



Full length article

Cognitive load of walking in people who are blind: Subjective and objective measures for assessment

Caroline Pigeon^{a,*}, Tong Li^b, Fabien Moreau^a, Gilbert Pradel^{b,c}, Claude Marin-Lamellet^a

^a Univ Lyon, IFSSTAR, TS2, LESCOT, F-69675, 25 Avenue François Mitterrand, 69500, Bron, France

^b U1179End:icap UVSQ INSERM CHU Raymond Poincaré APHP, 104 Boulevard Raymond Poincaré, 92380, Garches, France

^c ENS Cachan, 61 Avenue du Président Wilson, 94230, France

ARTICLE INFO

Keywords:

visual impairment
mental effort
gait analysis
simple reaction time task
subjective assessment

ABSTRACT

Background: Although walking without vision seems to carry a high cognitive cost, few studies have measured the cognitive load involved in this activity in blind people. The aim of this study was to assess the cognitive load of walking in blind people, using gait analysis, a dual task paradigm and a subjective assessment of cognitive load.

Methods: In a quantitative quasi-experimental design, 25 blind adults walked 40 meters. In one trial, participants walked normally (control condition). In another, they walked while performing an auditory simple reaction time task, and in the third trial they walked, performed the simple reaction time task and avoided obstacles. In addition to the simple reaction time task performance, walking speed was recorded, and participants provided a subjective assessment of cognitive load after each trial. Performance of participants aged less than 60 years were compared with those aged over than 60 years.

Results: Walking significantly reduced performance of the simple reaction time task; carrying out the simple reaction time task while walking significantly reduced walking performance and increased the subjective assessment of cognitive load; and simple reaction time task performance decreased and subjective assessment increased when obstacles were present. Few significant age effects were found.

Significance: Walking without vision involves a cognitive load that increases when the environment becomes complex. Each of the three methods used is relevant when assessing the cognitive load involved in walking in blind people, and could be useful in rehabilitation intervention. The results obtained allowed recommendations to be suggested for the design of technological mobility devices.

1. Introduction

A journey on foot is more difficult to accomplish in the absence of vision: spatial information perceived through non-visual modalities is less available, less reliable and less precise [1]. In addition, the sequential processing of non-visual information [2] and the lack of perceptual anticipation [3] involve a moment-to-moment monitoring of movement, which requires cognitive processing for walking without vision, while only perceptual strategies are necessary when walking is performed by sighted people [1]. Hence, while walking relies mainly on unconscious and automatic processes when carried out by sighted individuals, it involves a considerable cognitive load when carried out in the absence of vision [1]. Furthermore, several external factors (the

presence of obstacles and route complexity for example) seem to impact the cognitive cost of walking without vision. Since cognitive overload during walking without vision causes misestimation of distances travelled [4], and therefore, can result in accidents or in the person getting lost, assessing the cognitive load of blind pedestrians is particularly relevant. Several methods can be used to assess this cognitive load, for instance measuring variations in gait parameters, such as step speed [5,7], a dual task paradigm [4,8–13], or through a subjective assessment (for example, the NASA Task Load Index: NASA-TLX [14], developed for the aeronautical field, which has been used once with visually impaired participants [15]).

However, most of the studies carried out using these methods involved sighted participants (with a simulated visual impairment

* Corresponding author

E-mail address: Caroline.Pigeon@USherbrooke.ca (C. Pigeon).

¹ Currently postdoctoral fellowship researcher (financed by the Quebec Rehabilitation Research Network, the Quebec Network for Research on Aging and the *Fonds de Recherche du Québec en Santé*) in Research Centre on Aging, Eastern Townships Integrated University Centre for Health & Social Services—Sherbrooke Hospital University Centre (CIUSSS de l'Estrie – CHUS), Université de Sherbrooke, Sherbrooke, Quebec, Canada.

[8–9,16]), partially sighted participants [10,11], and blind participants who were not distinguished from partially sighted ones [5,17], [12,15] or from blindfolded, sighted ones [13]. Nevertheless, simulating a visual impairment is different from having a visual impairment (for example, different experiences when using non-visual information, learning to use mobility aids), and partially sighted people can rely on vision as the primary modality for accessing information, which introduces a different spatial behavior from that of completely blind people [1]. Moreover, the few studies carried out with only completely blind participants involved a small number of participants, and/or were conducted over a short distance [6,18,19]. In addition, in our knowledge, few of them took into account the age effects on participant's performance and none of them reported information about participant's mobility habits.

The main objective of the present study was to assess the cognitive load of walking in blind people using gait analysis, a dual task paradigm and subjective assessment. The hypotheses were that 1) walking performance would be decreased and subjective assessment would be increased by the simultaneous performance of a simple reaction time task, 2) simple reaction time task performance would be decreased and subjective assessment would be increased by walking, and 3) walking performance and simple reaction time task performance would be decreased and subjective assessment would be increased when obstacles were present. A secondary objective was to investigate the age effects on participant's performance, with the hypothesis that performance of participants aged less than 60 would be higher than the performance of participants aged over 60 years.

