criteria regarding participants cognitive skills [1, 7, 8, 10, 11, 16, 18, 19, 24, 27, 30]. Five studies do not report inclusion or exclusion criteria regarding cognitive skills of participants, only report that in their studies the participants were cognitively preserved [13, 20, 29, 31, 33].

3.1.4. Summary of participants characteristics

As the aging population is significantly increasing, gait training is one of the most frequent scenarios of physical rehabilitation. Ageing affect sensorimotor systems regulating static and dynamic balance, thus gait performance. Such as ageing, some movement disorders can also be related to cognitive decline, which in our study, is relevant to how users perceive and interpret cues. For this reason, we were interested in the criteria for including participants with different cognitive skills and walking skills in the reviewed studies. Our review shows most studies included older adults as participants, or people with health conditions resulting on decline of cognitive or mobility skills.

3.2. Experiment protocol and equipment

In this section, we are interested in evaluating the experimental protocol and how gait was assessed in rehabilitation processes using cues.

3.2.1. Settings

The experiment protocol in the reviewed studies used different settings. In 22 studies, participants walk on the ground, or on a walkway [1, 4–11, 15, 16, 19–22, 24, 27–31] and were tested under different conditions: with no cue (baseline) then with cues, or no cue and with cues only. In these settings, visual cues were added or displayed on the floor or walkway, or auditory cues provided for participants while walking on floor or walkway.

In the other six studies the participants walked over a specific equipment: a GAITRite carpet [13, 14, 25] or a treadmill [18, 26, 33]. In the studies where had a GAITRite carpet, the participants were tested under different conditions: in two studies [13, 14] they were tested with then without any cue, in one study [25] participants were tested using cues only. In the condition where were used cues, the cues were added over the carpet. The treadmill was a traditional treadmill [33] motorized medical treadmill Zebris FDM-T Gait analysis system, Zebris Medical GmbH, Isny, Germany) [18] and Rehawalk [26]. In these studies, the participants had to walk on treadmill under different conditions: first as baseline without any cue, then walk on a treadmill with the use of cues.

3.2.2. Walking tasks and instructions for the participants

Participants were instructed to walk at a normal speed in four studies [1, 5, 24, 29] or preferred speed in one study [4] self-selected speed and a comfortable pace in three studies [9, 14, 31], walk fastest speed [28] in one study or take long steps [13].

Task conditions varied from distances like short distances (i.e. equal or up 7 metre) [5, 25, 28, 31] and (i.e equal or up to 9 metre) [8, 21, 27], long distances (i.e up to 10 metre (11- 20) [10, 13, 20] and short period of times, i.e.. to 20 minutes [21], to 30 minutes [27] , number of sets (i.e equal or up to 3 times/3 cycles) [13, 27, 30].

Regarding the cues, participants were instructed to react to non-digital cues, e.g. step over the line [14, 16, 18, 31], step over cues during walks [27], walk over the stripes [5, 28], step over laserlight line [6] or marks such as footprint during treadmill walking [26], change their pace or walking speed to step to the rhythm of a metronome [15, 22, 28], step on the rhythm of the vibration [33] or music [8]. The instructions of walk of take long steps [13] was also given as instructions to react to cue. Some studies took repeated measures to evaluate the use of cues as well as monitor the progress of the gait rehabilitation. In the study about digital laser light cues [6], participants were assessed during three visits, at about a month interval each.

3.2.3. Summary of experiment protocol and equipment

Our review shows that the evaluation of cues for gait training took place mostly in controlled environments, with most participants instructed to walk on self-selected comfortable speed, on the ground, on instrumented carpet or on a treadmill. As mobility aid devices should support users in different settings, further studies should consider how use of cues in different scenarios would affect participants' performances.

3.3. Type of cues

In this section, we present the cues' modalities and the design of context-adaptive cues as described in the reviewed studies.

3.3.1. Cues modalities

Cues chosen in these studies used different modalities of interaction, ranging from using one type of cue, for instance visual cues or auditory cues or somatosensory; to using up to these three types of cues combined.

