MotorBrain: A mobile app for the assessment of users’ motor performance in neurology

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MotorBrain: A mobile app for the assessment of users' motor performance in neurology

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Abstract

Background and Objective

Human motor skills or impairments have been traditionally assessed by neurologists by means of paper-and-pencil tests or special hardware. More recently, technologies such as digitizing tablets and touchscreens have offered neurologists new assessment possibilities, but their use has been restricted to a specific medical condition, or to stylus-operated mobile devices. The objective of this paper is twofold. First, we propose a mobile app (MotorBrain) that offers six computerized versions of traditional motor tests, can be used directly by patients (with and without the supervision of a clinician), and aims at turning millions of smartphones and tablets available to the general public into data collection and assessment tools. Then, we carry out a study to determine whether the data collected by MotorBrain can be meaningful for describing aging in human motor performance.

Methods

A sample of healthy participants (N=133) carried out the motor tests using MotorBrain on a smartphone. Participants were split into two groups (Young, Old) based on their age (less than or equal to 30 years, greater than or equal to 50 years, respectively). The data collected by the app characterizes accuracy, reaction times, and speed of movement. It was analyzed to investigate differences between the two groups.

Results

The app does allow measuring differences in neuromotor performance. Data collected by the app allowed us to assess performance differences due to the aging of the neuromuscular system.

Conclusions

Data collected through MotorBrain is suitable to make meaningful distinctions among different kinds of performance, and allowed us to highlight performance differences associated to aging. MotorBrain supports the building of a large database of neuromotor data, which can be used for normative purposes in clinical use.

1. Introduction

Human motor control is the process by which people use their neuromuscular system to coordinate and perform motor actions. It is crucial for regulating motion, balance, stability, coordination, and our interaction with the world [1,2]. Studies in the literature have shown that motor performance changes across the life span, i.e. it improves from childhood to young adulthood and then it gets worse with aging [3,4].

Paper-and-pencil tests, such as the Trail Making [5] and the Spiral Drawing [6] tests, are a traditional method that neurologists use to assess patients' motor skills or impairments. The Trail Making Test requires subjects to connect several targets in a predefined order without taking off the pencil from the sheet. Subjects have to be as fast and accurate as possible in finding and connecting the targets. The Spiral Drawing Test requires instead individuals to draw a spiral from the center with increasingly larger radius. The spiral is then compared to a set of previously rated spirals displaying varying degrees of motor impairments. However, such tests allow neurologists to carry out only a qualitative evaluation of users' motor performance (the only measurable variable is the time spent by users to complete the task). Thus, since they do not offer any method to record all users' actions and movements performed during the test, they do not allow neurologists to carry out quantitative analyses to distinguish and/or explain the specific motor behavior, and make comparisons among different tests.

Other methods rely instead on special hardware that allows recording users' movements. For example, the Finger Tapping Test [7] is a motor test in which subjects have to tap with a finger over a stimulus, e.g. a button or a musical keyboard, following a predefined pace. Subjects have to match the rate of tapping responses to the rate of the pacer stimulus.

The advent of technologies such as digitizing tablets or touchscreens offered neurologists new, more convenient, and more precise methods to carry out the above mentioned and other motor tests. Indeed, by connecting these devices to a computer, data about patients' motor skills can be automatically acquired and analyzed, see e.g. [8–13]. This computer-based approach could now be further improved by exploiting touchscreen-based mobile devices such as smartphones and tablets, which might allow their users to easily perform motor tests anywhere and periodically without the need of going to a hospital or a lab. The computational capabilities of current smartphones would also allow processing locally the collected motor skills data, and providing users with an assessment of their motor performance.

A tablet version of the Spiral Drawing Test has been proposed by Surangsrirat and Thanawattano [14] on the Android platform, while the Java-based app for Windows Mobile PDAs developed by Westin [15] included also the Finger Tapping Test. Recently, smartphone-based apps that contain the Finger Tapping Test have been employed in the studies described in [16,17]. However, all these mobile apps are designed to specifically target Parkinson's patients. Moreover, the applications presented in [14,15] require participants to carry out the motor tests with a stylus pen. Thus, their use is restricted to a specific medical condition or to specific stylus-operated mobile devices.

In this paper, we propose a mobile app (called "MotorBrain") for all major mobile platforms (Android [18], iOS [19], and Windows Mobile [20], which we released on the respective stores) that is able to turn millions of smartphones and tablets available to the general public into data collection and assessment tools. MotorBrain provides the user with different versions of Trail Making and Finger-Tapping Tests. We designed the interface of the app to make it easily usable by different kinds of patients as well as healthy individuals, and let them interact more naturally and directly with the tests by using their finger. In addition to providing a preliminary assessment of motor performance on the device, the app sends the acquired motor skills data to a remote server, in order to support the building of a normative database of individual motor skills data, which is currently unavailable in neurology. Such database could be used for different purposes. First of all, it can allow neurologists to study the aging of the population's neuromuscular system and, in particular, investigate the physiological aspects that are involved in the aging process, which have been identified only recently [21]. Second, it can offer neurologists the possibility to compare motor skills data acquired from a specific patient with normative data for the same age group. By highlighting possible differences from normative motor behaviors, this comparison can allow neurologists to carry out an early differential diagnosis of movement disorders, e.g. Parkinson's disease, which at present cannot be accurately detected until they clearly manifest in patients with the traditional detection methods, i.e. paper-and-pencil tests, electroencephalography, or neuroimaging, that are instead administered in the hospital when symptoms of a pathology have already showed up. Early differential diagnosis is important because it allows neurologists to timely start clinical treatments and reduce the negative effects that degenerative disorders have on patients. In particular, such diagnosis can be useful when patients show (i) slowness of movements, which can be due to Parkinson's and Parkinsonism syndromes, segmental, focal and occupational dystonia, and essential tremor, and (ii) difficulty of coordination, which can be due to the cerebellar and spinocerebellar degenerations. Moreover, the data collected by the app and its comparison with the normative database can also be useful for patients with sensory processing disorders, e.g. peripheral neuropathies, which can be due to diabetes, toxic substance consumptions, vitamin deficiencies, and autoimmune disorders.

Finally, the data collected by MotorBrain offers neurologists the possibility to study how individuals learn and/or improve a new motor skill over time. Such information can be used to guide the rehabilitation process of a movement disorder. Indeed, the comparisons of data from a single patient with the normative database can allow assessing whether the differences that were due to a movement disorder have decreased over time as a result of pharmacological or physical therapies. These comparisons can also be used by neurologists for carrying out a follow-up of the efficacy of a therapy, and for assessing the evolution of a movement disorder over time.

In summary, our app significantly extends the population that can be assessed, makes it much easier for users to perform motor tests, increases the number of opportunities and the contexts in which users can assess their motor skills, and supports additional purposes other than individual assessment, in particular neurological studies, differential diagnosis and follow-up of movement disorders, and motor functions rehabilitation.

MotorBrain is the final outcome of an interactive user-centered design process. Starting from an initial prototype, we went through several iterations with samples of users in order to progressively increase comprehension and usability of the app. This paper first illustrates in detail the final design of MotorBrain that resulted from such process. Then, it presents the study we carried out to determine whether the data collected by MotorBrain is actually meaningful in the assessment of users' motor performance, and could thus also support the building of a normative database to be used by neurologists for better characterizing the normal motor behavior of the population and how it changes with aging.

2. Materials and Methods

2.1. The proposed application

MotorBrain was developed in Unity [22] for all three major mobile operating systems, i.e. Android, iOS, and Windows Mobile (interested readers can freely try it on such platforms [18–20]).

The app offers six motor tests organized in three categories based on the characteristic of motor control on which they primarily focus, i.e. accuracy, speed, or reaction time (in the following, *requirements*). Each category contains two motor tests that are presented to the user in a fixed order and require to be performed twice, first with user's dominant hand and then with the non-dominant one. Both times, the user has to interact with the index finger.

The first time the user launches the app, only one category is enabled and the completion of all the tests in that category enables the next one (Figure 1).

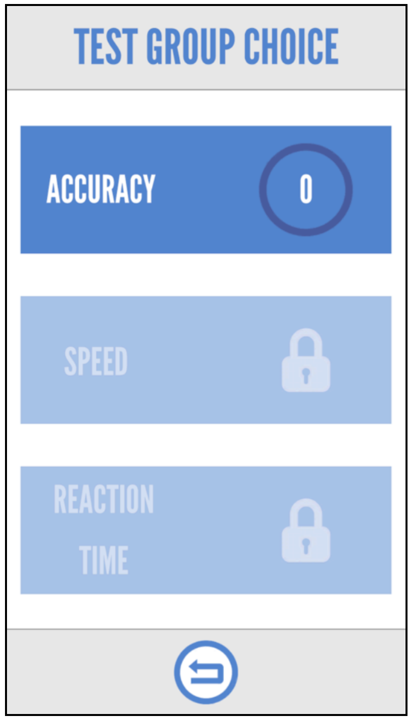


Figure 1: "Test Group Choice" menu of the MotorBrain app. In this figure, the "accuracy" category is the only one enabled. For enabled categories, the number on the right indicates how many times the user has completed all the tests in the category, while the circle surrounding the number indicates (in white) the percentage of completion of the category.