2. Methods

2.1. Study design and participants

This study was conducted using a quantitative quasi-experimental design. Twenty-five participants aged from 18 to 81 years old (M = 51.6, SD = 14.9; Table 1) were recruited through advertising in associations, and word of mouth. None of the participants had any residual eyesight (or only bright light perception), and they stated they

went outside their homes independently with a white cane 2 to 7 times per week on average (M = 6.2, SD = 1.6). They stated they had used their white canes for between 3 and 50 years (M = 22.9, SD = 12.7). Most of them (21/25) had had at least one Orientation and Mobility (O & M) training session, the last of which took place between 1 and 44 years before the experiment (M = 20.2, SD = 13.7).

Sixteen participants were aged less than 60 years (M = 43.1, SD = 10.8). Among them, eight participants were early blind and five were females. They were blind for 25.9 years (SD = 16.9). Nine participants were aged over 60 years (M = 66.9, SD = 6.2); all of them were late blind and three were females. They were blind for 38.4 years (SD = 17.1).

The study was approved by the IFSTTAR ethical committee and organized in accordance with the Declaration of Helsinki. Participants signed a consent form read by the experimenter or used a braille version of this form.

2.2. Material

The experiment took place in a hangar about 90 m by 13 m in size, and lasted approximately 60 minutes (min). For the dual task with obstacles condition, five obstacles of different shapes and sizes, made from weighted cardboard boxes, were placed along the path.

2.2.1. Video recording

The walking trial sessions were filmed with a video camera (GoPro Hero3+), which participants wore on a chest harness, and a JVC Pro HD camera placed 15 m from the end of the path at a height of 6.5 m (Fig. 1). Videoing the experiment permitted the recording of how participants negotiated obstacles, coded *a posteriori*.

2.2.2. Gait parameter recording

During the walking sessions, participants' gait parameters were recorded by the HemiGait system [20]. The system consists of 2 wireless Inertial Measurement Units (IMU), a pair of wireless rangefinders based on Ultra-WideBand technology (UWB) and a control unit. 2 IMUs attached to the insteps measure accelerations and angular velocities for

Table 1
Socio-demographic characteristics and information concerning the blindness of participants.

Age (year)	Sex	Manual laterality	Education duration (years)	Age of acquisition of blindness (years)	Partially-sighted before being blind (late blind people)	Bright light perception	Duration of cane use (years)
49	M	R	14	37	no	yes	11
63	M	R	17	10	yes	no	50
19	M	A	15	0	-	no	9
39	F	R	17	16	yes	yes	12
35	F	R	15	0	-	no	25
58	M	R	15	50	yes	yes	27
64	M	R	8	45	yes	yes	20
43	M	R	17	33	yes	yes	10
43	M	R	15	3	-	no	33
44	F	R	17	14	yes	no	30
25	M	R	15	13	yes	no	15
47	M	A	11	0	-	yes	34
68	F	R	15	38	no	no	30
44	F	R	7	0	-	no	32
72	F	R	9	28	yes	no	44
55	M	R	17	53	yes	yes	5
81	M	R	12	61	yes	yes	20
65	F	R	7	32	no	no	33
62	M	A	17	42	yes	yes	30
50	M	A	17	0	-	no	12
33	M	R	9	1	-	no	14
50	M	L	14	2	-	yes	35
65	M	R	12	60	yes	yes	7
55	F	R	17	52	yes	yes	3
62	M	R	14	30	no	no	31

M: male; F: female; R: right-handed, A: ambidextrous, L: left-handed.

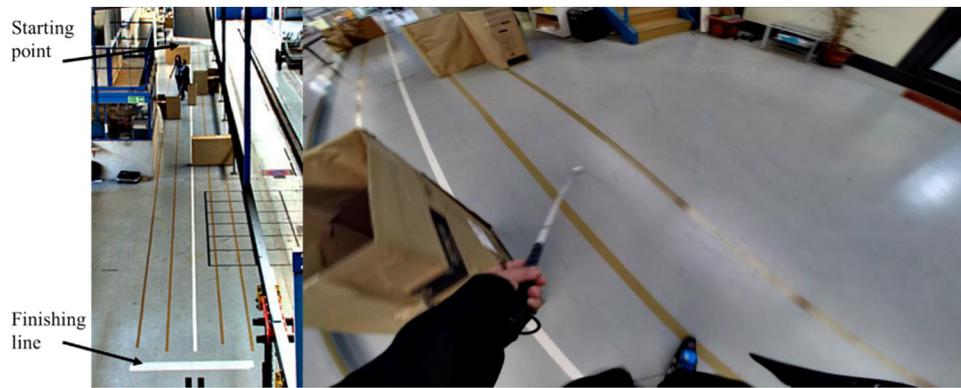


Fig. 1. Points of view of the two cameras during a dual task with obstacles (left side: bird view; right side: participant view).



