Driving Assistance by Deictic Control for a Smart Wheelchair: the Assessment Issue

F. Leishman, V. Monfort, O. Horn and G. Bourhis

Abstract— **In this paper, an assessment of a driving assistance by a deictic command for a smart wheelchair is proposed. This equipment enables the user to move with a series of indications on an interface displaying a view of the environment and bringing about automatic movement of the wheelchair. Two sets of tests were implemented to assess the advantages of this type of assistance compared to conventional wheelchair control. The first set evaluated the performance of the human-machine system based on a course time analysis, an observation of users' actions and an estimation of driving comfort. The second test was implemented to assess the cognitive requirements of the driving task, specifically the attentional and executive processes required when driving in assisted mode. A dual-task method was used to achieve this. The results show that driving assistance brings about a decrease in physical load for the same level of comfort as manual driving, but requires an additional cognitive effort for the user, especially in terms of executive abilities.**

Index Terms—**Human-machine system assessment, Smart Wheelchair, Deictic.**

I. Introduction

A lot of research has been conducted since the late 1980s to develop smart wheelchairs [1] and people with disabilities are proposed mobility aids for that they find it difficult to control on a standard powered wheelchair [2], [3]. Significant improvements have been made thanks to current technological developments. Among the first smart wheelchairs, some were developed on a mobile robot base [4], [5]. Quickly, the projects moved towards an instrumentation of off-the-shelf powered wheelchairs [6]. More recently, lighter, easier to integrate and lower-cost modular aids have been grafted onto wheelchairs [7]. A key aspect of this research is the place and the role of man in this man-machine combination. Many studies have focused on the sharing of tasks between the disabled person and the smart wheelchair [8], [9]. Thus, new ways of devising the driving assistance have emerged [10], such as driving through a series of elementary motions [11], [12], shared driving [6] or, recently, assistance with haptic feedback [10].

In this area, the deictic approach seems particularly interesting [11]. The concept of the deictic interface consists of offering an overview of the environment to the user on which he can target his goals. This overview should be close to human perception, making the interface intuitive. Several developments implementing this approach have been proposed in different application areas such as mobile robotics [13], [14], [15], [16], [17], augmented reality [18], [19], or smart wheelchairs development [11], [20]. Two possibilities are available to perform an action from this type of interface. The first is to specify the type of action to perform from a list and then indicate on an overview of the environment where to apply it. A second possibility is to trigger a predefined action related to the location indicated. For example, the act of pointing to a person on the interface automatically triggers a tracking action, reflecting the order "I want to follow that person". The advantage of this second approach is that the user order is executed in one pointing action on the interface, greatly simplifying human-machine interaction. The technical disadvantage is that it requires recognition of the elements on the interface in order to associate their corresponding actions.

Applied to a driving assistance, the deictic approach suggests driving differently. Users' order being given promptly, the overall movement is divided into a sequence of basic movements that are intuitively defined by the user through a series of pointing actions on the interface. In addition to the description of the proposed driving assistance for smart wheelchairs, the objective of this paper is to assess the performance of this assisted driving control compared to standard manual driving. In what follows, the deictic driving assistance, the existing evaluation methodologies for smart wheelchairs and the one adopted to evaluate our driving assistance, as well as the results and their discussions are described successively.

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II. Deictic Command

The proposed human-machine cooperative control is a "trading control system" where a circuit is performed by a succession of manual controls and automatic primitives. The mobility aid consists of two autonomous features: automatic passing through narrow passages and wall following. A driving assistance is intended for patients with significant muscle weakness, having dystonia or motor control problems that prevent them from using a standard electric wheelchair easily. These types of neuromuscular dysfunction can be observed primarily in patients with TBI (Traumatic Brain Injury), patients with multiple sclerosis or patients with CP (Cerebral Palsy) [2]. The narrow passage feature aims to facilitate difficult maneuvers such narrow door passage. The wall following feature is used to stabilize trajectories in long corridors for example and reduces user tiredness.

To perform this assisted control a smart VAHM-wheelchair prototype (Figure 1) was equipped with a video camera whose image was used as a user interface, together with three scanning laser rangefinders to probe the environment (URG-04LX by Hokuyo™). The deictic human-machine interface was displayed on the screen of a laptop placed on the wheelchair table. It provided an overview of the environment in which the possible features were represented: two green rectangles on the left- and right-hand sides of the image for wall following and blue quadrilaterals which overlapped on the existing passages for automatic passing through narrow passages (Figure 2).

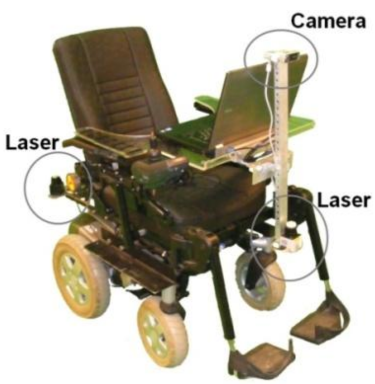


Fig. 1: Vahm-3 Prototype.

Fig. 2: Highlighted elements on the interface characterizing the features available (blue for a narrow passage, green for a wall)

The joystick of the wheelchair used for manual command, also served as a pointing device on the interface with its upper part being equipped with a push button. Pressing the button switched the joystick from its classical function to interface pointer control. Thus, to launch an autonomous feature, user had to press the button once to control the pointer and move it on its target (one of the highlighted elements) and then press it a second time to complete his command. The initial location of the cursor is the center of the screen and then its positioning depends on the last feature used; the cursor does not re-position automatically.

Achieving autonomous motion was carried out from a built-in wheelchair control system on successive target points. These were defined according to the wheelchair position, the analysis of the laser measurements, and the selected feature [21].

To pass through narrow passages in automatic mode, the laser measurements were combined into groups representing obstacles to determine the locations of possible paths. The successive measurements were congregated and the creation of a new group occurred when the distance between two measurements was greater than the minimum width foreseen for a passage (80cm). Then the passages were determined by finding the minimum distance between successive groups. Finally, a correspondence between laser perception and video image was done. Possible passages were deduced and represented on the user interface by a quadrilateral.

Thus, the user viewed the passages that could be selected at each laser measurement iteration. When this feature was activated, several concentric areas were established around the targeted narrow passage. For each of them, a target point was assigned which was the closest to the passage within the adjacent area. The wheelchair was locked to the target point of the area in which it was located. The trajectory which enabled the crossing was performed by target points successively obtained when the wheelchair crossed the successive areas. The shapes of areas and the location of the corresponding target points enabled a smooth trajectory which ensured passage from any orientation and/or starting position of the wheelchair.