Each of the six motor tests requires three repetitions of a task with the same hand to produce an assessment. Once users have completed the three trials, the app displays an assessment of motor performance concerning the test and the hand used.

2.1.1. Screen organization

In all motor tests, the screen is organized into three parts (see Figure 2 for an example): (i) the upper one provides users with the task instructions, (ii) the central one (hereinafter, *task area*) contains the graphic elements on which the user performs the task, and (iii) the lower one indicates the number of completed trials for the current test. For each motor test, the application checks the pixel density and the resolution of the device display and scales the graphical elements on which to perform the task to make sure they are displayed with the same size, regardless of the specific model of mobile device used. To draw the graphical elements with the sizes reported in Section 2.1.2 and make user's performance comparable across different devices, the diagonal display size of the device should be 4 inches or more (a requirement that is met by most recent smartphones, and by tablets). If the app is run on a phone with a tiny display (less than 4 inches), it has to reduce the size of graphical elements because the space available is insufficient: this allows the user to run the app even on a tiny screen and to compare results obtained with similar tiny displays, but such results must not be compared with those of the majority of users who have large enough displays to draw the graphical elements with the correct size.

2.1.2. Motor tests

The app offers four Trail Making Tests (respectively referred to as CIRCLE-A, SQUARE, PATH, and CIRCLE-S in this paper) and two Finger-Tapping Tests (referred to as TAPPING2 and TAPPING4 in this paper). In this section, we describe in detail each test, following the same order in which tests are presented to users by the app (the assessed requirement is highlighted between brackets):

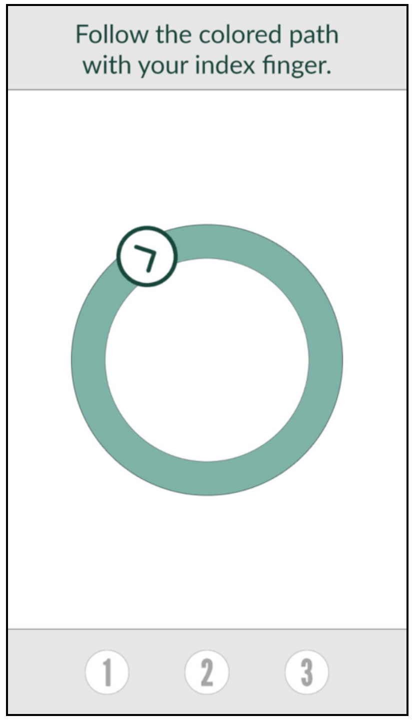


Figure 2: CIRCLE-A motor test

- CIRCLE-A (accuracy): The task area (see Figure 2) contains a ring (thickness=0.5 cm, diameter of outer circle=4 cm). Users have to move their index finger on the ring, following it all over its length once and without ever lifting the finger. The starting point and the direction of movement depend on the hand with which the user has to perform the test. For the right (left) hand, the starting point is located 30° on the left (right) with respect to the vertical diameter of the outer circle and the movement must be performed in the clockwise (counterclockwise) direction. A trial ends when the user has covered a distance equal to the mean between the perimeter length of the outer and inner circle of the ring, considering his/her movements over any location of the task area, or when (s)he has lifted the finger from the screen for more than 0.15 s.

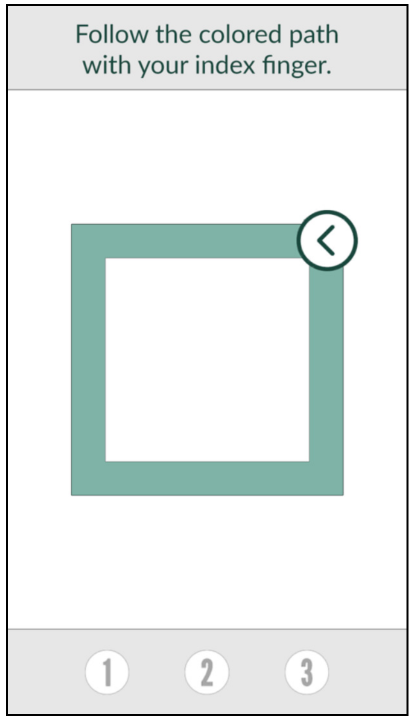


Figure 3: SQUARE motor test.

- SQUARE (accuracy): The task area (see Figure 3) contains a square frame (thickness of the frame=0.5 cm, side of the outer square=4 cm). Users have to move their index finger on the frame, following its entire length once and without ever lifting the finger. As in CIRCLE-A, the starting point and the direction of movement depend on the hand used. For the right hand, they are the upper left vertex of the frame and the clockwise direction; for the left hand, they are the upper right vertex of the frame and the counterclockwise direction. A trial ends when users lift the finger for more than 0.15 s or when they have covered a distance equal to the mean between the perimeter length of the outer and inner square, considering their movements over any location of the task area.

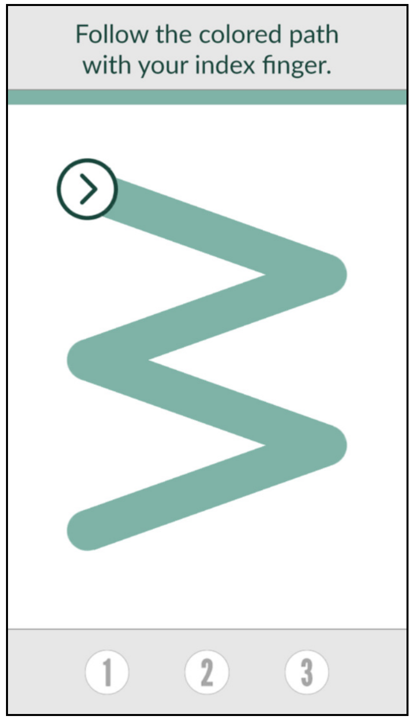


Figure 4: PATH motor test.

- PATH (speed): The task area contains a path (see Figure 4) composed by four connected lines (line thickness=0.6 cm, length of each line=3.72 cm, angle between each pair of connected lines=19.8°). The path starts either in the upper-left part of the task area (test for the right hand) or in the upper-right part (test for the left hand). Users have to move the index finger from the start to the end of the path as fast as possible within a 5-second interval. The timer starts when the user touches the starting point and time remaining is displayed by a decreasing green bar at the top of the task area (in Figure 4, the bar is indicating that the user has all the available time at disposal). A trial ends when time expires, when users lift the finger from the screen for more than 0.15 s, or when they have covered a distance equal to the path, considering their movements over any location of the task area.

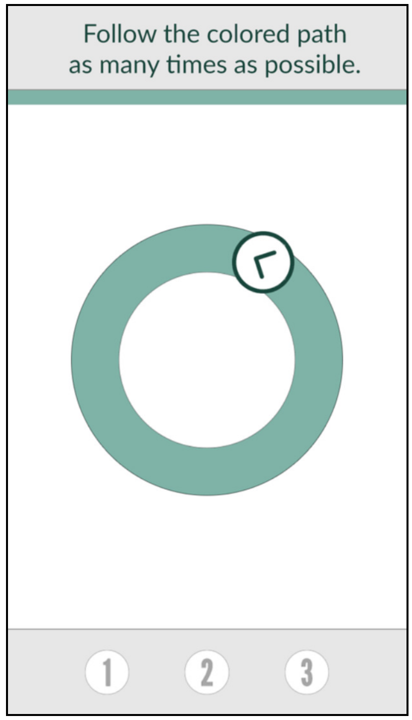


Figure 5: CIRCLE-S motor test.

- CIRCLE-S (speed): The graphic elements of this test (Figure 5) are the same of CIRCLE-A, but the thickness of the ring is larger (0.7 cm) and a time bar is added at the top of the task area. Users have to move the index finger over the ring following its entire length as many times as possible during a 7-second interval. The timer starts when the user touches the starting point and time remaining is indicated as in PATH. A trial ends when time expires or when users lift the finger from the screen for more than 0.15 s.