Fig. 2. HemiGait device worn by a participant.

each foot, and 2 UWB rangefinders fixed to the inside of the heel capture the relative foot distance (Fig. 2). The control unit synchronizes the wireless network of sensors, and records data on a Secure Digital card at a sampling frequency of 110 Hz. A data fusion algorithm was developed in MATLAB to estimate off-line gait parameters using acceleration, angular velocity and relative foot distance provided by the IMUs.

2.2.3. Simple reaction time task

The simple reaction time task was programmed using OpenSesame software (version 0.27.4; [21]). The presentation of stimuli and the recording of responses were performed on a Samsung Galaxy Tab 2 7.0 GT-P3110 tablet computer with the OpenSesame runtime for Android (version 2.9.7). The tablet computer was held by the experimenter and connected to a high-frequency transmitter. A high-frequency receiver connected to an earphone was worn by participants, and another was connected to the JVC camera. A wireless ring mouse placed on the index finger of the non-dominant hand of participants was used to record their responses.

In this task, the number “1” stimulus was auditory and presented several times with random inter-stimuli intervals of 2500, 3000 or 3500 milliseconds (ms). The participants had to press the wireless ring mouse as quickly as possible with their thumb each time they heard the stimulus. The stimuli were delivered until participants had finished walking on the path under the dual task conditions and for 90 s under the simple reaction time task only condition (SRTA).

2.2.4. Subjective assessment of cognitive load

A subjective assessment of cognitive load was carried out using a version of the NASA-TLX that was better suited to this study. The NASA-TLX has already been adapted for other fields (for example the Driving Activity Load Index; DALI [22]). Like the NASA-TLX, the modified version is composed of several dimensions. The *mental demand* of the original version, which described perceptual and mental activities as

“thinking, deciding, calculating, remembering, looking, searching”, has been broken down into *auditory demand*, *tactual demand* and *attentional demand*. The *physical demand*, *performance*, and *temporal demand* dimensions of the NASA-TLX have been retained. Finally, the *frustration* dimension, which groups together the notions of insecurity, discouragement, irritation, stress and annoyance, has been replaced by the *stress level* dimension, which is more specific (for each dimension, the question participants are asked is presented in a supplementary material file). The weighting process was removed, since the NASA-TLX version without this process (the Raw-TLX) is as sensitive as the NASA-TLX [23].

2.3. Procedure

After a practice trial, participants performed three walking trials in counterbalanced order: simple walking task condition (SWT), dual task condition (DT) and dual task with obstacles condition (DTO). All walking conditions consisted of walking at a self-selected speed on a linear path of 40 m with the white cane in the dominant hand. A sound, the one used for pedestrian crossing traffic signals in France, was broadcast from the end of the path to allow participants to walk in a straight line. Participants were informed of the end of the path by a tactile warning strip placed 3 m in front of the loudspeaker that broadcast the sound.

Prior to all walking conditions except the practice trial, participants were informed that obstacles might be present on the path, even when there were no obstacles. They were asked to walk at their usual speed and avoid bumping into obstacles.

Participants performed the SRTA by standing on the spot, in the middle of the path and with the sound being broadcast. The task was performed twice, once before the walking conditions (after a training session and sound level adjustment), and once afterwards.

For the DT and the DTO, participants were given no instructions regarding prioritization between the walking task and the simple reaction time task. However, at the end of the experiment, the participants had to estimate the percentage of priority they gave to walking when the two tasks were performed simultaneously.

2.4. Data analyses

For trial duration and response times, performance that were more than 2.5 standard deviations (SD) from the means of all participants were replaced by the value corresponding to the mean plus 2.5 SD.

All statistical analyses were conducted using SPSS Statistics 24. The data from each dependent variable (Table 2) were statistically analyzed with one-way analyses of variance (ANOVAs) to compare the performance of the participants under the different conditions. When the sphericity hypothesis was not verified (Mauchly test), Pillai's trace correction was used. Based on significant *F* values, the Bonferroni test

Table 2
Outcome variables.

Variables	Concerned conditions
Walking performances	
Trial duration	SWT, DT, DTO
Step speed	
Simple reaction time task performances	
Percentage of correct responses	SRTA ¹ , DT, DTO
Response times	
Subjective assessment of cognitive load	
Scores of each dimension ²	SWT, SRTA, DT, DTO
Total score of the scale ³	

¹ average of correct responses and response times obtained in the two trials; ² data presented in a supplementary file; ³ mean of the dimensions; SWT: simple walking task condition, DT: dual task condition, DTO: dual task with obstacles condition, SRTA: simple reaction time alone condition.

was used for the post hoc analyses.

For the DTO, the synchronization of videos, walking parameter recordings, and data from the simple reaction time task allowed for comparison of step speed and responses in the simple reaction time task to stimuli presented when an obstacle was negotiated (obstacle situation: the moment a participant came into physical contact with an obstacle to when the obstacle was passed) and the remaining time (between obstacles situation). In addition, the performance of participants in the first trial and in the third trial (regardless of the conditions considered) were compared. For these comparisons, Student's *t*-tests were used when data normality was met, and non-parametric Wilcoxon tests were used if not. For each dependent variable, performance of participants aged less than 60 was compared to those of participants aged over 60 years with non-parametric Mann-Whitney U tests.