For wall following, the goal was to drive the wheelchair in keeping a constant (or safety) distance from the wall. For this, laser perception was divided into three areas: left, right and in front. The distance between the wheelchair and the nearest obstacle was considered for each of these areas. At each iteration, the target point was defined according to these three distances and significantly enough to ensure an orientation command enabling to maintain the safety distance between the wheelchair and the wall, by slowing down when approaching an obstacle and adjusting the safety distance to the available space (reducing it if space was shrinking).

The execution of an automatic functionality stopped once the requested task was completed or on user request by any action on the joystick or button, switching wheelchair control immediately back to manual.

III. Assessment Methodology

A. Background

There are various methods for the assessment of driving assistance described in the literature and they depend on the type of assistance offered. Various assessment protocols have been proposed: comparing driving with or without mobility assistance [22], assessing assistance from several types of actuators [23], or comparing semi-autonomous, autonomous and manual driving [24].

Each method is based on the measurement and analysis of criteria that can be divided into several categories [25]. Firstly, the assessment can relate to the effectiveness of the proposed aid, for example by measuring performance and achievement of objectives. The chosen criteria include the measurement of moving time [23], collisions [26], [27], performance of the task [28], traveled distance [29], mean speed [30], and the differences between a performed trajectory and an optimal trajectory [31]. Then, the assessment can focus on the interactions between the user and the wheelchair, for example by measuring the number and difficulty of interactions with the interface [23], [24], or with the control unit [26], or by measuring errors during a user's order [29], [30]. Finally, the assessment may focus on the user by measuring his workload, his general condition, his emotional condition, and his level of confidence in the proposed assistance. For this, there are methods based on the use of ad hoc questionnaires [28], [29], or standardized TLX questionnaires (Task Load Index) [27], or the dual task paradigm in which subjects must perform a secondary task while driving [24].

The methods of analysis are mostly descriptive, for example, comparing the means for each criterion in each condition, or analyzing the feelings of subjects through questionnaires and observations made during different trials. Several statistical studies were conducted when a sufficient number of subjects and the type of measurements made it possible [28], [24].

Lastly, the evaluation from a panel of able-bodied people can be distinguished from those of a panel of persons with disabilities, the potential users of the system. In the case of healthy persons, the tasks to perform can be longer and more difficult; moreover, it is easier to have a large number of similar subjects at our disposal to perform larger studies. In the case of a panel of people with disabilities, the assessments generally involve a smaller number of subjects and are often similar to case studies [23], [26], [28], [30]. The difficulty is to establish a group of subjects having the same clinical features because of the wide variety of pathologies involved. However these experiments with end users are essential to assess the appropriateness of the proposed assistance.

B. *Justification*

The use of a wheelchair based on a manual or assisted driving requires the implementation of perceptual, attentional and executive processes that will enable patients to orient themselves in space, to focus their attention either on one navigation task or to share it between driving and a secondary task, to quickly take the right decision, or, to plan and anticipate maneuvers. However, various troubles may be described depending on the nature and location of the lesions involved for the patients with CP [32], [33], patients who had suffered from a severe TBI [34] or patients with multiple sclerosis [35], [36]: visual-perceptual deficits, decrease in the speed with which many processing operations can be executed and different types of attention and executive disorders. Achieving these complex cognitive processes in these patients may then interfere with the efficient use of these two types of control.

Consequently, the evaluation has to bring to light contributions and costs in terms of driving ergonomics and cognitive load of the driving assistance proposed; the aim being to target the user panel for which it may be both useful and usable, and to identify the difficulties a user with disabilities may encounter.

The evaluation will consist of determining rationally the parameters needed to discriminate between assisted driving and manual control. For this, two sets of tests were implemented (Table I provides a description of experimental protocols).

TABLE I
Description of experimental protocols

	Test 1: Measure of performance		**Test 2.1: Attention load**		**Test 2.2: Inhibition capacity**	
Subjects	Participant: 9 healthy persons (group 1)		Participant: 12 healthy persons (group 2.1)		Participant: 12 healthy persons (group 2.2)	
	one group		two subgroups		two subgroups	
	Group 1, group 2.1 and group 2.2 include different participants					
	circuit 1 : 80m		circuit 2 : 30m			
Tasks	Assisted Driving (AD)		Secondary Task (ST): Reaction time task (RT)		Secondary Task (ST): Go/NoGo task (GT)	
	Manual Driving (MD)		Assisted Driving with second task (AD+ST)			
			Manual Driving with second task (MD+ST)			
Protocols	All Subjects		Identical protocol for Test 2.1 and 2.2 defined as follows			
			Subgroup 1 (6 subjects)		Subgroup 2 (6 subjects)	
	Learning	10 to 20 min	Learning	10 to 20 min	Learning	10 to 20 min
	MD AD	five times each (25 to 30min)	ST AD+ST MD+ST	20 to 30 min	ST MD+ST AD+ST	20 to 30 min
	pause	10 min	pause	10 min	pause	10 min
	MD AD	five times each (25 to 30min)	MD+ST AD+ST ST	20 to 30 min	AD+ST MD+ST ST	20 to 30 min

The first one was designed to measure performance parameters, such as travel time, number of interactions with the control device or driving comfort. The second series of tests, using the dual task paradigm, aimed at the quantitative assessment of cognitive processes necessary for a driving task, including attentional mechanisms (alertness and sustained attention) measured with a reaction time task and executive functioning (inhibition capacity) measured with a Go-Nogo task. Each of these tasks used the auditory channel to help subjects travel course that drew on high levels of visuospatial resources simultaneously.

In the Go-Nogo task subjects had to decide to respond or inhibit their motor response based on the frequency of the auditory stimulus. This task is mainly described as a motor response inhibition task [37], while it could also involve sustained and selective attention. Executive functioning has been posited to be a critical domain in the utilization of safe driving behaviors [38] and executive disorders are frequently described in patients with CP, severe TBI or multiple sclerosis. Go-Nogo tasks are an ecological way to assess executive (inhibition capacity) and attentional mechanisms (alertness, sustained and selective attention) involved in the use of a driving assistance using a joystick as deictic control.

The assessment of cognitive processes is easier with subjects for which one can make sure that these processes are intact, which is the case in healthy subjects. This stage appears essential to determine if the use of this kind of assisted driving is possible for a patient for whom possible disturbances of these cognitive processes can be expected. This is why we chose panels of able-bodied people in order to collect statistically powerful data. Due to the wide variety of target users, this would have been almost impossible in practice if we had used a panel of people with disabilities. This is a dilemma already noted by other authors in the field [39].

