

Effect of On-Demand Cueing on Freezing of Gait in Parkinson's Patients

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Abstract—Gait disturbance, particularly freezing of gait (FOG), is a phenomenon that is common in Parkinson's patients and significantly contributes to a loss of function and independence. Walking performance and number of freezing episodes have been known to respond favorably to sensory cues of different modalities. However, a topic that has so far barely been touched is how to resolve freezing episodes via sensory cues once they have appeared. In this study, we analyze the effect of five different sensory cues on the duration of freezing episodes: (1) vibratory alert, (2) auditory alert, (3) vibratory rhythm, (4) auditory rhythm, (5) visual cue in form of parallel lines projected to the floor. The motivation for this study is to investigate the possibility of the design of a gait assistive device for Parkinson's patients. Test subjects were 7 Parkinson's patients regularly suffering from FOG. The patients had to repeatedly walk a pre-defined course and cues were triggered always 2 s after freezing onset. The effect was analyzed via experimental measurements and patient interviews. The measurements showed that all 5 sensory cues led to a decrease of the average duration of freezing: baseline (7.9s), vibratory alert (7.1s), auditory alert (6.7s), auditory rhythm (6.4s), vibratory rhythm (6.3s), and visual cue (5.3s). Nevertheless, interestingly, patients subjectively evaluated the audio alert and vibratory signals to have a significantly better effect for reducing their freezing duration than the visual cue.

Keywords—Auditory cueing, freezing of gait, gait assistance, Parkinson's disease, vibratory cueing, visual cueing.

I. INTRODUCTION

PARKINSON'S disease (PD) is a slowly progressing degenerative disorder of the central nervous system severely impairing the patient's motor skills. Amongst the typical symptoms of PD are gait disturbances and freezing of gait (FOG). FOG manifests itself as leg trembling in place, moving forward with very small steps, or total akinesia. Gait impairment and FOG seriously affect the quality of life of patients as it can lead to an unpredictable loss of control over movement and can result into falls. An interesting method to improve gait parameters and reduce or avoid FOG in PD patients is sensory cueing. A brief review of work so far performed in this field is given in the following:

The first group of studies has been concerned with investigating the effect of sensory cues on stride length, walking speed, and cadence. The effect of visual cues in form of bright stripes placed on the floor orthogonal to the walking direction was investigated in [1]-[5] with the general result of an improvement of stride length and walking speed. Rhythmic

auditory cues in the form of metronome beats, music, or a mix of metronome beats and music have been used in several studies [6]-[10]. The general outcome of these studies was that rhythmic auditory cues improved stride length, speed, and cadence. In the study of van Wegen et al. [11], it was shown that vibrations delivered at the wrist of users at a frequency 10% below the preferred stride frequency resulted in lower stride frequencies and larger stride lengths while walking on a treadmill.

The effect of sensory cueing on the number of freezing of gate episodes during normal walking has been tested in several studies. Dietz et al. [12] demonstrated that walking over parallel lines on the floor can reduce the number of FOG-episodes. However, a modified inverted stick was not effective in the same patients. Kompolti et al. [13] reported that a laser beam and a modified inverted walking stick did not have any effect on ON-FOG episodes. Arias et al. [9] outlined that rhythmic auditory stimulation (10% above the preferred walking cadence) led to a significant reduction of FOG. In contrast, Cubo et al. [14] showed that auditory cueing with a metronome had no effects on ON-FOG, even after patients took the device home to practice for 1 week.

Concerning cueing at gait initiation, the following observations have been made: Burleigh-Jacobs et al. [15] found that a single somatosensory cue was as effective as levodopa in order to improve the movement outcome and timing of gait initiation. Dibble et al. [16] reported a negative effect of rhythmic somatosensory and auditory cues on sacral displacement and step length at gait initiation. The adverse effects were explained by the unpredictable cueing intervals which impaired synchronization and thus negatively affected gait initiation. Jiang et al. [17] reported that for rhythmic auditory cues, no impact on gait initiation could be observed. Nevertheless, visual cues in the form of lines on the floor significantly improved movement amplitudes at gait onset but did not improve the timing/speed of gait initiation in patients suffering from freezing.

Apart from this, the effect of cueing on turns has been studied. Arias et al. [9] showed that rhythmic cues helped to speed up turns in Parkinson patients. The same outcome was found by the study of Nieuwboer et al. [18], where however patients experiencing freezing were excluded from the analysis. Willems et al. [19] found that rhythmic auditory cues helped to significantly reduce gait-timing variability during 180°-turns around an obstacle. In earlier work, they had shown that increased gait-timing variability is associated with an increased risk of falling and freezing. Hence they

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considered reduced gait-timing variability as a beneficial effect.