Differences at a level of 0.05 were considered significant. Effect sizes, Cohen's *d_z* for Student's *t*-tests and partial eta squared (η_p^2) for ANOVAs were calculated [24]. Due to occasional dysfunctions of the devices used, some data could not be recorded (in these cases, the number of participants analyzed is specified in the tables).

3. Results

3.1. Walking performance

An ANOVA on **trial duration** revealed a significant effect of condition ($F(2,44) = 22.254, p < .001, \eta_p^2 = .61$; Table 3). Post-hoc analyses showed that trial duration did not differ significantly between

Table 3
Performances according to condition.

	Means (SD, 95% CI)				F values	p values
	SWT	SRTA	DT	DTO		
Walking performance						
Trial duration (s) ¹	43.7 (10.5, [39.1; 48.2])		45.9 (13.7, [40.0; 51.8])	54.8 (16.0, [47.9; 61.8])	22.254	.000
Step speed ² (m/s)	0.89 (0.20, [0.8; 1.0])		0.88 (0.22, [0.8; 1.0])	0.79 (0.19, [0.7; 0.9])	16.715	.000
Simple reaction time task performance						
Correct responses (%)		98.9 (2.3, [98.0; 99.9])	96.8 (6.6, [94.1; 99.5])	94.7 (7.5, [91.6; 97.8])	5.132	.010
Response times (ms)		443.4 (67.9, [415.4; 471.5])	603.7 (155.1, [539.7; 667.7])	674.6 (163.4, [607.2; 742.1])	42.999	.000
Subjective assessments of the cognitive load						
Total score	1.2 (0.9, [0.8; 1.5])	1.2 (0.9, [0.8; 1.6])	1.5 (0.9, [1.1; 1.9])	1.9 (1.0, [1.5; 2.3])	19.990	.000
Auditory demand	1.0 (1.2, [0.5; 1.5])	1.1 (1.1, [0.6; 1.5])	1.6 (1.3, [1.0; 2.1])	1.6 (1.3, [1.1; 2.1])	5.585	.002
Tactical demand	1.0 (1.1, [0.6; 1.5])	0.78 (0.9, [0.4; 1.2])	1.2 (1.1, [0.7; 1.6])	1.8 (1.3, [1.3; 2.4])	6.185	.003
Physical demand	1.0 (1.1, [0.5; 1.5])	0.76 (1.0, [0.4; 1.2])	1.0 (1.1, [0.6; 1.4])	1.3 (1.3, [0.8; 1.9])	2.729	.068
Temporal demand	0.96 (1.2, [0.5; 1.4])	1.4 (1.3, [0.8; 1.9])	1.5 (1.3, [0.9; 2.0])	1.8 (1.1, [1.4; 2.2])	6.747	.000
Performance	4.2 (0.8, [3.9; 4.5])	4.3 (0.7, [4.0; 4.6])	3.9 (0.8, [3.5; 4.2])	3.3 (0.9, [2.9; 3.7])	14.788	.000
Attentional demand	1.9 (1.6, [1.3; 2.6])	2.2 (1.3, [1.7; 2.8])	2.6 (1.2, [2.1; 3.1])	3.0 (1.2, [2.5; 3.5])	11.383	.000
Stress level	1.3 (1.5, [0.7; 1.9])	1.3 (1.5, [0.7; 1.9])	1.6 (1.5, [1.0; 2.2])	1.6 (1.4, [1.1; 2.2])	2.597	.059

¹ n = 23, ²n = 18, SD: standard deviation, CI: confidence interval, SWT: simple walking task condition, SRTA: simple reaction time task alone condition, DT: dual task condition, DTO: dual task with obstacles condition.

the simple walking task condition (SWT) and the dual task condition (DT; $p = .146$). However, significant differences were found between the SWT and the dual task with obstacles condition (DTO; $p < .001$) and between the DT and the DTO ($p < .001$).

An ANOVA on **step speed** showed a significant effect of condition ($F(2,34) = 16.715, p < .001, \eta_p^2 = .50$). Post-hoc analyses revealed significant differences between the SWT and the DT ($p = .016$), the SWT and the DTO ($p = .022$) and the DT and the DTO ($p = .021$).

No significant difference was found between the first trial duration ($M = 52.2$ s; $SD = 16.4$) and the second trial duration ($M = 48.8$ s; $SD = 13.3$; $t(23) = 1.287, p = .211$, Cohen's $d_z = 0.26$); or between the step speed in the first trial ($M = 0.82$ m/s; $SD = 0.21$) and the step speed in the second trial ($M = 0.85$ m/s; $SD = 0.20$; $t(17) = 0.899, p = .381$, Cohen's $d_z = 0.18$).

3.2. Simple reaction time task performance

An ANOVA on **correct responses** revealed a significant effect of condition ($F(2,48) = 5.132, p = .010, \eta_p^2 = .18$; Table 3). Post-hoc analyses did not show a significant difference between the simple reaction time task alone condition (SRTA) and the DT ($p = .360$), or between the DT and the DTO ($p = .375$). However, a significant difference was found between the SRTA and the DTO ($p = .011$).