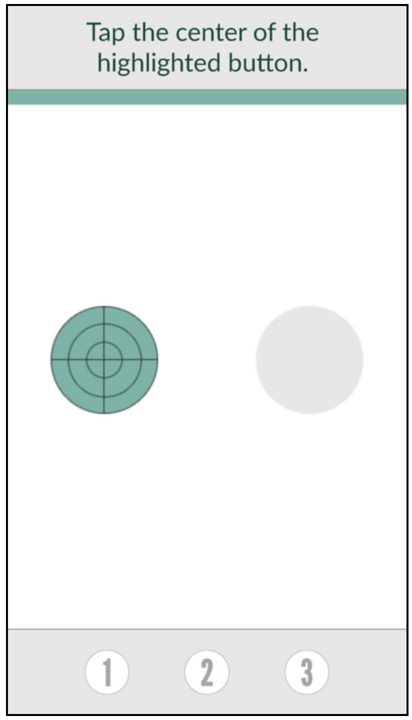


Figure 6: TAPPING2 motor test.

- TAPPING2 (reaction time): The task area (see Figure 6) contains two aligned round buttons (button diameter=1.6 cm). Only one button is enabled at any time. The enabled button is visually highlighted by color as well as a black viewfinder. The viewfinder is made of three concentric circles that divide the button area in three parts (*central, middle, external*). When a button is disabled, it is displayed in light grey and has no viewfinder. Users have to tap the highlighted button trying to hit the center of the viewfinder with the index finger. A black circle is shown as a feedback where the user has tapped on the screen (see Figure 7). Tapping a highlighted button (considering also taps made up to 0.2 cm out of the external part of the viewfinder) moves the highlight to the other button (after 0.15 s) and users have to tap on as many highlighted buttons as possible over a 10-second interval. The button that is initially highlighted depends on the hand with which the user has to perform the test: left button for the right hand and right button for the left hand. The timer starts when the user taps on the first highlighted button and time remaining is indicated as in the previously described timed tests.

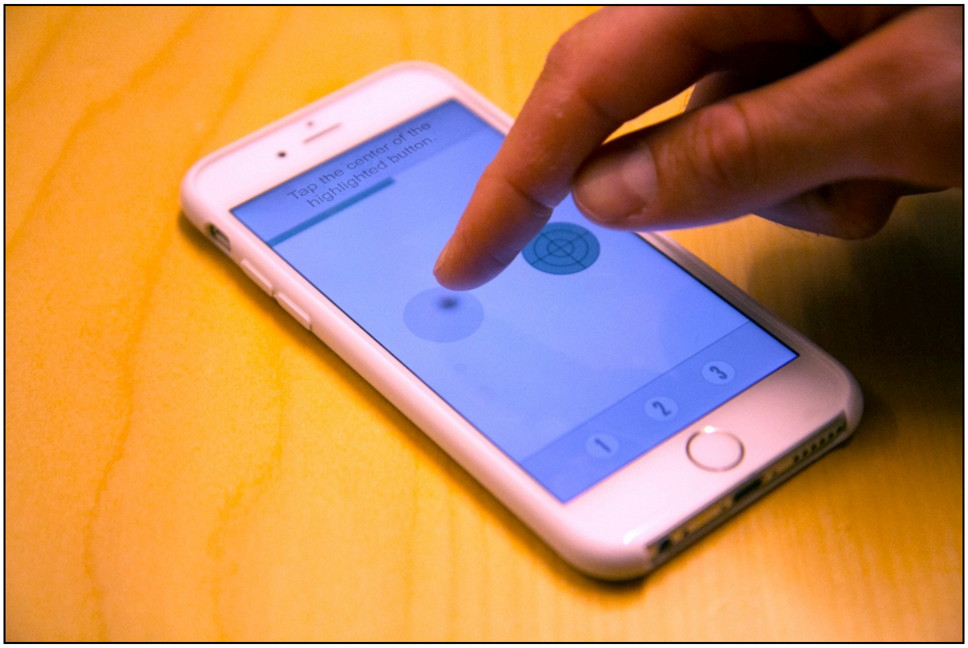


Figure 7: Feedback provided by the TAPPING2 motor test. The black circle on the screen indicates the position on which the user has just tapped. In this picture, the smartphone is kept on the table for demonstrative purposes.

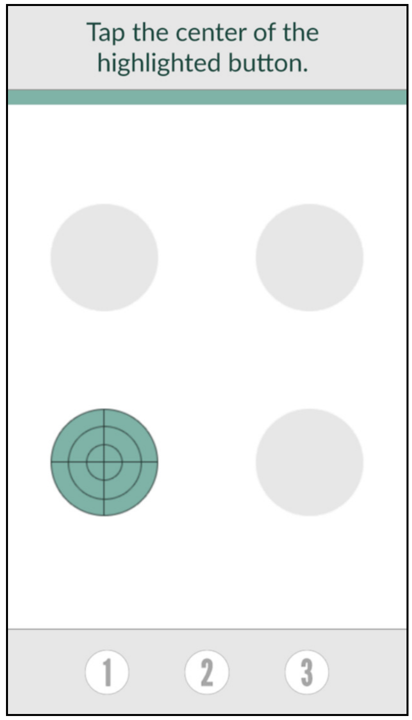


Figure 8: TAPPING4 motor test.

- TAPPING4 (reaction time): The task area contains four buttons (Figure 8). The buttons are of the same type of those in TAPPING2 and only one of them is highlighted at any time. Tapping a highlighted button (or at least up to 0.2 cm out of the external part of the viewfinder) moves the highlight to another (randomly selected) button. Unlike TAPPING2, the initial highlighted button is randomly selected, regardless of the hand with which the user has to perform the test. Users have to tap on the center of as many highlighted buttons as possible over a 10-second interval and a black circle is shown as a feedback where the user has tapped on the screen (see Figure 9).

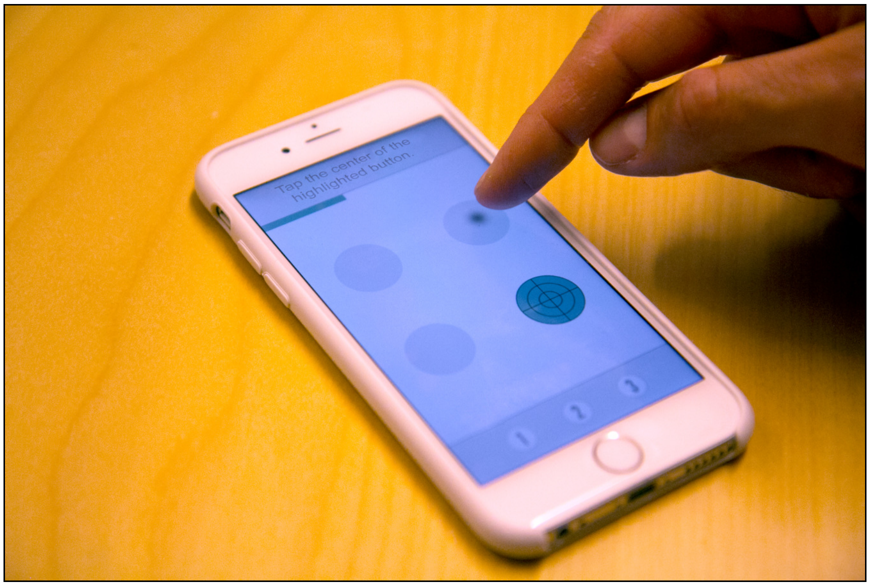


Figure 9: Feedback provided by the TAPPING4 motor test. The black circle on the screen indicates the position on which the user has just tapped. In this picture, the smartphone is kept on the table for demonstrative purposes.

2.1.3. Pre-test tutorials

When users choose a motor test category, they are presented with a tutorial of the motor test they have not yet performed in that category. The tutorial explains, through short texts, the actions required to perform the task and the requirement that will be assessed. To help users understand what they have to do, the tutorial allows them to perform the required actions two times (see Figure 10 for an example).