C. *First series of test: performance measurement*

This first series of tests ("test 1") aimed at assessing the performance of the driving assistance. The participant group consisted of nine healthy subjects, 6 men and 3 women aged 33.7 years on average (S.D. 10.2 years). Each of them followed a first phase of training in which they became familiar with both assisted and unassisted driving, and then experimented a circuit length of 80m which was described orally (Figure 3). When travel times in both driving modes reached a plateau, i.e. after a decreasing phase of the travel time, when the two last travel times did not exceed ±5% of the previous travel time (average around 20 minutes of driving; 3 to 6 times the course for each mode; depending on the subject), the subject was allowed to begin the assessment phase. It consisted of traveling ten times the course in each driving mode alternately: the whole circuit was covered manually before following the same sequence in assisted mode, as described in Figure 3.

The circuit chosen was long enough so that even good drivers had to provide efforts. It required a variety of driving situations such as passing through a doorway in a narrow room for which maneuvering was required, or wall following in a long corridor.

In assisted mode, the sequence of features to use was imposed (Figure 3). It was identical in the learning phase and test phase. The subjects were instructed to avoid collisions as a priority and then to minimize travel time. In manual mode, the subjects were to avoid stops as much as possible. In assisted driving mode, they were asked to minimize the time spent on the interface as much as possible (when the user selected an automatic feature, the wheelchair stopped).

Various measurements were taken along the course. First, several time parameters were measured: travel time, time spent in each function, and stop time. These measurements enabled to estimate the time efficiency, the time spent on the interface for assisted driving, and the hesitation time during manual driving (in this type of driving, the subject was instructed to accomplish the course in one go, each stop indicating hesitation in front of an obstacle). The number of stops and the number of features used were also recorded. In addition to time measurements, these ones enabled to detect the moments when the subjects used the control device either to interact with the interface or to drive manually.

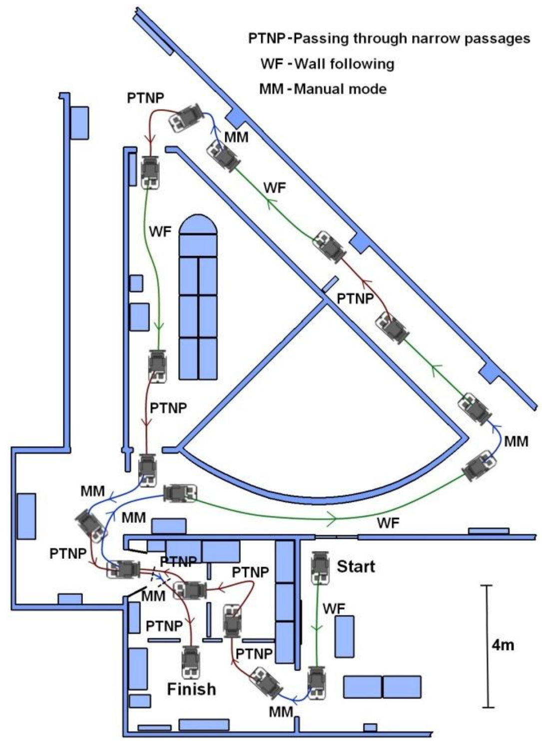


Fig. 3: Assisted driving circuit in the first series of tests (test 1).

Next, an index Ic was calculated to compare discomfort between the driving modes. Many authors had been interested in estimating comfort while a vehicle is in motion (car, elevator, etc.). The parameters most commonly used for this purpose are acceleration (longitudinal or lateral) and its derivative (jerk) [40], [41]. Thus in [42], the pilot's comfort in an electric wheelchair is evaluated from the joystick jerk defined as the third derivative of its position. In our case, the profile of acceleration did not depend on the driving mode chosen but on the dynamic characteristics of the wheelchair and its control unit. However our goal was not to measure the driving comfort intrinsically but to assess the difference between the driving modes. This difference in driving comfort resulted from the number of accelerations and decelerations of the wheelchair, which were indicative of erratic behavior or of a great number of stops to select an autonomous feature.

In practice, this can be deduced from variations of tensions Taa and Tgd obtained from the real or simulated joystick. The discomfort index Ic is determined from Equation (1), where Taa is the vertical tension of the joystick, reflecting forward speed, Tgd is the horizontal tension of the joystick, reflecting angular speed, K is the number of measurements during one circuit course, and τ is the time between two measurements empirically set at 300ms: lower values for τ are not compatible, in manual mode, with the psychomotor limits of the operator values, and, too large values for τ may obscure the rapid changes in speed of the wheelchair.

$$Ic = \frac{1}{K\tau} \times \sum_{i=1}^{i=K} \|Taa(i\tau) - Taa((i-1)\tau)\| + \|Tgd(i\tau) - Tgd((i-1)\tau)\| \quad (1)$$

D. Second series of tests: simple reaction time and Go/NoGo

The second series of tests ("test 2") were based on the dual task paradigm and divided into two parts. The first part ("test 2.1") was focused on assessing the attentional mechanisms (alertness and sustained attention) and the second part ("test 2.2") on assessing executive functioning (inhibition capacity) in both driving modes. The protocol and the course were identical for both parts, only the nature of the secondary task was changed.

The dual task methodology could be helpful in assessing cognitive demands of each driving modes. Cognitive load could be inferred by comparing performance between simple reaction time or Go/NoGo performed alone on the one hand and simultaneously with assisted or manual driving on the other hand. The simple reaction times tasks assessed alertness and sustained attention [43]. Lower performance in this task performed simultaneously with a driving task was supposed to reflect higher demands in terms of alertness and/or sustained attention. Go/NoGo tasks were supposed to assess mechanisms of inhibition but also alertness, sustained attention and decision [44], [45]. Lower performance in this task performed simultaneously with driving task was supposed to reflect higher demands in these mechanisms.

In "test 2.1", the subjects were asked to accomplish a simple reaction time task carried out in parallel to the driving task. In this task, the subject was instructed to press as quickly as possible on a response button each time an auditory stimulus sounded. At the first "beep", the user had one second to respond (over one second, his reaction was considered as an omission). After the user had pressed the response button or this time had elapsed, the next "beep" was generated randomly between 1.5s to 3s etc. These stimuli were delivered using a headset and the subjects used their left hand to answer (the right hand being reserved for the driving task).

In "test 2.2", the subjects performed the Go/NoGo task. In this task, the subject were to respond to target stimuli (high frequency "beeps") by pressing as quickly as possible the response button, and ignoring stimuli distracters (low frequency "bops"). Stimuli were generated in a pseudo-random manner (not more than three successive identical stimuli) and were spaced randomly between 1.5s to 3s as in the first task.

Both tests were performed by a group of different subjects each consisting of twelve healthy subjects including 8 men and 4 women aged 30.1 years on average (S.D. 9.3 years) for test 2.1 and 26.1 years on average (S.D. 5.5 years) for test 2.2. The subjects of this second series of tests (tests 2.1 and 2.2) were also different from those involved in the first series (Test 1).