An ANOVA on **response times** revealed a significant effect of condition ($F(2,48) = 42.999, p < .001, \eta_p^2 = .64$). Post-hoc analyses revealed significant differences between the SRTA and the DT ($p < .001$), the SRTA and DTO ($p < .001$), and between the DT and DTO ($p = .018$).

Concerning the prioritization between the walking task and the simple reaction time task during the DT and the DTO, participants stated they had prioritized the walking task at 56.2% ($SD = 15.6$).

3.3. Comparisons of during obstacle situation and between obstacles situation

For the DTO, step speed, correct responses and response times at the simple reaction time task in the obstacle situation were compared to those in the between obstacles situation. A *t*-test performed on **step speed** revealed a significant difference between the obstacle situation and the between obstacles situation ($t(17) = 9.765, p < .001$, Cohen's $d_z = 2.28$; Table 4). A Wilcoxon test performed on correct response did not reveal a significant difference between the obstacle situation and the between obstacles situation ($Z = 1.780, p = .075$). A *t*-test performed on response times revealed a significant difference between the

Table 4

Step speed and simple reaction time task performance during the dual task with obstacles according to obstacle management.

	Means (SD, CI)		test values	p values
	Between obstacles situation	Obstacle situation		
Step speed ¹ (m/s)	0.84 (0.21, [0.7; 0.9])	0.63 (0.15, [0.6; 0.7])	$t = 9.765$.000
Correct responses ² (%)	96.9 (6.1, [94.4; 99.4])	93.5 (8.8, [89.4; 97.6])	$Z = 1.780$.075
Response times ² (ms)	605.7 (137.4, [546.3; 665.2])	834.2 (330.0, [691.4; 976.9])	$t = 3.937$.001

¹ $n = 18$, ² $n = 23$, SD: standard deviation, CI: confidence interval.

obstacle situation and the between obstacles situation ($t(22) = 3.937$, $p = .001$, Cohen's $d_z = 0.82$).

3.4. Subjective assessment of cognitive load

An ANOVA on the **total score** revealed a significant effect of condition ($F(3,72) = 19.990$, $p < .001$, $\eta_p^2 = .45$; Table 3). Post hoc analyses demonstrated significant differences between the total scores obtained in the SRTA and in the dual task ($p = .026$), and in the DTO ($p < .001$). Significant differences were also shown between the total scores obtained in the SWT and the DT ($p = .001$), and in the dual task with obstacles ($p < .001$), and between the total score in the DT and the score in the DTO ($p = .010$). No significant difference was found between the total scores obtained in the SRTA or in the SWT ($p = 1.000$). The results for the different dimensions are presented in a supplementary material file.

3.5. Age effects

3.5.1. Walking performance

Mann-Whitney U tests did not reveal significant differences between the younger participants (aged less than 60) and the older ones (aged over 60 years) for the SWT duration ($U = 68.0$, $p = .423$; Table 5), for the DT duration ($U = 55.0$, $p = .305$), for the DTO duration ($U = 60.0$, $p = .417$), for the SWT step speed ($U = 27.0$, $p = .137$), for the DT step speed ($U = 34.0$, $p = .316$), or for the DTO step speed ($U = 26.0$, $p = .119$).

3.5.2. Simple reaction time task performance

Mann-Whitney U tests revealed significant differences between the younger participants and the older ones for the SRTA response times ($U = 34.0$, $p = .015$) and for the DT response times ($U = 41.0$, $p = .042$). However, no significant difference was found for the SRTA correct responses ($U = 64.0$, $p = .349$), for the DT correct responses ($U = 64.0$, $p = .349$), for the DTO correct responses ($U = 71.0$, $p = .489$), or for the DTO response times ($U = 53.0$, $p = .151$).

3.5.3. Subjective assessment of cognitive load

Concerning the subjective assessment of cognitive load, Mann-Whitney U tests did not reveal significant differences between the younger participants and the older ones for the STW total score ($U = 45.5$, $p = .068$), for the SRTA total score ($U = 43.0$, $p = .054$), for the DT total score ($U = 60.5$, $p = .262$) or for the DTO total score ($U = 62.5$, $p = .299$).

4. Discussion

The simultaneous execution of the simple reaction time task significantly decreased the step speed of participants and increased their subjective assessment of the cognitive load; this outcome verified our

Table 5

Performances of participants aged less than 60 years and of participants aged over 60 years.