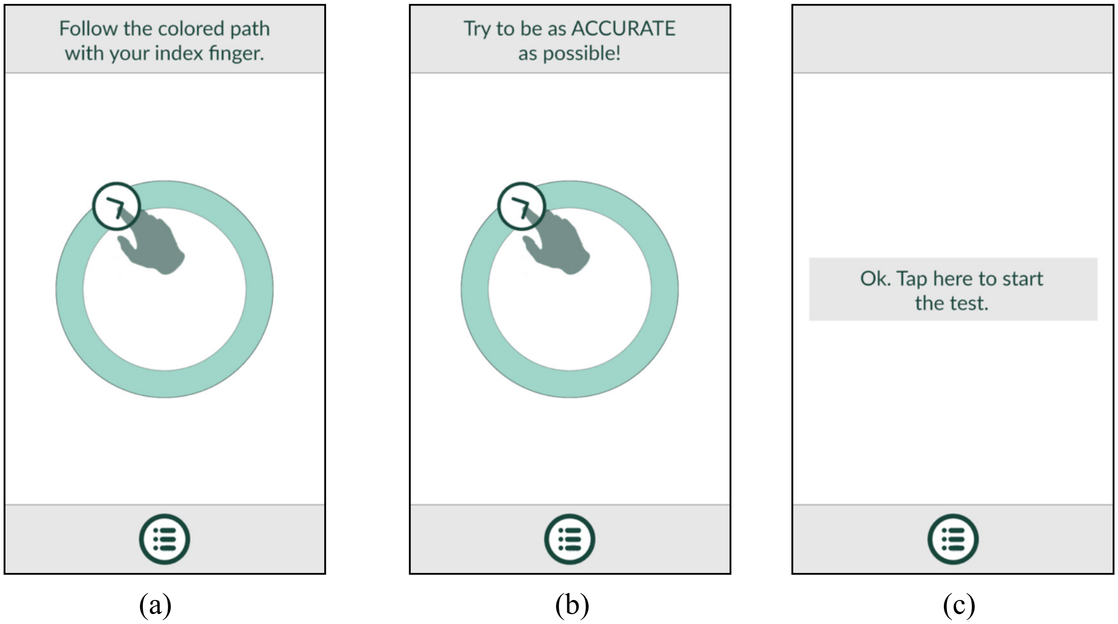


Figure 10: Tutorial of the CIRCLE-A motor test: (a) the first screen shows the instructions to play and invites the user to try the task, i.e. follow the circle, by indicating the starting point with an hand icon and lighting up the colored path; (b) the second screen explains what features of user's performance are important (in capital letters) and allows the user to try the task a second time; (c) the third screen ends the tutorial and allows the user to start the motor test. In the timed tests, i.e. PATH, CIRCLE-S, TAPPING2, and TAPPING4, the first and the second screens of the tutorial show also the decreasing green bar. Users are then invited to try the task within the available time, which is set to 5 seconds for all those tests.

For the motor tests in the "speed" and "reaction time" category, the second screen of the tutorial invites users to be also as accurate as possible when performing the required task (in the following, *second requirement*) (see Figure 11 for two examples).

(a) (b)

Figure 11: Second screen of the tutorial for the PATH (a) and TAPPING2 (b) motor tests respectively, which invites users to be also as accurate as possible when performing the required task.

2.1.4. Assessed variables and data collection

When the user completes a motor test, the app shows the "Assessment" screen for that test (see Figure 12 for an example). The screen includes two buttons, one to perform the next test and one to go back to the "Test Group Choice" menu.

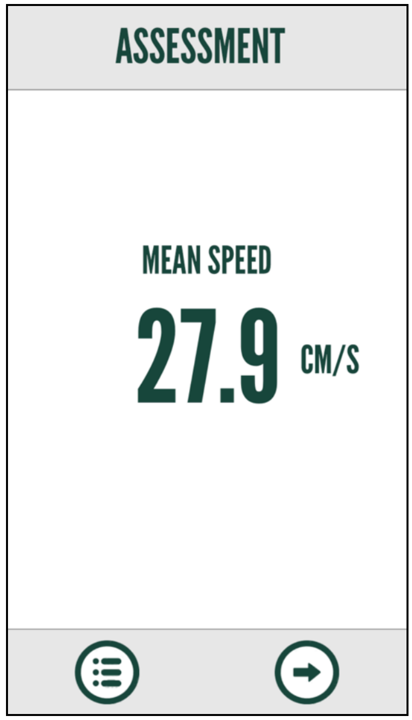


Figure 12: Assessment screen of the CIRCLE-S test.

To provide users with an assessment of their motor performance, we took inspiration from the measures employed by other studies that evaluated users' motor skills in terms of accuracy, speed and reaction time, e.g. [13,23,24], and adapted them to the motor tests offered by MotorBrain. In the following, we describe the variables that the app computes during each trial considering the requirement of the corresponding motor test:

- accuracy (CIRCLE-A, SQUARE): distance covered by the user with the index finger on the ring (CIRCLE-A) or the frame (SQUARE) in the direction associated to the hand used, expressed as a percentage of the target distance. As explained in Section 2.1.2, the target distance is the mean between the perimeter length of the outer and inner circle of the ring in CIRCLE-A and the mean between the perimeter length of the outer and inner square in SQUARE;

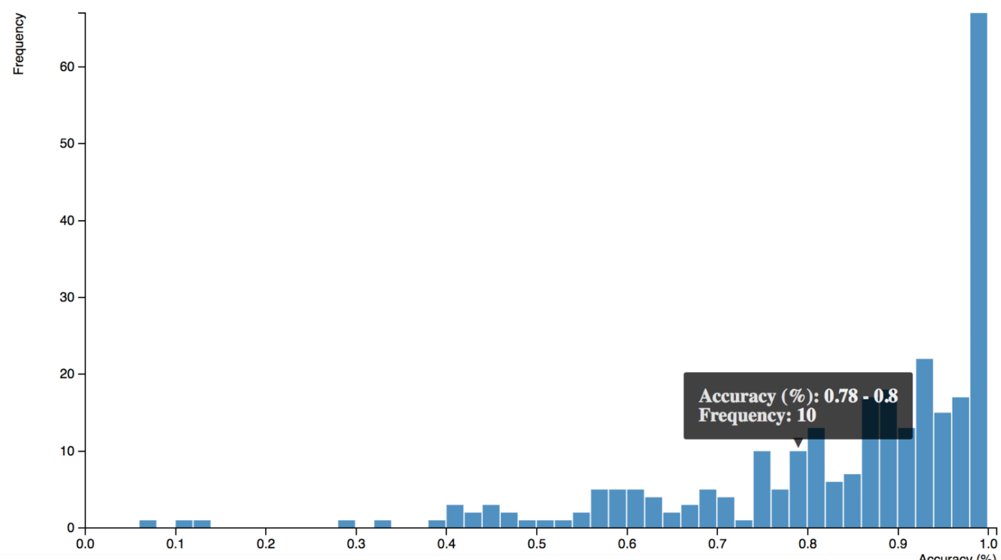
- speed (PATH, CIRCLE-S): mean speed (in cm/s) of the user's finger when performing the required movements, calculated considering the amount of distance covered on the ring in CIRCLE-S and on the path in PATH, and time (s)he spent in performing the movements.
- reaction time (TAPPING2, TAPPING4): mean of all the reaction times (in seconds), i.e. time elapsed between the appearance of a highlighted button on the screen and user's tapping on that button during the trial. For the calculation, the first tap is not considered since the user could wait some time before starting the test, thus providing a higher reaction time than the ones (s)he could provide from the subsequent taps.

For each motor test, the assessment displayed by the app is the mean of the three values of the variable assessed with the three trials. If the app is used in clinical settings, such assessment can allow neurologists to carry out a preliminary evaluation of a patient's motor performance and/or detect the presence of motor impairments.

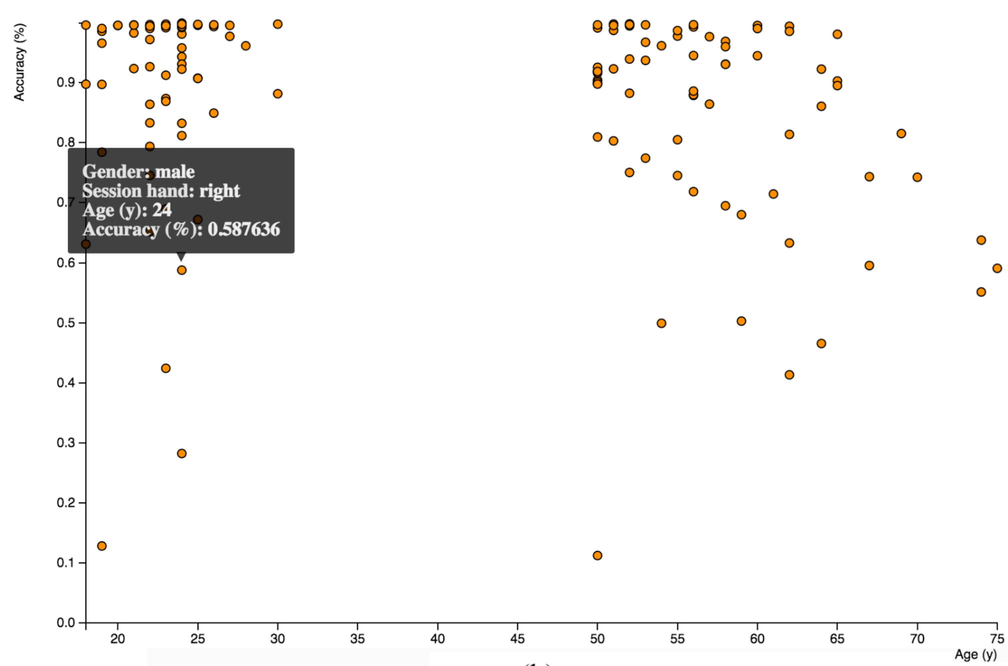
All data required to compute these assessments is automatically recorded by the app with an event-driven sampling: each time the user touches the screen or changes finger position on the screen, the coordinates in pixels and the timestamp of the event are automatically saved. The availability of this data supports more detailed off-line analyses of users' motor performance, such as those we carried out in the study (described in Section 2.2). For the purpose of off-line analyses, the app collects also the screen resolution and pixel density of the device, the coordinates in pixels of the graphical elements in the task area, and the number of seconds the user spent to perform a trial.
In particular, all the data collected by the app is then sent to a server in a secure way at the end of each motor test, and saved in a relational MySQL database [25] (stored in a secure server at our university). In this way, the data can be accessed by tools that support more complex off-line analyses. We are currently building a web-based interface using PHP [26], Python [27], and D3.js

[28] to access the stored database and provide visualizations of accuracy, speed, and reaction time, organized by motor test and age group.