First, each subject went through a learning phase of the two driving modes and of the secondary task. The learning phase of the dual-task was considered completed when the travel time (same condition as test 1) and the average of reaction times were stabilized, when the average of reaction times on the two last courses did not exceed ±5% compared to the previous average (3 to 6 times the course for each mode; depending on the subject).

At the end of the learning phase, the subjects were to carry out three tasks: a control task, in which the secondary task was performed alone, an assisted driving task in parallel with the secondary task, and finally, an unassisted driving task in parallel with the secondary task. The subjects performed each task ten times in a different order. To assess the rank and fatigue effects, each test group (2.1 and 2.2) was divided into two subgroups. Firstly, the two subgroups performed the first half of the control tasks at the beginning and the second half at the end of experimentation in order to test the rank effect (fatigue and learning effects). Then, between these two phases, the subjects in subgroup 1 completed the first half of the circuit course with driving assistance, then the whole course in manual driving, followed by the second half of the circuit in assisted mode. Subgroup 2 performed these tasks following the same pattern in reverse order as shown in Table I. It is difficult to evaluate all order effects in such complex experiments. That's why, a partial counterbalancing groups was used to test the order effect which seemed most important, i.e. the influence of a driving task on the other one.

The instructions to be followed during the tests were given before the learning phase. For the driving tasks, the subjects were to perform the circuit course presented in figure 4. They were given a priority to avoid collisions and complete the circuit as quickly as possible, and finally limit stationary times. For the secondary task, they were asked to respond to stimuli as fast as possible. They also had to accomplish both tasks simultaneously, and under no circumstances abandon a task for another.

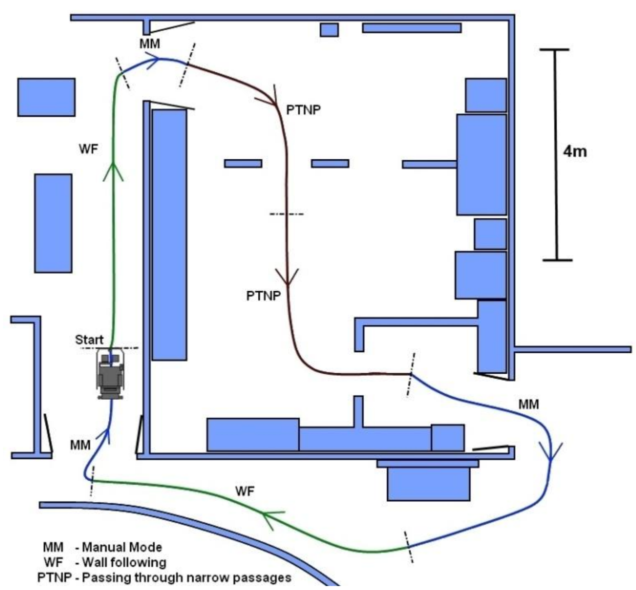


Fig. 4: Assisted driving circuit in the second series of tests (tests 2.1 and 2.2).

During the tests, several parameters related to the secondary task were measured, such as the reaction time of subjects to target stimuli (in ms), and different errors (a response to the distracting stimulus, a response whilst no stimulus was generated, or an absence of response to a target stimulus). The circuit during the second series of tests was shorter than in the first (length of 30m). The secondary task imposed to subjects a great effort, too long a course would thus induce fatigue and possible bias in the results. This circuit was established in order to balance the use of features (manual mode, wall following and passing through a narrow passage).

IV. Results

First of all, normality was tested separately by task type (reaction time & Go/No-go tasks). A Shapiro-Wilk test was performed on each group of data being compared, i.e. all control task reaction times, those obtained in parallel with the manual driving task, and those from the assisted driving task. Distributions did not follow normality. So a transformation was applied to the data groups (Box-Cox transformation), without obtaining normal distributions for all groups: hence our decision to use non-parametric statistical tools, a Mann-Whitney test for comparison between two groups when the variables were independent, the Wilcoxon test in the case of paired variables, and the Kruskal Wallis test with multiple comparisons (nonparametric ANOVA) in the case of multiple variables. All tests were performed for $\alpha = 0.05$.

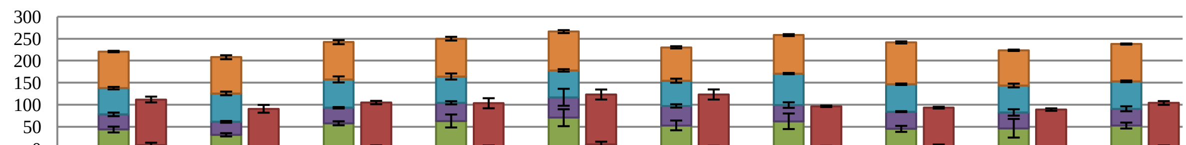
A. *Performance Criteria (test 1)*

1) *Time and frequency of control modes*

The measurements of time and of frequency of control modes used enabled to assess the performance of the human-machine combination. These measurements tell about the progression of subjects on the circuit, on how the subjects used the features, and highlight the difficulties encountered. The results are presented in summary tables. Figure 5 presents the average time and the standard deviation in each type of driving for a whole run of the circuit course, the mean time for all subjects, and the time distribution of features along the circuit. Figure 6 presents the frequency of use of different features.

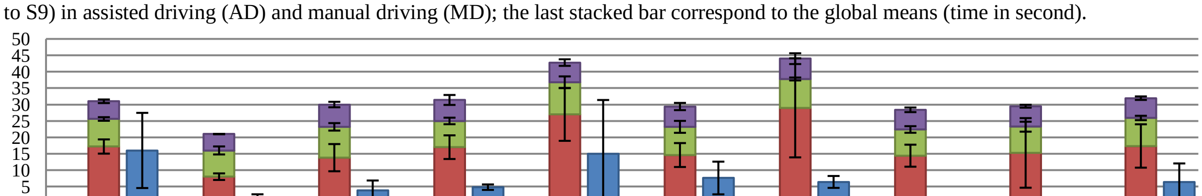
All subjects used the automatic mode without difficulty. The time spent in each function is very close for all subjects, which was initially predictable: the driving type was the same; only the start and end point of the autonomous features were slightly changed. On these courses, an average subject was motionless 22.3% of the time, spent 16% of the time driving manually, 26.2% passing through narrow passages, and finally, 35.5% following walls. For manual driving, the subjects were motionless 5.7% of the time while they spent 94.3% of the time driving manually. Conversely, overall travel time in assisted driving was twice longer than in manual driving (on average, 104.4s in manual driving, and 237.8s in assisted driving). The two means are significantly different (from a Wilcoxon Test ($p<0.001$)). This is due to the time required for each change of functionality (stop and selection on the interface). Most subjects did not find it difficult to drive in manual mode. However, some of them drove erratically, with frequent short stops when they were faced with obstacles or hard maneuvers.