In summary, the focus of existing studies has so far generally been put on the investigation of the effect of sensory cues on different walking parameters like stride length, cadence, and walking speed during normal walking and the influence of sensory cues on gait initiation and turning. Experiments were usually carried out with PD patients not suffering from FOG. Only few studies consider freezing of gait and the only parameter investigated so far was the number of freezing episodes in different cueing conditions. The cueing used in these studies was continuous cueing, meaning that the cue was provided no matter if the patient currently showed walking impairments and FOG or not. What has so far hardly been investigated is the effect of cues when not cueing continuously but just “on-demand” when a FOG episode has actually occurred. In two former publications [20], [21] related to this study, we have verified the hypothesis that the presentation of sensory cues during freezing can help to overcome freezing episodes. There were investigated the effects of visual, auditory, and vibro-tactile cues on the duration and number of FOG by means of objective measurements. This allowed determining the most suitable cue for avoiding freezing of gait or recovering normal gait after freezing episodes occurred. A secondary motivation was to evaluate these sensory cues with respect to the development of an assistive device for PD patients suffering from FOG to be used in daily life. For such an assistive device, however, not only the objective measurement of FOG duration is relevant but also the patients’ subjective perception of the effectiveness of those cues. Accordingly, this article compares the objective measurements reported in our former publication [20] with subjective patient evaluations of the effect of sensory cues obtained via patient questionnaire.

II. METHODS

A. Patients

In order to test the effect of perceptual cues on freezing episodes in Parkinson’s patients, the gait of 7 subjects (see Table I) regularly suffering from FOG was investigated. Similar like in [20], [21], the inclusion criteria for the patients were:

1. Diagnosis of idiopathic Parkinson's disease

2. Gait disturbance with score > 1 on the Unified Parkinson’s Disease Rating Scale (UPDRS; item 29)
3. Hoehn and Yahr stage II – IV
4. Experiencing severe freezing either in the off phase or the on phase of medication
5. Able to walk for extended duration

The exclusion criteria were:

1. Participation in a physiotherapy program up to 2 months before starting the trial
2. Unusual impairments of perceptual capabilities (vision, audition, tactile sense)
3. Previous pallidotomy
4. Deep brain stimulation (DBS) surgery or other striatal or extrapyramidal brain surgery
5. Comorbidities affecting gait

The average age of the patients was 75 years and their average FOG score according to Giladi et al. [22] was 13.4. Ethical approval for the performed study was received from the CEIC-E (Comité Ético de Investigación Clínica de Euskadi).

B. Experiment Protocol

Experiments always took place in the morning and were performed over a whole medication cycle, i.e. took approximately 4-5 hours. Patients arrived on medication at the observation laboratory. After arrival, they were informed about the details of the experiment and signed an informed consent sheet. Next, necessary sensor measurement and cueing equipment was attached to the patient (see Section II E). The experiment was organized in blocks. In each block, patients had to repeatedly perform the same walking task (see Section II C) six times in six different cueing conditions (see Section II D). The blocks were repeated over the whole medication cycle with breaks between them in which the patients were offered refreshments. Within the limits of the physiological condition of the patients, durations of breaks were scheduled such that the largest proportion of testing was made when freezing episodes were most probable to be observed, i.e. at the end of the medication cycle for OFF-freezers and at the beginning of the medication cycle for ON-freezers. After the last block, patient interviews were performed to obtain their subjective impression of the effect of the different cues.

TABLE I
SUMMARY OF PATIENT CHARACTERISTICS

Patient ID	Gender	Age	Walk Aid	Falls	Type of FOG	FOG Score
P1	M	80	-	1-2/month	ON/OFF	12
P2	F	69	Cane	-	ON	11
P3	M	74	-	0.5/month	OFF	13
P4	M	83	-	-	OFF	14
P5	M	74	-	1-2/month	OFF	13
P6	M	75	Wheelchair/Walker	-	ON/OFF	19
P7	M	72	Cane	1/month	ON/OFF	12