Figure 13 shows two examples of such web visualizations (bar chart and scatterplot), generated from the data we collected for the study described in Section 2.2, focusing on the CIRCLE-A motor test and the accuracy of motor performance.



(a)



(b)

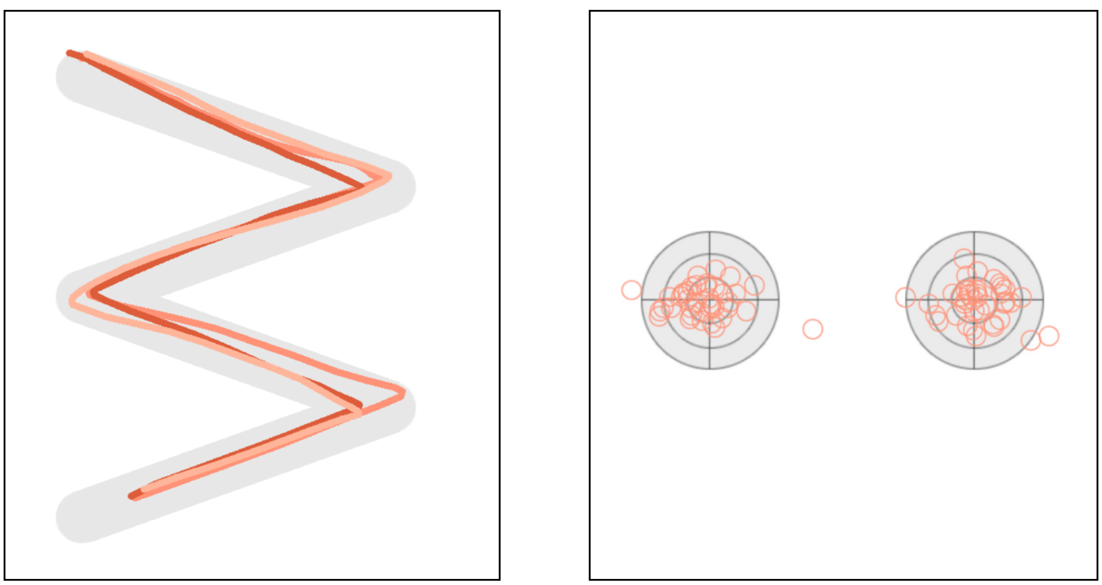
Figure 13: Examples of a bar chart (a) and a scatterplot (b) created with our web-based interface. The two visualizations focus on the CIRCLE-A motor test and accuracy of motor performance. The bar chart shows the number of trials for each accuracy interval (expressed in decimal format). The scatterplot displays the relationship between the accuracy of each trial and the age of the participant who performed it. Both bar chart and scatterplot are interactive: users can obtain more detailed information by pointing the mouse on a specific bar or point, respectively.

For the off-line analysis carried out in the current study, we calculated the following variables (*performance assessments*) for each trial:

- Shape Accuracy (SA) (CIRCLE-A, SQUARE, PATH, CIRCLE-S): for CIRCLE-A and SQUARE this variable is the same as the *accuracy* defined before, but here it is expressed in decimal format. For CIRCLE-S, the variable is calculated in the same way as in CIRCLE-A; for PATH this variable is the distance covered by the user with the index finger over the path with respect to the length of the path (expressed in decimal format).
- Tap Accuracy (TAPPING2, TAPPING4): this variable is calculated with the formula $\frac{\sum_{i=1}^{(N-1)} w_i}{(N-1)*5}$, where *(N-1)* are the total taps made by the user after discarding the first one, and for each tap the value of w_i can be 1, 2, or 5 depending on whether the user tapped the external, middle or central area of the viewfinder, respectively. The maximum value reachable by tap accuracy, i.e. 1, reflects the situation in which the user tapped the center of each highlighted button.
- Speed on Graphic Element (SGE) (PATH, CIRCLE-S) this variable is the same as the *speed* defined before.

- Speed on Task Area (STA) (PATH, CIRCLE-S): this variable is the mean speed of the user (in cm/s) calculated considering the amount of distance covered inside the entire task area.
- Reaction Time (RT) (TAPPING2, TAPPING4): this variable is the same as the *reaction time* defined before.

In addition, considering the three trials in a motor test, a bidimensional visualization (Movement Visualization) is generated on the server to show user's movement trajectories inside the task area (CIRCLE-A, SQUARE, PATH, CIRCLE-S). For TAPPING2 and TAPPING4, this graph contains all the points where the user tapped on the screen. Figure 14 shows two examples generated from the data collected by the PATH and TAPPING2 motor tests, respectively.



(a) (b)

Figure 14: Movement Visualization for the PATH (a) and TAPPING2 (b) motor tests. The graphic elements on which the user performed the task are displayed in grey. For PATH, the orange lines show user movements. In this example, three different trials are shown (to better distinguish the three lines for PATH, a different shade of orange is used for each of them). For TAPPING2, the orange dots indicate where the user tapped on the screen.

2.2. Study

The goal of the present study was to evaluate whether the data collected by MotorBrain can be meaningful for describing aging in human motor performance.

2.2.1. Participants

Participants (N=133, 67 M, 66 F) were recruited on a voluntary basis through direct contact with a snowball sampling approach, asking them if they were willing to try a mobile app that offers an assessment of their motor performance. Participants that agreed were then asked to indicate their handedness, i.e. with which hand they normally write or interact with the touchscreen, and all of them answered to be right-handed. During the study, none of them suffered from: (i) headache or migraine, or (ii) any illnesses or pain at the wrist, elbow, or hand. Moreover, none of them were under the effects of drugs or abused substances that could impair performance. Then, they were further divided into two groups (Young, Old) based on their age (less than or equal to 30 years, greater than or equal to 50 years, respectively).

The Young group consisted of 68 participants (39 M, 29 F) whose age ranged from 18 to 30 (M=22.97, SD=2.56). The Old group consisted of 65 participants (28 M, 37 F) whose age ranged from 50 to 75 (M=56.68, SD=6.33). Participants were asked to perform the six motor tests with the index finger of both hands. When performing the test with one hand, they had to keep the smartphone in the other hand. They were asked by the experimenter to repeat the entire motor test in those cases when they made *wrong movements,* i.e. (i) did not move the finger in the right direction for the hand used, e.g. they followed the ring in CIRCLE-A in the counterclockwise direction when performing the test with the right hand, (ii) did not follow with the finger the colored shape, e.g. they moved the finger outside the frame in SQUARE, (iii) started the test with the wrong hand, or (iv) lifted the finger from the screen before the completion of the test. Participants did not receive any previous training or illustration of the app from the experimenter. This was done to check that the tutorial and the user interface were clear, intuitive, and immediately usable as planned. All the instructions for using the app were provided by the tutorial as illustrated in Section 2.1.3.

2.2.2. Ethics

Since all the data collected by the app was anonymized, and the study involved no risk of harm to users, formal ethical approval was not required by Italian regulations. Consent from participants was obtained, and they were informed that the collected data was going to be used for the present research study only in anonymized form.

2.2.3. Measures

Since all participants were right-handed, for the purpose of this study we considered all trials performed with users' right hand, consistently with other studies in the literature, e.g. [21,23]. Then, we calculated the mean of the performance assessment variables described in Section 2.1.4.

3. Results

All participants were able to understand the instructions received by MotorBrain and use the app and its interface.

The app collected data from all trials, including those in which participants made wrong movements. Therefore, prior to the calculation of the performance assessment variables, we quantitatively and qualitatively (through the Movement Visualization) analyzed the collected data to detect and discard such cases. For TAPPING2 and TAPPING4, we also analyzed the data for outliers and discarded those cases where the number of taps was below the 10th percentile. Overall, based on these analyses, we discarded 149 trials.

Table 1 reports the means of the performance assessment variables for the resulting trials for each motor test and age group. The table indicates also the results of the non-parametric *Wilcoxon* *signed-rank test* we employed to assess the statistical significance of differences between the two groups, since none of the assessed variables follow a normal distribution.