Finally, it is important to compare the time during which the user operates the control device depending on the driving mode. In manual driving, the user held the joystick continuously and retained control over it during the entire travel time, averaging 104.4 seconds. This implies complex maneuvers without interruption imposing users a lot of effort. In assisted driving, the subject used the joystick in manual driving between features during adjustments or basic movements (short and without maneuver), and when the



	S1	AD	MD	S2	AD	MD	S3	AD	MD	S4	AD	MD	S5	AD	MD	S6	AD	MD	S7	AD	MD	S8	AD	MD	S9	AD	MD	Tot	AD	MD
Time in WF(AD)		83,0			82,0			84,4			85,6			87,9			75,6			87,1			94,7			79,8			84,5	
Time in PTNP(AD)		59,4			64,4			64,2			59,6			60,9			57,2			71,3			62,0			61,1			62,2	
Time in manual(AD)		34,4			29,3			35,2			41,2			46,2			44,1			36,7			39,1			35,8			38,0	
Stop time(AD)		44,1			32,2			58,3			63,5			71,0			53,5			62,9			45,6			47,0			53,1	
Time in manual(MD)			103,			88,4			98,9			97,7			113,			118,			90,0			87,0			88,4			98,4
Stop Time(MD)			9,0			2,7			6,4			6,0			10,2			4,9			6,7			6,7			1,0			5,9

Fig. 5: Time analysis (test 1), mean and standard deviation of each driving condition (WF – Wall following, PTNP – Passing through narrow passage) for each subject (S1 to S9) in assisted driving (AD) and manual driving (MD); the last stacked bar correspond to the global means (time in second).



	S1	AD	MD	S2	AD	MD	S3	AD	M	S4	AD	MD	S5	AD	MD	S6	AD	MD	S7	D	MD	S8	AD	MD	S9	AD	MD	Tot	AD	MD
N. of WF(AD)		5,4			5,0			6,8			6,4			6,0			6,2			6,2			6,0			6,3			6,0	
N. of PTNP(AD)		8,4			8,0			9,4			8,0			9,8			8,6			8,8			8,0			8,0			8,6	
N. of Stop(AD)		17,2			8,0			13,8			17,0			27,0			14,6			29,0			14,4			15,3			17,4	
N. of Stop(MD)			16,0			1,8			3,8			4,8			15,0			7,6			6,4			1,2			1,0			6,4

Fig. 6: Frequency of use of different features for each subject in both driving mode (AD and MD).

subject performed a command on the interface (i.e. 22.3% of travel time). Joystick use took an average of 91.1 seconds with many breaks and with the wheelchair at a halt most of the time (the user had all the time to complete the order without collision risk). A Wilcoxon test was performed between the sum of stop time and manual driving time for two driving tasks. The difference was significant (p <0.001).

2) Comfort criterion

The discomfort index is estimated through the number of "fits and starts" endured by the subject during the course; the more numerous the accelerations, the higher the index. Table II presents the discomfort index means for each subject in both types of driving modes.

TABLE II
Discomfort Index Analysis (test 1)

Subject	Global Discomfort Index in manual driving	Global Discomfort Index in assisted driving
S01	1.028	0.712
S02	0.716	0.676
S03	0.626	0.700
S04	0.932	0.782
S05	1.058	0.806
S06	1.012	0.760
S07	0.604	0.716
S08	0.488	0.802
S09	0.566	0.690
Av.	0.781	0.738
S.D.	0.225	0.050

In manual driving, the comfort index is highly variable depending on the subject and it also depends on the mastery level of the wheelchair's user. Thus, it could be very low (0.488) for quasi-faultless driving (smooth, fluid trajectories) and high (1.058) for uncertain driving (many stops, erratic motions). For assisted driving, the comfort index was fairly stable (0.676 to 0.806) corresponding to normal driving (the only "fit and starts" in this mode being caused by micro-motions needed to adjust the wheelchair direction when a target was out of sight of the camera). The circuit in assisted driving required a lot of stops to switch from a feature to another, or from manual driving to a feature, adding a large number of accelerations and decelerations. These last were progressive so as to avoid discomfort. The acceleration ramps were defined by the features and were limited by the control system of the wheelchair (hence the longer travel times).

Overall, there is an equivalent level of discomfort index in both modes. However, two trends can be observed: a significant improvement of comfort in automatic mode for those having an uncertain or normal (smooth) manual driving, and a decrease of comfort for subjects driving the wheelchair in manual mode optimally. A Wilcoxon test was also performed between the discomfort level for the two driving tasks, the difference was not significant (p = 0.55).

B. Attentional mechanisms and executive functioning (test 2)

1) Simple reaction time task (test 2.1)

The analysis of reaction times and the error numbers (mostly omissions) allows differences in terms of attentional demands to be assessed (i.e. alertness and sustained attention mechanisms) throughout the course. For each course, each response of a subject was recorded in a timeline in order to view the reaction time associated with the action performed at that time. Figures 7 and 8 show two examples of chronologies corresponding to the assisted driving task and the manual driving task respectively. Table III defines the actions of the chronologies.

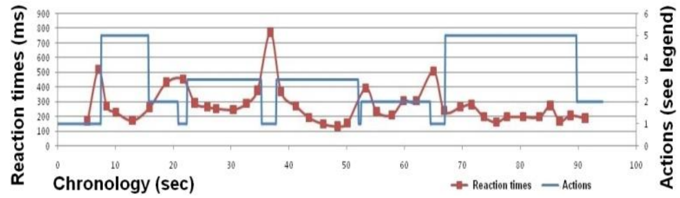


Fig. 7: Chronology of assisted driving (simple reaction time).

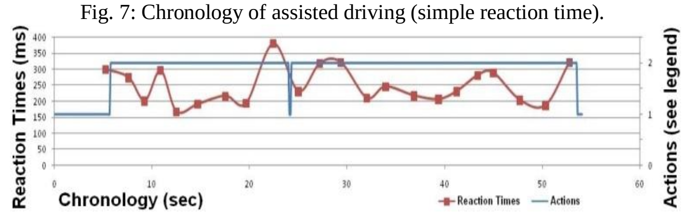


Fig. 8: Chronology of manual driving (simple reaction time).

TABLE III
Legend of the actions of the chronologies

Identifier	Description of actions
0	Debug Mode
1	Stop
2	Manual Driving with Joystick
3	Passing Through a Narrow Passage
4	-Reserve-
5	Wall following

The descriptive analysis of the chronologies is used to identify the difficulties encountered by the subjects. The reaction time distribution was very different in the two types of driving. During assisted driving, the subjects found it difficult to activate controls on the interface. This is shown by increases in reaction time, short and intense peaks, in the stoppage phases before feature use. For manual driving, the difficulties occurred when the subject had to perform a maneuver, like passing a doorway or a narrow passage. The peaks observed are longer and less intense.