	Means (SD)		U values	p values
	60- participants (N = 16)	60+ participants (N = 9)		
Walking performance				
SWT duration (s)	44.9 (11.7)	42.8 (7.8) ¹	68.0	.423
DT duration (s)	47.6 (15.6)	41.9 (6.9) ¹	55.0	.305
DTO duration (s)	56.9 (18.2)	52.6 (10.7) ¹	60.0	.417
SWT step speed ² (m/s)	0.85 (0.22) ²	0.95 (0.16) ¹	27.0	.137
DT step speed ² (m/s)	0.85 (0.24) ²	0.93 (0.20) ¹	34.0	.316
DTO step speed ² (m/s)	0.74 (0.21) ²	0.85 (0.15) ¹	26.0	.119
Simple reaction time task performance				
SRTA correct responses (%)	98.7 (2.7)	99.4 (1.3)	64.0	.349
DT correct responses (%)	97.3 (4.3)	95.9 (9.8)	64.0	.349
DTO correct responses (%)	94.6 (7.9)	94.7 (7.2)	71.0	.489
SRTA response times (ms)	430.2 (74.8)	467.0 (48.5)	34.0	.015
DT response times (ms)	565.4 (142.5)	671.7 (161.0)	41.0	.042
DTO response times (ms)	656.1 (164.4)	707.5 (166.1)	53.0	.151
Subjective assessments of the cognitive load				
STW total score	1.3 (0.8)	0.9 (1.1)	45.5	.068
SRTA total score	1.4 (0.9)	0.9 (1.0)	43.0	.054
DT total score	1.6 (0.8)	1.4 (1.2)	60.5	.262
DTO total score	1.9 (0.9)	1.7 (1.2)	62.5	.299

$n = 8$, ² $n = 10$, SD: standard deviation.

first hypothesis and extends previous findings with partially sighted and small samples of blind participants [12] to a larger totally blind sample. The activity of walking significantly increased the response times in the simple reaction time task and the total score of the subjective assessment of cognitive load, validating our second hypothesis. Taken together, these results indicate that walking without vision, even in a straight line, is not an automatic activity, and is based on controlled processes. When blind people had to process external stimuli while walking (auditory stimuli or obstacles perceived tactually through the white cane), they adapt their gait by slowing down in response to the increase in their cognitive load. In addition, step speed recorded in the simple walking task condition of the present study ($M = 0.89$ m/s, $SD = 0.20$) was comparable to step speed in Nakamura's study ([18]; $M = 0.86$ m/s, $SD = 0.09$), but slower than the speed in the study by Hallemans et al. ([25]; $M = 1.09$ m/s, $SD = 0.25$). However, in the Hallemans study, participants carried out five practice trials. This could have given them more confidence and may explain their faster speed.

The presence of obstacles significantly decreased the walking performance, and increased response times in the simple reaction time task and the subjective assessment of cognitive load. When the dual task with obstacles condition was analyzed in greater detail, step speed decreased significantly and response times increased when obstacles were negotiated. Our third hypothesis was therefore verified, both on a large scale (condition) and on a smaller scale (obstacles situation). Hence, this study shows that increasing the complexity of the environment (with the presence of obstacles) increases the cognitive load involved in the walking activity of blind people, as was already found with partially sighted participants [10,11]. These results also suggest that each one of the three measures used in the present study is relevant, and sensitive enough to assess the cognitive load involved in walking in the absence of vision. More specifically, the subjective assessment of cognitive load seems to be as sensitive as the objective

measures used, but, in contrast to them, it does not require any material and has no impact on mobility performance.

The parameters chosen for the simple reaction time task can be discussed. The first issue concerns the sensory modality targeted by this concurrent task, which is generally auditory ([10,12]) or tactile ([8,11]). Auditory stimuli can interfere with the ambient sounds blind people use to travel, and tactile stimuli can interfere with vibrations from the white cane. The auditory modality seemed to be the more ecological option, since most of the technological mobility aids used by blind people deliver auditory information (tonal and/or verbal). The level of difficulty of the concurrent task is also important – it needs to be difficult enough so as not to be carried out automatically, but not so difficult that it can result in failure or can interfere too strongly with performing the mobility task [11]. In the present study, the level of difficulty of this task seems to have been appropriate, since participants' performance in the simple reaction time task indicates that this task was not performed automatically, and since carrying it out while walking had an impact on mobility without preventing participants from performing the mobility task. Another parameter concerns the level of prioritization that participants can be asked to provide for each of the simultaneously performed tasks. In the present study, no instructions regarding prioritization were given to participants. If participants were asked to prioritize one of the tasks, it is likely that their performance in this task would not have declined. This choice was made to ensure that observations on adaptation for carrying out the simultaneous tasks were as ecological as possible. The participants reported they had prioritized the mobility task slightly, and this might explain why the performance of both the tasks were affected by being carried out simultaneously.

Concerning the age effect, few differences were found between the younger and the older participants. The younger participants did not obtain higher performances for the variables related to the walking task. However, they were significantly faster in the simple reaction time task when it was performed alone and when it was performed while walking without obstacles. With the presence of obstacles, the younger participants were not faster than the older ones in this task. These results can be explained by the fact that age-related cognitive decline observed in the simpler conditions might be compensated by experience when the difficulty was increased. Indeed, the older participants were blind for twelve years more than the younger ones, inducing a greater experience in walking without vision. This hypothesis might be confirmed by comparing two groups of participants for which the duration of blindness is controlled.