Table 1: Means of the performance assessment variables for each motor test and age group. The last column provides the results about statistical significance of the differences between the two groups. NT indicates number of trials.

Test	Variable	Young group	Old group	Wilcoxon test
CIRCLE-A				
	SA	NT=194, M=0.93, SD=0.13	NT=194, M=0.89, SD=0.14	U=23451, p<.001, r=.21
SQUARE				
	SA	NT=204, M=0.94, SD=0.11	NT=196, M=0.87, SD=0.15	U= 27612, p<.001, r=.33
PATH				
	SA	NT=215, M=0.86, SD=0.06	NT=214, M=0.87, SD=0.06	U=19930, p<.05, r=.12
	SGE	NT=215, M=10.55, SD=4.63	NT=214, M=7.88, SD=3.35	U=30678, p<.001, r=.29
	STA	NT=215, M=10.59, SD=4.62	NT=214, M=7.97, SD=3.30	U=30571, p<.001, r=.28

CIRCLE-S				
	SA	NT=181, M=0.80, SD=0.16	NT=180, M=0.89, SD=0.12	U=10439, p<.001, r=.31
	SGE	NT=181, M=14.98, SD=5.64	NT=180, M=11.86, SD=5.37	U=22011, p<.001, r=.30
	STA	NT=181, M=19.90, SD=8.92	NT=180, M=13.98, SD=7.56	U=23161, p<.001, r=.36
TAPPING2				
	TA	NT=209, M=0.81, SD=0.14	NT=196, M=0.85, SD=0.12	U=17643, p<.05, r=.12
	RT	NT=209, M=0.20, SD=0.12	NT=196, M=0.35, SD=0.23	U=10558, p<.001, r=.42
TAPPING4				
	TA	NT=201, M=0.78, SD=0.13	NT=192, M=0.76, SD=0.13	U=20384, p=.33
	RT	NT=201, M=0.50, SD=0.05	NT=192, M=0.63, SD=0.26	U=7149.5, p<.001, r=.54

In the following, we briefly describe the obtained result for each motor test.

3.1. CIRCLE-A

The analysis revealed a significant difference ($p<.001$) between the SA scores of the two groups: accuracy of participants in the Old group was lower than the one of participants in the Young group when performing this motor test.

3.2. SQUARE

The analysis outlined a significant difference ($p<.001$) between the SA scores of the two groups: participants in the Old group were less accurate than those in the Young group when performing this motor test.

3.3. PATH

The analysis revealed a significant difference ($p<.05$) between the SA scores of the two groups: participants in the Old group were more accurate than those in the Young group when performing this motor test. Results outlined also a significant difference ($p<.001$) between the SGE scores, and a significant difference ($p<.001$) between the STA scores of the two groups: speed on both the graphic element and the task area of participants in the Old group was lower than the one of participants in the Young group.

3.4. CIRCLE-S

The analysis outlined a significant difference ($p<.001$) between the SA scores of the two groups: accuracy of participants in the Old group was higher than the one of participants in the Young group. Results revealed also a significant difference ($p<.001$) between the SGE scores, and a significant difference ($p<.001$) between the STA scores: speed on both the graphic element and the task area of participants in the Old group was lower than the one of participants in the Young group when performing this motor test.

3.5. TAPPING2

The analysis revealed a significant difference ($p<.05$) between the TA scores of the two groups: accuracy of participants in the Old group was higher than the one of participants in the Young group. Results outlined also a significant difference ($p<.001$) between the RT scores: reaction time of participants in the Old group was higher than the one of participants in the Young group when performing this motor test.

3.6. TAPPING4

The analysis revealed a significant difference ($p<.001$) between the RT scores of the two groups: reaction time of participants in the Old group was higher than the one of participants in the Young group when performing this motor test. For the TA scores of the two groups, the analysis found no significant difference.

4. Discussion

The literature on the aging of motor control has been extended only recently with quantitative observations of *motor synergies*, i.e. the synergetic action of elements within the system for movement production such as limbs, joints, digits, muscles, and motor units [29]. Indeed, the observation of a particular motor synergy can explain phenomena that involve the upper-limb such as (i) the muscle coordination necessary to perform motor tasks (*Synergy-B*), and (ii) the motor redundancy needed to perform pointing tasks that require stability (*Synergy-C*), but also more complex mechanisms such as (i) anticipatory postural adjustments (APAs), i.e. the postural preparation to fast arm movements or load manipulations, and (ii) anticipatory synergy adjustments (ASAa), i.e. changes in synergy indices in preparation to a whole-body action, see [29] for a review. In particular, studies in the literature revealed that Synergy-B and -C change with aging by affecting muscle coordination [30] and the control of the hands' fingers [31,32], respectively, while both APAs and ASAs mechanisms occur with delay and reduced extent in older adults [33,34].

Changes in motor synergies can also explain the onset of some movement disorders, such as the muscular spasticity (*Synergy-A*) [35,36] and the modification of patterns of movement [37] that typically appear after a cortical stroke, or the loss of ASAs mechanisms of both hands' fingers in Parkinson's patients [38,39].

However, more studies are needed to better investigate the aging of motor control and the onset of movement disorders. The availability of a large dataset of individual motor performance can be useful for this purpose, since it can allow better explaining the above-described motor synergies and the changes that occur in them when a movement disorder is still in subclinical stage.

The purpose of the present study was to assess whether the data collected by the MotorBrain app can be suitable for building such normative database. We will discuss the obtained results in the following.

The fact that all participants were able to understand and use MotorBrain without having previous knowledge about the app suggests that people can directly use MotorBrain in their everyday settings, without the need of external help. In particular, since participants in the Old group did not experience problems when using the app, results suggest that MotorBrain can be suitable for use by older adults who are in general less familiar with smartphones than younger people. Moreover, a recent market research [40] revealed that the gap between people over-55 and younger generations in terms of smartphone penetration is going to decrease in the next few years. However, the report also underlines that very few apps are designed for this age group. Thus, MotorBrain can offer an assessment of motor skills to a wider sample of the population than traditional tools, and can support the building of a normative database that includes people from different age groups, a characteristic that makes it very useful for neurological studies, differential diagnosis and follow-up of movement disorders, and motor functions rehabilitation.

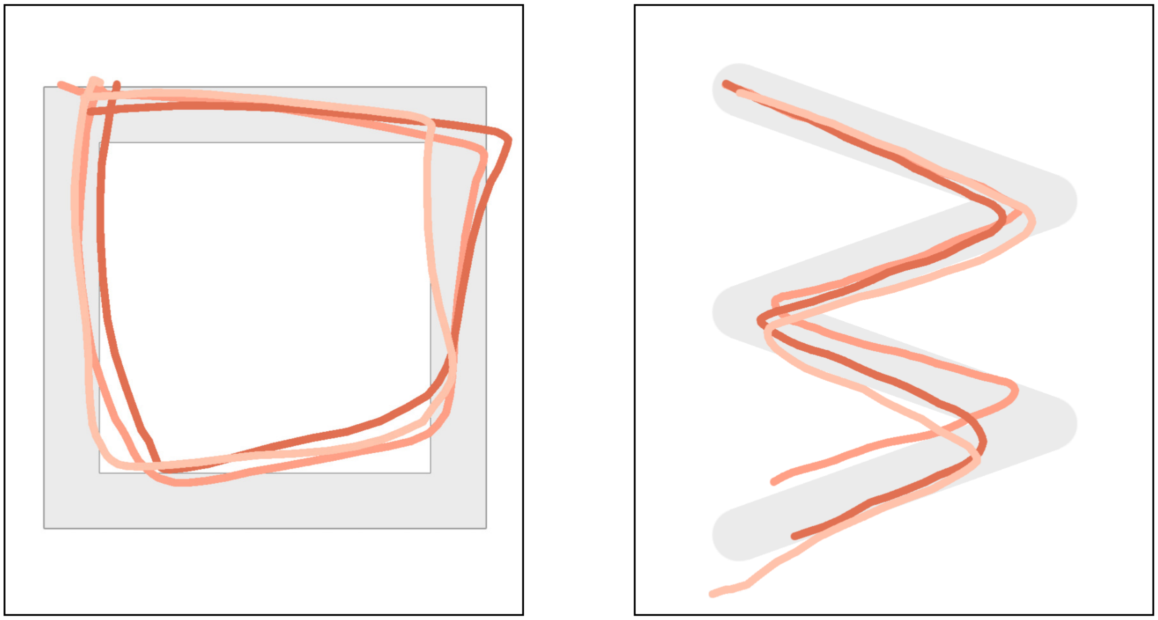
The analysis of the performance assessment variables for participants' dominant hand revealed that accuracy was lower for the Old group than the Young group on those tests where the requirement was accuracy, i.e. CIRCLE-A and SQUARE. This result is consistent with the decline in sensorimotor control and functioning that comes with aging [4], which might include a deterioration of spatial coordination of finger and wrist movements [41].
In the tests which focused on speed and reaction time, the Old group performed worse than the Young group. Indeed, speed on both the graphic element and the task area of participants in the Old group was lower in the PATH and CIRCLE-S tests, while in the TAPPING2 and TAPPING4 tests reaction time in the Old group was higher than the Young group. These results can be explained by the loss of performance of the central and peripheral nervous systems and of the neuromuscular system that occur with aging [4,24,42,43]. Such changes include a reduced conduction velocity in nerve fibres, a reduction of muscle elasticity, and an increased musculoskeletal rigidity that affects muscle activation and coordination in the initial stages of movement. All these deficits affect motor control and can result in slower movement and higher reaction times in older adults [4,24,42,43]. The reduction in speed and the increase in reaction time in the Old group can also explain the fact that the second requirement, i.e. accuracy, was higher for the Old group in the PATH, CIRCLE-S, and TAPPING2 tests, while no differences were found between the two groups in TAPPING4. Indeed, by slowing their movements, participants in the Old group could have performed a repetitive task (TAPPING2) or followed a shape (PATH, CIRCLE-S) more accurately. In the case of a less predictable task that can be more prone to errors, i.e. the one required by TAPPING4, slower movements could have helped the Old group focus on the center of each highlighted button and thus maintain the same level of accuracy as younger participants.