Overall (Figure 9 and 10), the average reaction time of the control task is well below the average reaction time for both types of driving, thus showing that important attentional resources were required by the driving tasks from the subjects. A statistical analysis was performed to estimate whether the measured differences of the mean reaction times and errors percentages between both driving modes were significant.

First, the order effect was checked with a Mann-Whitney test between the mean reaction time of each type of driving for both groups of subjects (subgroup 1 was compared with subgroup 2 in assisted driving with p = 0.70, and p = 0.59, without assistance), and the rank effect was checked with a Wilcoxon test between the mean reaction time of control tasks carried out at the beginning and at the end of trials (p = 0.20). These two effects did not have a significant influence; the data from both groups could be merged. Next, the normality of our data is tested with the Shapiro-Wilk test. The data did not follow a normal distribution, so the nonparametric Kruskal-

Wallis test with multiple comparisons was used. The average reaction time ($\chi^2(2)=137.12$; $p<0.001$) and the number of errors ($\chi^2(2)=76.79$; $p<0.001$) by circuit course for all subjects and for each type of task were compared with this test (Table IV). The overall cognitive demands for both driving tasks were not significantly different, although both differed from the reaction time task performed alone. The same results can be observed with the error analysis during the two driving modes: both are not separable but still higher than the control condition.

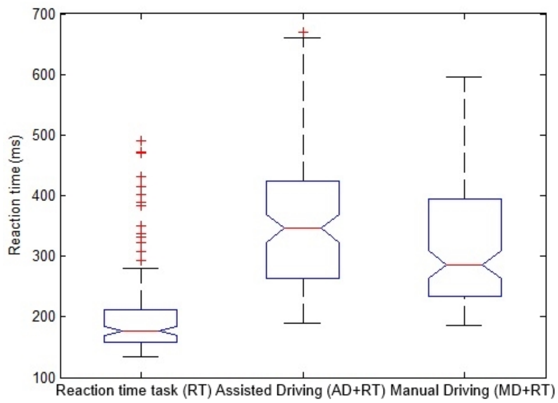


Fig. 9: Boxplots of reaction time for all subjects in different driving modes (test 2.1).

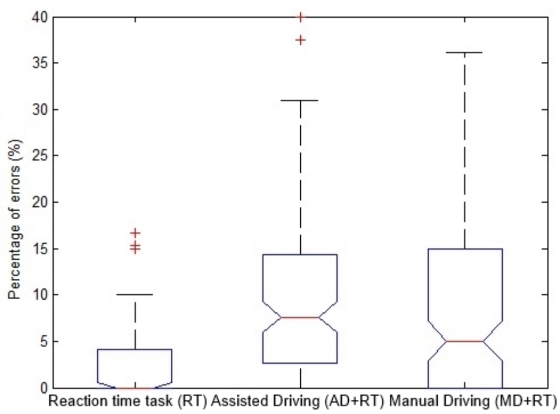


Fig. 10: Boxplots of percentages of errors for all subjects in different driving modes (test 2.1)

TABLE IV
Kruskal-Wallis test: difference between driving modes for average reaction times and errors (test 2.1)

	Confidence interval for the reaction time averages	Significant difference at $\alpha = 0.05$	Confidence interval for the errors number	Significant difference at $\alpha = 0.05$
RT↔ AD+RT	-177,5 to -114,5	yes	-89,8 to -29,7	yes
RT↔ MD+RT	-155,3 to -92,3	yes	-111,4 to -51,4	yes
MD+RT↔ AD+RT	-9,4 to 53,6	no	-51,7 to 8,4	no

On the other hand, it would be interesting to focus more precisely on reaction times in assisted driving mode in order to identify the actions that are the most demanding of attentional resources. For this, a Kruskal-Wallis test was performed between the mean reaction time of each type of action ($\chi^2(3)=298.51$; $p<0.001$), during stops (Av_Rt_Stop), wall following (Av_Rt_Wf), narrow passage maneuvers (Av_Rt_Ptnp), and in manual driving (Av_Rt_Manu). Figure 11 shows the mean and the distribution of reaction times for each condition. The multiple comparisons (Table V) lead to concluding that there are significant differences between each condition, as seen from reaction times in ascending order: the wall following, the passing through narrow passage, manual driving, and the wheelchair command establishment at stops.

Slower reaction times for motionless phases corresponding to the command establishment may be observed: for the subject, it is a phase of decision making and action planning that consumes attentional resources and therefore may extend the reaction time. Faster reaction times for the phases in assisted driving may also be noted. During manual driving the reaction times have intermediate values between these two extremes.

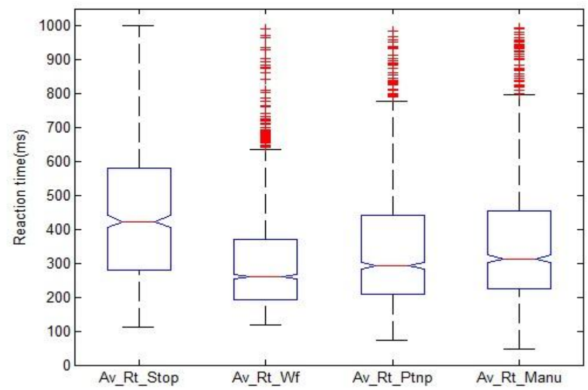


Fig. 11: Boxplots of reaction times for all subjects in assisted driving for each condition (Stop, Wall Following, Passing Through Narrow Passage and Manual Driving) (test 2.1).

TABLE V
Kruskal-Wallis test: difference between different conditions of driving with assistance (test 2.1)

	Confidence interval for the reaction time averages	Significant difference at $\alpha = 0.05$
Av_Rt_Stop↔ Av_Rt_Wf	827,6 to 1205,7	yes
Av_Rt_Stop↔ Av_Rt_Ptnp	508,5 to 896,3	yes
Av_Rt_Stop↔ Av_Rt_Manu	301,9 to 714,9	yes
Av_Rt_Wf ↔ Av_Rt_Ptnp	-465,7 to -162,9	yes
Av_Rt_Wf↔ Av_Rt_Manu	-675,6 to -341,0	yes
Av_Rt_Ptnp↔ Av_Rt_Manu	-366,7 to -21,2	yes

2) *Go/NoGo task (test 2.2)*

In addition to attentional requirements (i.e. alertness and sustained attention), the role of executive abilities (inhibition capacity) in the driving tasks can be assessed by comparing the disturbances obtained from the Go/NoGo response inhibition task performed simultaneously with driving and the Go/NoGo performed alone. Figures 12 and 13 show two examples of chronologies with the Go/NoGo response inhibition task corresponding respectively to assisted and manual driving. The actions described in the chronologies are the same as before (see Table III).