TABLE II
DESCRIPTION OF USED SENSORY CUES

Name	Description
(1) Baseline	Without cue
(2) Vibratory Alert	The cue consists of three vibration pulses (0.5s vibration, 1s break, 0.5s vibration, 1s, break, 1s duration). The vibrations are delivered through a vibrotactor at the right calf of the participant
(3) Audio Alert	The cue consists of three beeps of 0.5s duration with breaks of 0.5s in between. The sound level of the last beep is twice as high as the sound level of the first two beeps.
(4) Vibratory Rhythm	The cue consists of 10 vibration pulses indicating the preferred walking rhythm of the patient. The rhythm alternates on the left and on the right leg. The vibrotactors are attached to both calves below the knee.
(5) Auditory Rhythm	The cue consists of an acoustic beep signal indicating the preferred walking rhythm of the patient. After 7 pulses, the volume of the beats fades to zero and disappears completely after the 10th pulse.
(6) Visual	The cue consists of two green parallel lines projected on the floor for always 10s; line length: 1.5 m, interline distance: 40 cm, lines start at distance of 30 cm in front of patient and are orthogonal to walking direction

C. Walking Task

The objective of the experiment was to quantify how sensory cues affect the duration of FOG episodes. For this purpose, participants were asked to repeatedly walk a predefined course in an observation laboratory having the floor plan of a normal flat (see Fig. 1) under different cueing conditions. The course consisted of the following tasks:

1. Standing up from a chair and getting a glass of water from the kitchen
2. Going with the glass to the bathroom and leaving the glass on the washbasin
3. Walking to the bedroom and picking up a clothes hanger from the cupboard
4. Carrying the clothes hanger to the washing room and leaving it there
5. Going back to the chair
6. Performing tasks 1-5 in reverse order starting with task 5

To avoid falls, an assistant closely followed the patients in order to intervene in case of loss of balance.

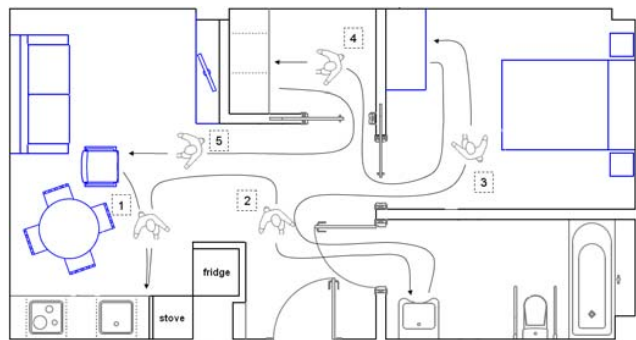


Fig. 1 Course and tasks performed by the participants

D. Cueing Conditions

During the walking task, the following cueing conditions were tested: (1) baseline, (2) vibratory alert, (3) auditory alert, (4) vibratory rhythm, (5) auditory rhythm, and (6) visual cue in form of parallel lines projected to the floor (for details see Table II). The succession of the conditions was altered in every block to avoid carry over effects. Always before starting the walking task, the selected cue was played back one time and specific instructions were given to the patients. For the baseline, the patients were asked to walk normally. For the

vibratory and auditory alert, the patients were instructed to try to start walking as soon as they perceive the beginning of the alert. In case of the vibratory and auditory rhythm, they should concentrate on the given walking rhythm and start walking according to this rhythm as quickly as possible. When perceiving the visual cue, patients should try to step between the first and second line projected on the floor. An assistant experienced in the recognition of FOG episodes was instructed to observe the participant performing the course and to trigger a cue always 2s after a FOG episode occurred.

E. Equipment

To avoid cueing, patients wore a backpack with a small and lightweight laptop computer while performing the walking tasks. The laptop was remote controlled from another computer via WIFI and served the purposes of triggering and controlling cues. For cueing, three different devices were used. For the vibratory cues, two C2 vibrotactors, produced by Engineering Acoustics Inc., were used. The vibrotactors were attached to the calves of the patient below the knees with Velcro straps. For the auditory modality, lightweight headphones were used. For the visual modality, a laser device was used. The device consisted of a small and lightweight support frame attached to the chest of the patient on which two green lasers with specific lenses were mounted that projected two parallel lines on the floor in front of the participant. For later analysis, patients were videotaped during their walking task. The video data were synchronized with time stamps of the triggered cues.

F. Data Analysis

The evaluation of the effect of the different sensory cues on FOG was based on both measurements and patient interviews.