This experiment presents some limitations concerning the mobility task. Firstly, the mobility of blind people is not limited to the activities of walking and avoiding obstacles. Navigation without vision includes cognitive subtasks such as wayfinding, route learning, storage and processing of landmarks, and construction of cognitive maps [2,26]. In addition, walking without vision in an ecological environment is accompanied by emotional components [1,27], and these may have been mitigated in the present study conducted in a protected environment. This was highlighted by the lack of significant differences between conditions in the stress dimension of the subjective assessments of cognitive load. Since stress and emotions increase the cognitive load of a task [28], greater differences between the different conditions might have been found in a less protected environment. In addition, as the different walking trials were done along the same linear path, the participants had the opportunity to learn it from one trial and use that knowledge in another. However, the trials were counterbalanced to control this learning effect, which otherwise seems to have been limited, as shown by the lack of significant differences of walking performance between the first and the last trials. Finally, the distance travelled per trial in the present study was shorter than the distance travelled in a real pedestrian journey. However, this distance was greater than those used in the majority of studies in which the step speed of blind participants was recorded (5 m [19]; 10 m [18], or 25 m [17] for example). Nevertheless, these measures needed to be validated

in a simple and protected environment first, before being used in an ecological environment.

Considering of the heterogeneity of the participants (especially in terms of age, age of blindness onset, duration of cane use), and more generally of the population studied in terms of mobility skills [29,30], the study of several individual factors is an interesting perspective. Analyses are required to evaluate whether the cognitive load involved in walking without vision is different according to personal characteristics such as blindness onset, mobility habits and cognitive abilities. Replicating this study with other participants could also be interesting, to assess whether using a guide dog as a mobility aid or having residual vision (which concerns 90-95% of legally blind people [1]) impacts the cognitive load involving in walking differently.

Finally, three measures used in the present study seem to be useful in the context of rehabilitation and the design of technological mobility aids. The subjective measurement of cognitive load, which is particularly easy to use, could be used to adapt the difficulty and the duration of an O&M session to the individual, to compare the effectiveness of different kinds of O&M training or several technological mobility aids, or to assess the evolution of the learning level for a technological mobility aid. Secondly, the results obtained allow us to put forward recommendations for the design of technological mobility aids. The comparison of the obstacle situation and the between obstacles situation revealed that negotiating obstacles decreased the processing of information in the simple reaction time task and walking speed. This suggests that when a significant decrease in speed is observed, processing of information is less efficient. Moreover, the decrease in step speed observed in the present study when participants performed the simple reaction time task demonstrates that responding to simple external stimuli while blind people travel diverts their attention. A technological mobility aid designed to adapt the complexity, and/or the frequency, of information provided based on variations in walking speed would have the least negative impact on the mobility task of the blind user. Such an aid would provide additional relevant information (i.e., that cannot be obtained from the white cane or the guide dog [1]), and at the appropriate time (i.e., when the cognitive load of the blind user is not overloaded). Such a device could also be multimodal and adapt the delivery method for the information according to the cognitive load of the user at any point. Indeed, spatial information delivered verbally requires more cognitive load than spatialized audio or touch for guidance and cognitive map development [1,8], and should preferably be used when the user is not involved in a complex cognitive task (for example, negotiating an obstacle, remembering the route to take or thinking about an alternative itinerary in case of a blocked road). Thus, such an aid should not distract the attention of the blind user away from important information coming from the environment and crucial for his safety.

In conclusion, this study showed, via two objective and one subjective measures, that walking without vision involves a cognitive load that increases when the environment is made more complex by the presence of obstacles. Few age effects on performance were found. The results confirm the relevance of each of the three measures used to assess the cognitive load involved when blind people are walking. Of the three measures for the cognitive load, the subjective assessment we proposed, which is an adapted version of the NASA-TLX, is innovative in this context and can be easily used during the rehabilitation process or for technological mobility aids.

The authors declare no conflicts of interest

Acknowledgments

The authors wish to thank all the participants for their time, Annie Pauzié for her advice in the adaptation of the NASA-TLX, Philippe Deleurence and Bruno Piechnik of their assistance in the setting up of the study and Myriam Hugo for her advice for the statistical analysis. The study was partially supported by the Institut Fédératif de

Recherche sur le Handicap.