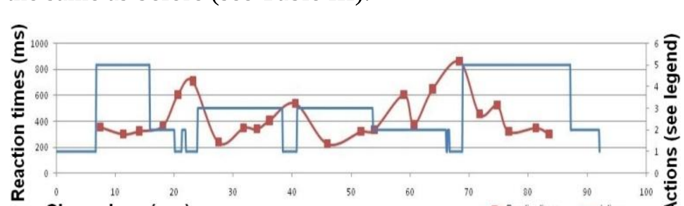


Fig. 12: Chronology of assisted driving (inhibition capacity).

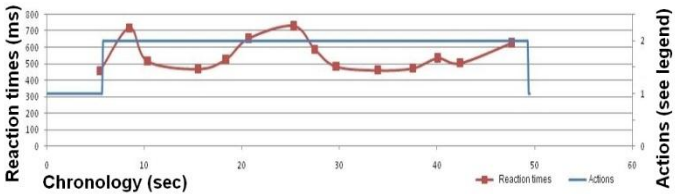


Fig. 13: Chronology of manual driving (inhibition capacity).

Reaction time variations are similar to those observed during the previous task, except that the peaks are wider for the driving tasks. In assisted mode, the subjects had a higher cognitive load during command establishment, and also at the end of the action preceded by this command. In manual mode, the subjects had often a higher cognitive load during a maneuver, as before.

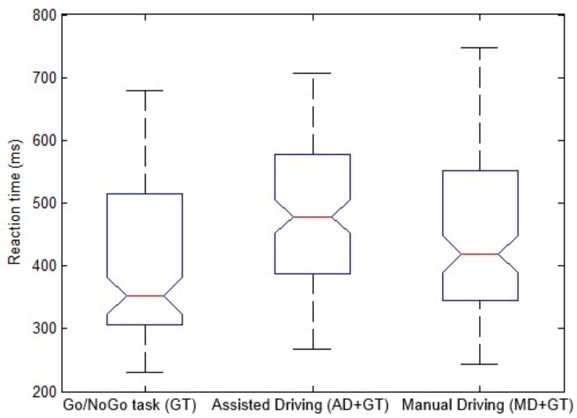


Fig. 14: Boxplots of reaction time for all subjects for different driving modes (test 2.2).

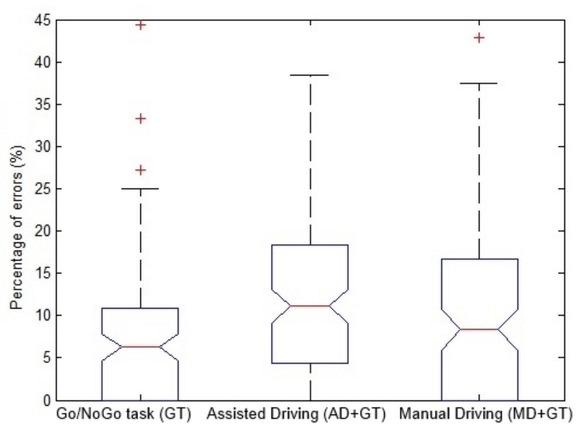


Fig. 15: Boxplot of percentages of errors for all subjects for different driving modes (test 2.2).

TABLE VI
Kruskal-Wallis test: difference between driving modes for average reaction times (test 2.2)

	Confidence interval for the reaction time averages	Significant difference at $\alpha = 0.05$	Confidence interval for the errors number	Significant difference at $\alpha = 0.05$
GT↔ AD+GT	-110,6 to -47,7	yes	-98,8 to -36,7	yes
GT↔ MD+GT	-77,9 to -14,9	yes	-83,9 to -21,8	yes
MD+GT↔ AD+GT	1,2 to 64,2	yes	-16,2 to 45,9	no

The measurement protocol being the same as for the estimation of the simple reaction times task, the same statistical tests were performed leading to similar conclusions (the order effect by comparing the mean reaction time of both groups obtained in the task of assisted driving, p = 0.18, and manual driving, p = 0.24; the rank effect by comparing the average reaction time of the Go/NoGo task at the start with that at the end of the test for all subjects, p = 0.09; and normality with the Shapiro-Wilk test). The comparisons were therefore also tested with a nonparametric Kruskal-Wallis test between the mean reaction times ($\chi^2(2)=35.05$; $p<0.001$) and between the errors ($\chi^2(2)=28.87$; $p<0.001$) for each task (Table VI), and a test between the types of actions performed during assisted driving ($\chi^2(3)=177.48$; $p<0.001$) (Table VII). Figures 14 and 15 illustrate the mean reaction times and errors for the different types of driving. For assisted driving, Figure 16 shows the average reaction time for each condition.

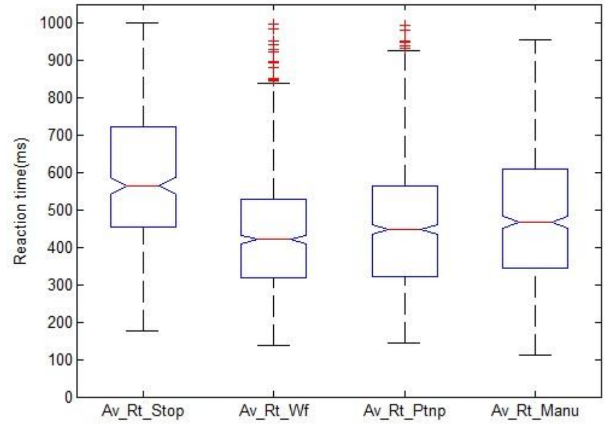


Fig. 16: Boxplots of reaction times for all subjects in assisted driving for each condition (Stop, Wall Following, Passing Through Narrow Passage and Manual Driving) (test 2.2).

TABLE VII
Kruskal-Wallis test: difference between different conditions of driving with assistance (test 2.2)

	Confidence interval for the reaction time averages	Significant difference at $\alpha = 0.05$
Av_Rt_Stop↔ Av_Rt_Wf	463,0 to 755,0	yes
Av_Rt_Stop↔ Av_Rt_Ptnp	349,9 to 646,7	yes
Av_Rt_Stop↔ Av_Rt_Manu	224,9 à 535,2	yes
Av_Rt_Wf↔ Av_Rt_Ptnp	-227,1 to 5.6	no
Av_Rt_Wf↔ Av_Rt_Manu	-353,8 to -104,2	yes
Av_Rt_Ptnp↔ Av_Rt_Manu	-245,8 to 9.4	no

During these tests, a high mean of reaction times can be observed, even for the control task. The subjects had a higher cognitive load than during the tests with the simple reaction task. The differences between the two types of driving are significant, which was not the case in previous tests (test 2.1). The same results can be observed with the error analysis during the two driving modes. This shows that assisted driving requires executive mechanisms which are higher than for manual driving. The multiple comparisons led us to conclude that there are significant differences between each condition; except between the passing through narrow passage and the manual driving.