For quantitative analysis, the mean duration of the freezing episodes under the different cueing conditions was determined. For this purpose, the video data were analyzed and the duration of each freezing episode was noted down with a resolution in the range of 1 s. A freezing episode was defined following the work of Kompoliti et al. [23] as "stop and/or hesitation until the next step was accomplished independently of the number of hesitations in place". For further analysis in the five cueing conditions, all FOG episodes were taken into account for which a cue was triggered, i.e. that were longer than 2s. Accordingly, for the

baseline, all freezing episodes were processed further that had a duration of equal or greater 2 s. From these data, the mean and standard deviation of the duration of freezing episodes

were calculated for each patient in each cueing condition (see Table III).

TABLE III

MEAN AND STANDARD DEVIATION OF DURATION OF FREEZING EPISODES IN SECONDS OF PATIENTS IN DIFFERENT CUEING CONDITIONS (ORIGINALLY REPORTED IN [20])

Patient	Baseline	Auditory Alert	Vibratory Alert	Auditory Rhythm	Vibratory Rhythm	Visual
Duration P1	4.3 ± 2.9	6.4 ± 4.1	10.0 ± 4.8	6.8 ± 3.7	8.0 ± 4.8	5.3 ± 2.6
Duration P2	3.9 ± 1.5	3.8 ± 0.8	4.7 ± 1.9	4.4 ± 1.7	4.8 ± 2.5	3.6 ± 1.6
Duration P3	3.7 ± 2.3	4.6 ± 2.1	5.4 ± 2.8	3.3 ± 1.2	5.1 ± 2.0	4.4 ± 2.1
Duration P5	18.1 ± 17.0	13.2 ± 11.5	13.2 ± 11.5	13.0 ± 12.7	14.2 ± 10.1	7.3 ± 6.3
Duration P6	3.6 ± 1.1	3.0 ± 0.5	3.3 ± 0.8	3.3 ± 0.8	3.3 ± 0.8	3.3 ± 0.8
Duration P7	13.6 ± 14.1	9.0 ± 6.8	5.7 ± 0.6	7.7 ± 5.6	2.5 ± 0.7	7.7 ± 5.6
Duration Avg.	7.9 ± 6.4	6.7 ± 3.9	7.1 ± 3.8	6.4 ± 3.7	6.3 ± 4.3	5.3 ± 1.9

In the patient interview, patients had to evaluate how effective they experienced the 5 different perceptual cues to reduce the duration of their freezing episodes with respect to the baseline condition. For this purpose they gave each cue points on an evaluation scale ranging from -5 to +5 (see Table IV). Negative values signified deterioration, i.e. a prolongation of the FOG durations. Positive values meant an improvement, i.e. a reduction of the FOG duration. 0 represented the case that they experienced no effect, ±2.5 meant moderate, and ±5 significant deterioration / improvement. As reference, patients were told that a value of +5 equals an almost immediate resolving of FOG after stimulus onset and a value of -5 a doubling of the FOG duration.

In order to set the quantitative measurements in graphical relation with the point scores of the patient questionnaire (see Fig. 2), a mapping scale was defined using the following formula:

$$FreezingDurationMapping_{Cue_i} = \frac{Duration_{Baseline} - Duration_{Cue_i}}{Duration_{Baseline}} \cdot PointScore_{Max}$$

where $Duration_{Baseline}$ is the duration of FOG in baseline condition averaged over all patients, $Duration_{Cue_i}$ is the duration of FOG in cueing condition i averaged over all patients, and $PointScore_{Max}$ is the maximum scale value of patient evaluation scale (equal 5).

According to this formula, an average duration of freezing in a certain cueing condition equaling the average freezing duration in the baseline condition results in a value of 0 (no effect). An immediate resolving of the freezing episode after cue onset results in a value of +5 and a doubling of the length of freezing in the cued condition leads to a value of -5.

III. RESULTS

Out of the 7 patients, 6 were able to complete the walking task in all cueing conditions defined for a block. One patient (P4) showed over the whole walking circuit severe freezing manifested as continuous severe shuffling with very small steps or complete immobility and needed to sit down various

times while performing the circuit. For this reason, he was excluded from the further data analysis.

Depending on their overall physical condition, patients performed 3 to 7 blocks with breaks of 10 to 45 minutes between the blocks. In sum, 239 freezing episodes were analyzed. The minimum number of freezing episodes per walking circuit was 0, the maximum number 9, and the mean number 4, independent of the cueing condition. The number of occurring freezing events depended on the patient and the phase in medication cycle. The time from the occurrence of a freezing event to the triggering of a cue was in average 2 s with a standard deviation of 0.1 s.

In Table III, the average duration *mean* and the standard deviation *std* of the freezing episodes of the different patients in the different cueing conditions is given. In the last line of the table, these values are averages over all patients.