Finally, it must be noted that both web visualizations (see Figure 13) and Movement Visualization (see Figure 14) can be useful to qualitatively observe interesting characteristics of motor control at the population or individual level, respectively.

Indeed, web visualizations can be used by neurologists to study the normal motor behavior of the population and how it changes with aging, once the publicly available MotorBrain app will have collected a large database of individual motor skills data.

Considering Movement Visualization, since our study involved healthy participants, we employed it to detect wrong movements, such as when participants lifted the finger before the completion of the test. However, its use can be extended to individuals with movement disorders for outlining motor control impairments. For example, in the SQUARE and PATH tests, inaccuracy of trajectories across the corners of the path can be helpful for highlighting rigidity or slowness in initiating a new movement, which are typical of Parkinson's disease [44], and have been used in [45]. As a preliminary test, we have recently used the app with eight patients with movement disorders and, predictably, their results were very different both qualitatively and quantitatively from the sample analyzed in this paper. We include in Figure 15 an example of Movement Visualization for such two motor tests that have been carried out by a patient with postural instability (male, aged 71, right-handed, diagnosed with mild cognitive impairment) – the quantitative assessment provided by the app after three trials was: accuracy 0.60 for SQUARE (reported here in decimal format) and speed 6.3 cm/s for PATH. For both tests, the Movement Visualization shows the patient's general inability of following the path correctly. In particular, it highlights his difficulties in stopping and initiating a new movement across the corners of the paths, i.e. actions that happen instead before or after the corners, and his tendency of cutting them (especially in the SQUARE test).

In addition to these qualitative considerations, the quantitative assessment provided by the MotorBrain app outlines the patient's lower accuracy and slowness of movements compared to the healthy sample of participants of the same age group analyzed in this paper, whose mean accuracy and speed were 0.87 (SQUARE) and 7.88 cm/s (PATH), respectively.



(a) (b)

Figure 15: Movement Visualization for the SQUARE (a) and PATH (b) motor tests that have been carried out by a patient with postural instability (male, aged 71, right-handed, diagnosed with mild cognitive impairment). For both tests, the Movement Visualization shows the patient's general inability of following the path correctly (especially across the corners).

To sum up, other than building a normative database of normal motor behavior, the data collected, computed, and displayed by MotorBrain offers neurologists the possibility to carry out quantitative and qualitative assessments of individuals' motor performance, which can allow them to detect movement disorders when they are still in subclinical stage. This makes the app a better assessment tool than traditional detection methods, which can only be administered in the hospital when symptoms of a pathology have already showed up.

5. Conclusion

By contrasting performance assessment variables obtained with MotorBrain in the two age groups, we obtained results that are consistent with those of studies conducted with digitizing tablets, desktop computers, or ad-hoc surfaces, e.g. [13,23,24]. Unlike such devices, MotorBrain exploits smartphones as a more convenient and low-cost solution, which is accessible to and easily usable by a wide population of users.

The obtained results show that the data collected through the MotorBrain app is suitable to make meaningful distinctions among different kinds of performance, such as accuracy, speed, and reaction time, and is able to highlight performance differences due to aging. This is promising with respect to the next goal of the research, i.e. to collect large datasets of human motor performance by making the MotorBrain app freely available to the general public through on-line app stores.

In our future work, we will explore if an instrument that is able to detect motor performance differences due to aging such as MotorBrain can be useful to detect the presence of movement disorders that totally or marginally involve the upper-limb when they are still in a subclinical stage, which cannot be detected by physician’s clinical observation by using traditional detection methods, i.e. paper-and-pencil tests, electroencephalography, or neuroimaging. This will be done by conducting detailed clinical assessments of subjects who are outliers in their age group in the analysis of MotorBrain data. For example, the Movement Visualization of these subjects on a single test trial can be quantitatively compared to predefined templates of the same test, or qualitatively rated by experts, to identify motor impairments.

We will also study the possibility to use the app as an instrument in rehabilitation: patients could perform the motor tasks repeatedly over a period of time and clinicians could receive an assessment of possible motor learning obtained through such training. This can allow neurologists to assess whether the effects of a movement disorder have decreased over time as a result of pharmacological or physical therapies.

Overall, to support the two above-described usages of the app in clinical setting, i.e. detection of movement disorders and rehabilitation, we will include an extra feature to the app that will allow neurologists to enter an identification code for each patient and then retrieve such data, which will be sent and stored into a separate database (for example, local to their hospital). In case of hospital use with patients, neurologists will have to apply the privacy and ethics procedure they routinely follow for medical tests.

Finally, when the publicly available MotorBrain app will have acquired a large dataset of individual motor characteristics such as speed and accuracy of movement, we will explore the use of normative data with theoretical models of motor control that aim to explain the links between the central nervous system and the rest of the body when people perform movements [29]. These models can be used to better investigate some movement disorders, and phenomena such as motor variability and muscle activation patterns during fast and slow movements [29].

The availability of such large dataset will also allow us to calculate optimal values for the speed, accuracy, and reaction time motor characteristics for each age group. We will then extend the MotorBrain app to include new visualizations that will show users the comparison between their motor performance on a single test with normative data and optimal values of the same age group.

References

[1] D.A. Rosenbaum, Human motor control, Academic Press, 2009.

[2] S.P. Wise, R. Shadmehr, Motor control, in: Encycl. Hum. Brain, Elsevier Science, 2002: pp. 137–157.

[3] J.S.R. Leversen, M. Haga, H. Sigmundsson, From children to adults: Motor performance across the life-span, PLoS One. 7 (2012) e38830. doi:10.1371/journal.pone.0038830.

[4] R.D. Seidler, J.A. Bernard, T.B. Burutolu, B.W. Fling, M.T. Gordon, J.T. Gwin, Y. Kwak, D.B. Lipps, Motor control and aging: Links to age-related brain structural, functional, and biochemical effects, Neurosci. Biobehav. Rev. 34 (2010) 721–733. doi:10.1016/j.neubiorev.2009.10.005.

[5] R.M. Reitan, Validity of the Trail Making Test as an indicator of organic brain damage, Percept. Mot. Ski. 8 (1958) 271–276. doi: 10.2466/PMS.8.7.271-276.

[6] P.G. Bain, L.J. Findley, Assessing tremor severity: A clinical handbook, London: Smith-Gordon, 1993.

[7] C.E. Collyer, H.A. Broadbent, R.M. Church, Preferred rates of repetitive tapping and categorical time production, Percept. Psychophys. 55 (1994) 443–453. doi: 10.3758/BF03205301.

[8] S.L. Pullman, Spiral analysis: A new technique for measuring tremor with a digitizing tablet, Mov. Disord. 13 (1998) 85–89. doi:10.1002/mds.870131315.

[9] F. Miralles, S. Tarongí, A. Espino, Quantification of the drawing of an Archimedes spiral through the analysis of its digitized picture, J. Neurosci. Methods. 152 (2006) 18–31. doi:10.1016/j.jneumeth.2005.08.007.

[10] R. Saunders-Pullman, C. Derby, K. Stanley, A. Floyd, S. Bressman, R.B. Lipton, A. Deligtisch, L. Severt, Q. Yu, M. Kurtis, S.L. Pullman, Validity of spiral analysis in early Parkinson's disease, Mov. Disord. 23 (2008) 531–537. doi:10.1002/mds.21874.