Descriptively, the chronologies show wide and relatively high peaks in manual driving, but there are few of them. They reflect in most cases the situations in which subjects hesitated during a complex maneuver. There were a lot of errors in these cases (many responses to "bops" especially). For assisted driving, there were also wider peaks than in trials with the single secondary task (test 2.1). They happened during feature shifts and especially when the subject chose his target on the interface, and also, at the end of features when the subject anticipated what to do next.

V. Discussion

The different experiments highlight the advantages provided by our driving assistance in comparison with manual driving, and also, helps identify its requirements in terms of attentional load and executive abilities. In the first series of tests (test 1), we notice that assisted driving required less effort and fewer controls on the joystick to perform the same course with the same level of comfort than in manual driving. However it required more time to accomplish this task. The decrease in effort and physical demand was due to the change of control type. In manual driving, physical efforts provided by the users were mainly required during difficult maneuvers. With the driving assistance, the maneuvers were performed by functionalities and only the activation of controls on the interface was physically demanding. In terms of comfort, the same level was reached with both driving modes and corresponds to good manual driving. The improvement concerns therefore people with disabilities that experience driving difficulties with a conventional powered wheelchair. The main drawback is the increase in travel time compared to manual driving due to stops during feature changes and to the time required to activate a control on the interface. This finding will however not be necessarily always true for people with heavy difficulties to control their wheelchairs. Let us note at last a limitation of this study: we designed a lighter driving assistance easy to implement on any kind of wheelchair. For this reason no specific location device was implemented. So the comfort index did not measure the real comfort of the person but only enabled to compare the difference of comfort between the driving modes.

Then, for simple reaction times tasks, the two types of driving required the same average level of attention but at different moments. In assisted driving, the attentional load was more intense during the activation of a control (motionless wheelchair), whereas for manual driving, the attentional load increased during difficult maneuvers (moving wheelchair). In contrast, attentional and executive mechanisms needed for assisted driving were slightly higher than in manual driving. This is understandable because the user had to switch frequently from one feature to another, and had to decide and anticipate the type of action to carry out, whereas in manual driving, there is only one type of control.

These experiments allow identifying the general physical and cognitive prerequisites needed for the use of assistance by comparing it to the reference manual driving for the same control device. This can help target the individuals for whom such assistance can be useful and usable. For example, people having a great difficulty to drive a standard powered wheelchair due to their imprecise (for some people with cerebral palsy) or unstable movements (tremors), can use manual driving to perform simple movements and can use automated features for difficult maneuvers. It can also be as effective for people with significant fatigue. The physical efforts required by assisted driving are short and spaced by released times, while manual driving requires continuous effort.

On the other hand, for our assistance to be usable, the person must be able to bear attention peak loads imposed during the activation of controls on the interface. Similarly, the executive abilities required in assisted driving are higher than in manual driving.

Thus, our results highlight the necessity to take into account more elements than the motor deficits of patients. The different cognitive problems that potential users may encounter should also be estimated. However, users may suffer from various cognitive disorders in addition to their motor impairments. If some may be hardly disturbed or even undisturbed by the attentional and executive processes involved in assisted driving, others may experience great difficulties in the execution of a task implementing these processes. Indeed, the degree of cognitive impairment of a patient in comparison to another can vary within a population suffering from the same disease, as in the case of populations with two different pathologies. Thus, cognitive impairment is generally less severe in cases of muscular dystrophy than in TBI or CP cases [34], [35]. It is therefore necessary to estimate the attentional and executive mechanisms off-line before testing in real conditions. Then, as the result of a neuropsychological evaluation made to measure attentional and executive performance, it could be possible to assess the driving performance using a simulator to determine the cognitive impairment level for which the use of this type of command is no longer possible.

It is also necessary to consider the various options to improve the mobility aid in order to reduce its cognitive prerequisites. For example, the ergonomics of the interface can be changed in order to reduce the time spent to establish the command, like positioning the cursor on the element of the interface closest to the center of the screen when the user switches from manual to autonomous driving. In the case where this element represents the desired autonomous movement of the user, the establishment of command does not require the cursor to be moved. The command would be reduced to switching into automatic mode and validating (pressing the button twice). Otherwise, the control device used in our driving assistance is the joystick, which is the most used on current electric wheelchairs [3]. The main goal of this option is to preserve traditional manual driving while providing autonomous features additionally. To improve the adaptability of our assistance to a larger number of people, other human-machine interfaces can be considered. For example, automatically scanning highlighted items on the screen would make it feasible to use a switch device, or a brain-computer interface (BCI). But in this case, in addition to the autonomous features described in this article, one should consider developing a "go to this point"-like command as described for example in [29].

In addition, other types of human-machine cooperation were considered for smart wheelchair control. If we refer to the taxonomy of [46], [9], the control mode proposed here is a traded system while control sharing systems have been developed and evaluated by other teams. Thus, in [39], the assessment of a shared control allows authors to conclude that performances in terms of collision numbers are improved and the workload is reduced. Another study [24] compares three driving modes: automatic, manual and shared control modes. The performance obtained in automatic mode is better both in terms of travel time as for a mathematical secondary task. Conversely, manual mode is the least frustrating while automatic the most frustrating for users. Given that the differences in the assistance modes available and in the assessment criteria of performances, the results obtained from the literature combined with our data do not allow us to define the optimal mode of cooperation. Indeed, in general, the option of technical assistance for disabled persons must be taken individually according to the person's motor and cognitive skills on the one hand and his own state of mind about it on the other. The object of this study is to help provide a rational framework for such a choice. One of its major interests is to focus on the need for carrying out a fine analysis of the various cognitive processes involved in healthy subjects. This then makes it possible to better understand the weight of these processes in assisted driving by deictic control and then to be able to better adapt all evaluations (technical and clinical) necessary to determine the usability of the device for each potential user.

VI. Conclusion

This paper describes the assessment of a new mobility aid for a powered wheelchair designed in our laboratory. It is based on a traded control method which provides the user with two autonomous features in addition to traditional manual driving: automatic passing through narrow passages and wall following. Its activation is performed by a deictic interface that makes it possible to use these features ergonomically with the same control device as the one used to manually steer the wheelchair, the joystick. We highlight the cognitive prerequisites for its use such as attentional load and executive abilities. It appears that this assistance brings about a decrease in physical load for an equal level of comfort as manual driving, but requires an additional cognitive effort for the user, especially in terms of executive abilities. The potential users are people who are likely to endure strong difficulties to drive a wheelchair with a joystick. This assessment also helps to determine among them the persons for whom the system is usable: people who do not present severe cognitive impairments.

VII. References

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