In case a patient's physical condition and performance deteriorated drastically during the experiment due to a reduction of the effectiveness of medication (P6, P7), the number of tested cues per cycle was reduced.

Table IV summarizes the point scores given by the patients to the different cues as well as the averaged value over all patients expect patient 4, who had to be excluded from the objective measurements for the reasons explained above and whose scores in the questionnaire were therefore also not considered.

Fig. 2 graphically puts into relation the patient evaluations to the quantitative measurement for the different cueing conditions according to the equation given in Section II F.

TABLE IV
POINT SCORE GIVEN BY PATIENTS TO THE DIFFERENT CUES CONCERNING THEIR EFFECTIVENESS TO REDUCE FOG DURATION.
SCALE RANGE (-5 TO 5)

Patient	Auditory Alert	Vibratory Alert	Auditory Rhythm	Vibratory Rhythm	Visual
Score P1	-2	0	-3	0	-1
Score P2	3	4	2	3	0
Score P3	0	2	0	2	0
Score P5	0	0	0	0	0
Score P6	0	0	0	0	0
Score P7	3	4	3	4	4
Score Avg.	0,7	1,7	0,3	1,5	0,5

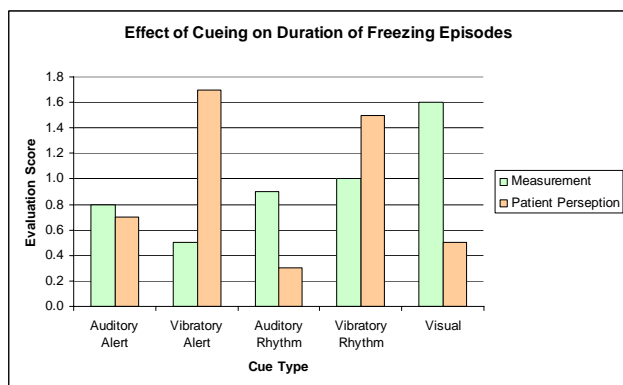


Fig. 2 Comparison of patient evaluation of sensory cues with results from measurement concerning the duration of FOG

IV. DISCUSSION AND CONCLUSION

As can be seen from Tables III and IV, both the experimental measurements and the patient evaluation showed a reduced mean duration of freezing in all cued conditions in average in comparison to the baseline. An interesting result is how these measurements stand in relation with the patients' subjective perception what cue helps them best, which is illustrated in Fig. 2. In the patient questionnaires, the highest points were given to the audio alert followed by the audio rhythm and the vibratory alert. The vibratory rhythm and the visual cues were evaluated as helping least in the process of overcoming FOG. Looking at Fig. 2, a clear discrepancy can be seen between patient perception and objective measurement, particularly in the visual cueing condition but also for the auditory alert. While the visual cue was significantly undervalued in its effect by patients, the contrary effect could be observed for the auditory alert.

In the following this outcome shall be analyzed a bit more in detail for the different patients. Patient P1 evaluated both the vibratory and the visual cue as having a negative effect on his freezing episodes, which was in accordance to the measurements. Two of the patients (P5 and P6) reported no effect of the sensory cues on their FOG duration although measurement results indicated for P5 a significant and for P6 a moderate improvement in all cases. Two of the patients (P2, P7) reported a significant improvement of FOG duration due to the auditory alert and the auditory rhythm with the explanation that this "alarm signal" helped them to refocus on

the walking task. For patient P7, this was in accordance with the measurement results. For patient P2, a discrepancy could be observed. The patients P2, P3, and P7 reported a positive effect of the vibratory cues on their FOG for the same reasons, which could however only be actually observed in patient P7. Interestingly, only patient P7 reported an improvement through visual cueing although a significant decrease of FOG duration could also be observed in P2, P5, and P6. Patient P2 explained that the lines on the floor distracted her attention from her planned walking path. The other two patients simply did not perceive any influence of the visual cue on their gait.

Looking at the difference of subjective patient perception and objective measurements about the helpfulness of sensory cues in order to overcome FOG episodes, this raises the question what measure actually to use for evaluation purposes, particularly when aiming at developing an assistive device. When trying to convince a patient to use such a device, an objective improvement of gait fluency alone is not sufficient when the patient is not aware of this enhancement. Nevertheless, patient perception might be subject to change over longer periods of use and open to influence via convincing scientific studies proving the effectiveness of such a cueing device.

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