[11] M. Rabuffetti, M. Ferrarin, R. Spadone, D. Pellegatta, V. Gentileschi, G. Vallar, A. Pedotti, Touch-screen system for assessing visuo-motor exploratory skills in neuropsychological disorders of spatial cognition, Med. Biol. Eng. Comput. 40 (2002) 675–686. doi: 10.1007/BF02345306.

[12] W.J. Tippett, L.E. Sergio, Visuomotor integration is impaired in early stage Alzheimer's disease, Brain Res. 1102 (2006) 92–102. doi:10.1016/j.brainres.2006.04.049.

[13] K.A. Hubel, B. Reed, E.W. Yund, T.J. Herron, D.L. Woods, Computerized measures of finger tapping: Effects of hand dominance, age, and sex, Percept. Mot. Ski. 116 (2013) 929–952. doi:10.2466/25.29.PMS.116.3.929-952.

[14] D. Surangsrirat, C. Thanawattano, Android application for spiral analysis in Parkinson's Disease, in: Southeastcon, 2012 Proc. IEEE, IEEE, 2012: pp. 1–6. doi: 10.1109/SECon.2012.6196943.

[15] J. Westin, M. Dougherty, D. Nyholm, T. Groth, A home environment test battery for status assessment in patients with advanced Parkinson's disease, Comput. Methods Programs Biomed. 98 (2010) 27–35. doi:10.1016/j.cmpb.2009.08.001.

[16] R. Lakshminarayana, D. Wang, D. Burn, K.R. Chaudhuri, G. Cummins, C. Galtrey, B. Hellman, S. Pal, J. Stamford, M. Steiger, A. Williams, Smartphone-and internet-assisted self-management and adherence tools to manage Parkinson's disease (SMART-PD): Study protocol for a randomised controlled trial (v7; 15 August 2014), Trials. 15 (2014) 374. doi:10.1186/1745-6215-15-374.

[17] S. Arora, V. Venkataraman, A. Zhan, S. Donohue, K.M. Biglan, E.R. Dorsey, M. A. Little, Detecting and monitoring the symptoms of Parkinson's disease using smartphones: A pilot study, Parkinsonism Relat. Disord. 21 (2015) 650–653. doi:10.1016/j.parkreldis.2015.02.026.

[18] HCI Lab – University of Udine, MotorBrain for Android (version 1.0.2) [mobile application software], (2015). https://play.google.com/store/apps/details?id=it.uniud.hcilab.motorBrain&hl=it (accessed January 04, 2017).

[19] HCI Lab – University of Udine, MotorBrain for iOS (version 1.0) [mobile application software], (2015). https://itunes.apple.com/it/app/motorbrain/id981876240?mt=8 (accessed January 04, 2017).

[20] HCI Lab – University of Udine, MotorBrain for Windows Mobile (version 1.0.0) [mobile application software], (2015). https://www.microsoft.com/it-it/store/p/motorbrain/9nblggh2j3vm (accessed January 04, 2017).

[21] A. Cicerale, E. Ambron, A. Lingnau, R.I. Rumiati, A kinematic analysis of age-related changes in grasping to use and grasping to move common objects, Acta Psychol. 151 (2014) 134–142. doi:10.1016/j.actpsy.2014.06.004.

[22] Unity Technologies, Unity3D (version 4.6.2) [computer software], (2005). http://unity3d.com/get-unity/download/archive (accessed January 04, 2017).

[23] R.K. Raw, G.K. Kountouriotis, M. Mon-Williams, R.M. Wilkie, Movement control in older adults: Does old age mean middle of the road?, J. Exp. Psychol. Hum. Percept. Perform. 38 (2012) 735–745. doi:10.1037/a0026568.

[24] I. Bautmans, S. Vantieghem, E. Gorus, Y.R. Grazzini, Y. Fierens, A. Pool-Goudzwaard, T. Mets, Age-related differences in pre-movement antagonist muscle co-activation and reaction-time performance, Exp. Gerontol. 46 (2011) 637–642. doi:10.1016/j.exger.2011.03.002.

[25] Oracle Corporation, MySQL (version 5.5.52) [computer software], (2016). https://dev.mysql.com/downloads/mysql/5.5.html (accessed January 04, 2017).

[26] Zend Technologies, PHP (version 5.5.9) [computer software], (2014). http://php.net/releases/ (accessed January 04, 2017).

[27] Python Software Foundation, Python (version 2.7.6) [computer software], (2010). https://www.python.org/download/releases/2.7.6/ (accessed January 04, 2017).

[28] M. Bostock, D3.js (version 4.4.0) [computer software], (2016). https://d3js.org (accessed January 04, 2017).

[29] M.L. Latash, V.M. Zatsiorsky, Biomechanics and motor control: Defining central concepts, Academic Press, 2015.

[30] Y. Wang, T. Asaka, K. Watanabe, Multi-muscle synergies in elderly individuals: Preparation to a step made under the self-paced and reaction time instruction, Exp. Brain Res. 226 (2013) 463–472. doi:10.1007/s00221-013-3449-9.

[31] M. Shinohara, J.P. Scholz, V.M. Zatsiorsky, M.L. Latash, Finger interaction during accurate multi-finger force production tasks in young and elderly persons, Exp. Brain Res. 156 (2004) 282–292. doi:10.1007/s00221-003-1786-9.

[32] H. Olafsdottir, W. Zhang, V.M. Zatsiorsky, M.L. Latash, Age related changes in multi-finger synergies in accurate moment of force production tasks, J. Appl. Physiol. 102 (2007) 1490–1501. doi:10.1152/japplphysiol.00966.2006.

[33] M. Woollacott, B. Inglin, D. Manchester, Response preparation and posture control.

Neuromuscular changes in the older adult, Ann. N. Y. Acad. Sci. 515 (1988) 42–53. doi:10.1111/j.1749-6632.1988.tb32964.x.

[34] H. Olafsdottir, N. Yoshida, V.M. Zatsiorsky, M.L. Latash, Elderly show decreased adjustments of motor synergies in preparation to action, Clin. Biomech. 22 (2007) 44–51. doi:10.1016/j.clinbiomech.2006.08.005.

[35] M. Sin, W.S. Kim, D. Park, Y.S. Min, W.J. Kim, K. Cho, N.J. Paik, Electromyographic analysis of upper limb muscles during standardized isotonic and isokinetic robotic exercise of spastic elbow in patients with stroke, J. Electromyogr. Kinesiol. 24 (2014) 11–17. doi:10.1016/j.jelekin.2013.10.002.

[36] A.M. Acosta, H.A. Dewald, J.P. Dewald, Pilot study to test effectiveness of video game on reaching performance in stroke, J. Rehabil. Res. Dev. 48 (2011) 431–444. doi: 10.1682/JRRD.2010.04.0052.

[37] D.S. Reisman, J.P. Scholz, Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis, Brain. 126 (2003) 2510–2527. doi:10.1093/brain/awg246.

[38] J. Park, M.M. Lewis, X. Huang, M.L. Latash, Effects of olivo-ponto-cerebellar atrophy (OPCA) on finger interaction and coordination, Clin. Neurophysiol. 124 (2013) 991–998. doi:10.1016/j.clinph.2012.10.021.

[39] J. Park, Y.H. Wu, M.M. Lewis, X. Huang, M.L. Latash, Changes in multi-finger interaction and coordination in Parkinson's disease, J. Neurophysiol. 108 (2012) 915–924. doi:10.1016/j.clinph.2012.10.021.

[40] Deloitte, The smartphone generation gap: Over-55? There's no app for that, (2014). https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Technology-Media-Telecommunications/gx-tmt-2014prediction-Interactive.pdf (accessed January 04, 2017).

[41] J.L. Contreras-Vidal, H.L. Teulings, G.E. Stelmach, Elderly subjects are impaired in spatial coordination in fine motor control, Acta Psychol. 100 (1998) 25–35. doi:10.1016/S0001-6918(98)00023-7.

[42] P.R. Mahant, M.A. Stacy, Movement disorders and normal aging, Neurol. Clin. 19 (2001) 553–563. doi:10.1016/S0733-8619(05)70034-7.

[43] O. Levin, H. Fujiyama, M.P. Boisgontier, S.P. Swinnen, J.J. Summers, Aging and motor inhibition: A converging perspective provided by brain stimulation and imaging approaches, Neurosci. Biobehav. Rev. 43 (2014) 100–117. doi:10.1016/j.neubiorev.2014.04.001.

[44] M.M. Hoehn, M.D. Yahr, Parkinsonism: Onset, progression, and mortality, Neurology. 17 (1967) 427–442. doi:10.1212/WNL.17.5.427.

[45] R. Agostino, A. Berardelli, A. Formica, N. Accornero, M. Manfredi, Sequential arm movements in patients with Parkinson's disease, Huntington's disease and dystonia, Brain. 115 (1992) 1481–1495. doi:10.1093/brain/115.5.1481.