Thirteen papers were examined using visual cues as a type of cueing. Eight studies focus on non-digital visual cues: Galletly Brauer et al. [9] and Morris et al. [21] used white strips of cardboard, Azulay et al. [1] used parallel transverse high contrasting white lines (5 cm wide) on grey flat surface, Luessi et al. [18] used white horizontal stripes on treadmill, Vitorio et al.[31] used white horizontal lines on black carpet and Sidaway et al. [27] used blue masking tape placed orthogonal to the direction of walking on walkway. The other six studies used digital visual cues: Griffin et al. [10] used virtual cues were delivered through a pair of 'virtual reality glasses', Schlick et al. [26] used a laser device for the visual cues to be projected, the shapes of the subject's footprints were used as individual cues. Donovan et al. [6] used a laser light green line, Lebold et al. [14] and Velik et al. [30] used parallel lines projected and Ferrarin et al. [7] used two types of visual cues: taped step length (SL) markers and two laser lines projected on the floor with an subject-mounted light device (SMLD). Lewis et al. [16] used vertical lines using of a device called optical stimulating glasses (OSGs), which can be worn as standard glasses to appear as visual cues, visual optical stimulating glasses.

Auditory cues accounted for seven out of the 28 reviewed papers. Legder et al. [15] and Rochester et al. [25] used metronome beat, Hayashia et al. [11] used music embedded by rhythmic auditory stimulation (2 Hz), McIntosh et al. [20] and Thauth et al. [29] used rhythmic auditory stimulation (RAS) music, Lebman et al. [13] used verbal instruction and Ford et al. [8] used music.

Three studies combine visual and auditory cues. Chen et al. [4] use transverse green stripes combined with a metronome. Icco et al. [5] used colored stripes on the floor combined with rhythmic sounds to train participants. Suteerawattananon et al. [28] used visual cue and auditory cue, visual cue was bright, yellow-colored strips of tape placed on the floor. For the auditory was a metronome beat (min).

One study using somatosensory cues, combined with visual cues. Wegen et al. [33] used projection visual flow and vibration, applied to gait training or physical rehabilitation in the studies we selected.

Finally, four studies combined three modalities of cues [17, 19, 22, 24]. Lu et al. [17] used yellow and green vertical array of light, warning, vibrotactile. McCandless et al. [19] used a laser line projected, metronome, and a vibration. Nieuwboer et al. [22] used light flashes, beep and pulsed vibrations. Pongmala et al. [24] used transverse line projected, buzzer to generate the sound and the vibration.

3.3.2. Summary of cues modalities and usages

Our review showed that there is an interest in exploring different interaction modalities for the use of cues. The impact of the use of cues was evaluated through different gait parameters, in different study conditions and heterogeneous participants characteristics. Overall, results highlight that external cue (visual and auditory cues) can improve gait by directing attention to the tasks of walking and controlling movement. Further studies should be developed to compare different modalities, in particular taking into account context of use and special needs of participants. Table 1 show the types of cues evaluated according to the characteristics of the participants included in the reviewed studies.

Table 1
Type of cues evaluated according to the characteristics of participants

Authors	Type of participants	Type of cues
Galletly et al. [9]	Walk independently	white stripes cardboard
Morris et al.[21]	Walk independently	white stripes cardboard
Luessi et al. [18]	Walk independently	transverse lines of white cloth tape
Schlick et al. [26]	Walk independently	projection of visual cues, the shapes of the subject's footprints
Lewis et al. [16]	Walk independently	taped step length markers and two laser lines on the floor
Ford et al. [8]	Walk independently	music
Chen et al. [4]	Walk independently	transverse green stripes combined with a metronome
McCandless et al. [19]	Walk independently	laser line projected, metronome, and a vibration
Pongmala et al. [24]	Walk independently	transverse line projected, buzzer, and the vibration
Vitorio et al. [31]	Gait impairment	white horizontal lines
Lebold et al. [14]	Gait impairment	parallel lines projected
Hayashia et al.[11]	Gait impairment	music embedded by rhythmic auditory stimulation (2 Hz)
Nieuwboer et al. [22]	Gait impairment	light flashes, beep and pulsed vibrations
Sidaway et al. [27]	Assistive device	masking tape
Donovan et al. [6]	Assistive device	laserlight green line
Suteerawattananon et al. [28]	Assistive device	bright yellow colored strips and metronome beat
Griffin et al. [10]	No inclusion criteria specified but describe the walking condition of participants	virtual cues were delivered through a pair of virtual reality glasses
Ferrarin et al. [7]	No inclusion criteria specified but describe the walking condition of participants	vertical lines
Velik et al. [30]	No inclusion criteria specified but describe the walking condition of participants	green parallel lines projected
McIntosh et al. [20]	No inclusion criteria specified but describe the walking condition of participants	RAS music
Thaut et al. [29]	No inclusion criteria specified but describe the walking condition of participants	RAS music
Azulay et al. [1]	No inclusion criteria specified	transverse white lines
De Icco et al. [5]	No inclusion criteria specified	colored stripes and beep