References

- [1] N.A. Giudice, Navigating without vision: Principles of Blind Spatial Cognition, in: D.R. Montello (Ed.), *Handbook of Behavioral and Cognitive Geography*, Edward Elgar Publishing, Santa Barbara, 2018.
- [2] C. Thinus-Blanc, F. Gaunet, Representation of space in blind persons: Vision as a spatial sense? *Psychol Bull* 121 (1) (2017) 20–42.
- [3] E. Foulke, The cognitive foundations of mobility, in: D.H. Warren, E.R. Strelow (Eds.), *Electronic Spatial Sensing for the Blind*, Springer, Dordrecht, 1985.
- [4] K.M. Rand, S.H. Creem-Regehr, W.B. Thompson, Spatial learning while navigating with severely degraded viewing: The role of attention and mobility monitoring, *J Exp Psychol Hum Percept Perform* 41 (3) (2015) 649–664.
- [5] S. Haymes, D. Guest, A.D. Heyes, A. Johnson, Mobility of people with retinis pigmentosa as a function of vision and psychological variables, *Optom Vis Sci* 73 (1996) 621–637.
- [6] D.D. Clark-Carter, A.D. Heyes, C.I. Howarth, The efficiency and walking speed of visually impaired people, *Ergonomics* 29 (1986) 779–789.
- [7] D.D. Clark-Carter, A.D. Heyes, C.I. Howarth, The gait of visually impaired pedestrians, *Hum Mov Sci* 6 (3) (1987) 277–282.
- [8] R.L. Klatzky, J.R. Marston, N.A. Giudice, R.G. Golledge, J.M. Loomis, Cognitive load of navigating without vision when guided by virtual sound versus spatial language, *J Exp Psychol Appl* 12 (2006) 223–232.
- [9] N. Richer, N. Paquet, Y. Lajoie, Impact of age and obstacles on navigation precision and reaction time during blind navigation in dual-task conditions, *Gait Posture* 39 (3) (2014) 835–840.
- [10] K.A. Turano, D.R. Geruschat, J.W. Stahl, Mental effort required for walking: Effects of retinis pigmentosa, *Optom Vis Sci* 75 (1998) 879–886.
- [11] D.R. Geruschat, K.A. Turano, Estimating the amount of mental effort required for independent mobility: persons with glaucoma, *Invest Ophthalmol Vis Sci* 48 (2007) 3988–3994.
- [12] V.K. Ramsey, B.B. Blasch, A. Kita, B.F. Johnson, A biomechanical evaluation of visually impaired persons' gait and long-cane mechanics, *J Rehabil Res Dev* 1999 36 (4) (1999) 323–332.
- [13] C.A. Shingledecker, The effects of anticipation on performance and processing load in blind mobility, *Ergonomics* 21 (5) (1978) 355–371.
- [14] S.G. Hart, L.E. Staveland, Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research, *Adv Psychol* 52 (1988) 139–183.
- [15] N.A. Bradley, M.D. Dunlop, An experimental investigation into wayfinding directions for visually impaired people, *Pers Ubiquitous Comput* 9 (6) (2005) 395–403.
- [16] M.A. Timmis, A.C. Scarfe, S. Pardhan, How does the extent of central visual field loss affect adaptive gait? *Gait Posture* 44 (2016) 55–60.
- [17] S.J. Mason, G.E. Legge, C.S. Kallie, Variability in the length and frequency of steps of sighted and visually impaired walkers, *J Vis Impair Blind* 99 (12) (2005) 741–754.
- [18] T. Nakamura, Quantitative analysis of gait in the visually impaired, *Disabil Rehabil* 19 (5) (1997) 194–197.
- [19] K.M. Knutzen, J. Hamill, B.T. Bates, Ambulatory characteristics of the visually disabled, *Hum Mov Sci* 4 (1) (1985) 55–66.
- [20] T. Li, G. Pradel, A. Supiot, N. Roche, D. Pradon, Development of an embedded gait analysis system for brain damaged patients, *Ann Phys Rehabil Med* (60) (2017) 41.
- [21] S. Mathôt, D. Schreij, J. Theeuwes, OpenSesame: An open-source, graphical experiment builder for the social sciences, *Behav Res Methods* 44 (2) (2012) 314–324.
- [22] A. Pauzié, A method to assess the driver mental workload: The driving activity load index (DALI), *IET Intell Transp Syst* 2 (4) (2008) 315–322.
- [23] J.C. Byers, A.C. Bittner, S.G. Hill, Traditional and raw task load index (TLX) correlations: Are paired comparisons necessary? in: A. Mital (Ed.), *Advances in Industrial Ergonomics and Safety I*. London, Taylor & Francis, 1989.
- [24] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs, *Front Psychol* 4 (2013) 1–12.
- [25] A. Hallems, E. Ortbis, F. Meire, P. Aerts, Low vision affects dynamic stability of gait, *Gait Posture* 32 (4) (2010) 547–551.
- [26] R.M. Kitchin, M. Blades, R.G. Golledge, Understanding spatial concepts at the geographic scale without the use of vision, *Prog Hum Geogr* 21 (1997) 225–242.
- [27] N. Baltenneck, S. Portalier, P.-M. Chapon, F. Osiurak, Parcourir la ville sans voir : effet de l'environnement urbain sur la perception et le ressenti des personnes aveugles lors d'un déplacement in situ, *L'année Psychol* 112 (2012) 403–433.
- [28] L. Chanquoy, A. Tricot, J. Sweller, La charge cognitive, théorie et applications, Paris: Armand Colin (2007).
- [29] G. Douglas, S. Pavey, C. Corcoran, B. Clements, Evaluating the use of the ICF as a framework for interviewing people with a visual impairment about their mobility and travel, *Br J Vis Impair* 30 (2011) 6–21.
- [30] S. Mac Cobb, Mobility restriction and comorbidity in vision-impaired individuals living in the community, *Br J Community Nurs* 18 (12) (2013) 608–613.