Rochester et al. [25]	No inclusion criteria specified	metronome beat
Lebman et al. [13]	No inclusion criteria specified	verbal Instruction
Wegen et al. [33]	No inclusion criteria specified	digital projection visual flow and vibration
Lu et al. [17]	No inclusion criteria specified	yellow and green vertical array of light, warning, vibrotactile
Ledger et al. [15]	Exclusion criteria	metronome beat

3.3.3. Discussion

This preliminary review outlined factors to be considered for the design and evaluation of novel assistive tools exploiting digital cues for physical rehabilitation processes. In regards of our analysis of the existing use of cues, our recommendations for future studies and design are:

- Visual versus Auditory cues:

When comparing different types of cues, designers need to carefully consider attention, focus, context, and environment issues of the rehabilitation system that will be developed. It is necessary to further study how different types of cue could improve different gait parameters. A digital cueing system could adapt the modality – as well as the intensity of the stimuli – according to the patient's profile and rehabilitation stage. Visual cues are predominant in many application domains [32] therefore can be considered distracting for longer walking tasks. A recent advance in design of auditory stimuli is a 3-dimensional reproduction of sound, currently evaluated for advisory information. For instance, a 3D auditory advisory traffic information system (3DAATIS) was evaluated in a drive simulator study with 30 participants [32]. Their findings indicate that overall, drivers' performance and situation awareness improved when using this system. However, the results also point towards the advantages and limitations of the use of advisory 3D-sounds in cars, e.g., attention capture vs. limited auditory resolution. The same limitations may apply to cues in rehabilitation systems, where 3D representations should be further studied.

- First-person Experience: It should be noted by designers that, from a participant's perspective, a first-person experience is often better than just observing therapists or other people performing the training task(s). The design of digitally-enabled cues should take this recommendation into consideration, ensuring the orientation of text and animations are appropriate to be interpreted from the user's perspective.
- Adaptation and Flexibility: Digital cueing systems should adapt to the patient's rehabilitation stage and should also be flexible enough to be successfully used by different types of users in different environments. Any cueing system is not meant to replace the human experience provided by a physical therapist, but instead they complement the training process when the therapist is not present or when the patient feels more inclined to train. Therefore, digital cues should ideally work well in a variety of environments (home, office, outside) and contexts (during spare time, in parallel with social activities, etc.).
- Animations: Digital visual cues for gait training or motor rehabilitation could use animated graphics, however design should be solid, with high contrast and legibility. Animated cues could be particularly useful when the training process is hard to explain or if there is a steep learning curve. Animations supporting patients when learning how to walk with crutches for the first time is a good example of this application [23].
- Gamification and Behaviour Change: There are many advantages for using gamification strategies embedded into digital tools fo rehabilitation processes, and have been evaluated in many contexts (e.g. post-stroke rehabilitation) [12]. Gamification strategies should be employed when intrinsic motivation is particularly low. The use of technologies enabling motion sensing and tracking user's engagement would allow personalisation of the system at different stages of the rehabilitation process, which can be particularly beneficial to improve adherence to the program.

- Combined Modalities: Naturally, modalities can be combined, as the usage of different types of cues will depend on the actual goal and user needs. We believe that users who are becoming proficient with gait training processes, the use of low-tech cues (visual and/or auditory) can actually be effective. There is currently not enough research on somatosensory cues, which should be further explored.

4. Conclusion

We conducted a review of the literature on the usage of cues for gait rehabilitation, which supported multimodal stimuli, in multiple contexts and objectives, providing metrics and instructions to help patients to correct their movements. Our main motivation was to explore how the design of digitally enabled cues can extend the accessibility of care to home settings, dynamically adapting interactive system, so assistive devices could better meet environment and patient requirements.

Throughout our review of literature, it became quite clear that the use of external cueing (visual cues, auditory cues) can improve gait performance by directing attention to the tasks of walking and movement control. However, further studies should be done to understand how different modalities of stimuli could be used to provide cues, addressing user needs and adapting the interaction to include patients with different cognitive and motor skills.

The importance of good design should not be understated when studying or deploying training systems for all kinds of physical rehabilitation processes. The use of digital cues can influence the perception of the patient regarding their way of walking, not just the awareness and feedback regarding training sessions. Advances in motion sensing and wearable interaction create should be further explored for medical devices and assistive technologies used in gait rehabilitation. The use of cueing has been growing within the medical community for training people with all sorts of movement disorders, but there are ample opportunities for exploring digital cues as interactive systems engineering for users with disabilities. An extended and detailed analysis of the existing should highlight the most encouraging results as well as the gaps to be addressed in order to create more effective assistive tools, for personalised care in gait training and rehabilitation.

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