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Don't plan, just do it: Cognitive and sensorimotor contributions to manual dexterity

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ABSTRACT

Manual dexterity is referred to as the skill to perform fine motor movements and it has been assumed to be associated to the cognitive domain, as well as the sensorimotor one. In this work, we investigated with functional near-infrared spectroscopy the cortical activations elicited by the execution of the 9-HPT, i.e., a standard test evaluating manual dexterity in which nine pegs were taken, placed into and then removed from nine holes on a board as quickly as possible. For comparison, we proposed a new active control task mainly involving the sensorimotor domain, in which the pegs must be placed and removed using the same single hole (1-HPT). Behaviorally, we found two distinct groups based on the difference between the execution time of the 9-HPT and the 1-HPT (ΔHPT). Cortical areas belonging to the network controlling reaching and grasping movements were active in both groups; however, participants showing a large ΔHPT presented significantly higher activation in prefrontal cortical areas (right BA10 and BA11) during 9-HPT and 1-HPT performance with respect to the participants with a small ΔHPT, who showed a deactivation in BA10. Unexpectedly, we observed a significant linear relationship between ΔHPT and right BA10 activity. This suggested that participants performing the 9-HPT more slowly than the 1-HPT recruited prefrontal areas implicitly exploiting the cognitive skills of planning, perhaps in search of a motor strategy to solve the test activating attentional and cognitive control processes, but this resulted not efficient and instead increased the time to accomplish a manual dexterity task.

1. Introduction

Manual dexterity is referred to as the skill to perform fine motor movements, typically resulting in the ability to write with a pencil, pick up small items, cut with scissors, and other actions requiring precise movements. It is worth noting that most motor tasks also involve cognitive control, such as attention, planning, and prediction (Kobayashi et al., 2004). Indeed, cognitive factors are increasingly being recognized as important for motor control (Mullick et al., 2015; Rinne et al., 2018). Disentangling sensorimotor from cognitive decline in a manual dexterity task has been found to be useful for early detection of age-related functional decline and for prediction of cognitive decline (Carment et al., 2018).

A standard method for evaluating manual dexterity is the Nine-Hole Peg Test (9-HPT), according to which a subject is asked to take nine pegs from a container, one by one, place them into nine holes on a board as quickly as possible, and then remove the pegs from the holes, one by one, replacing them back into the container. The 9-HPT is used in clinical settings in patients with various neurological diagnoses, such as stroke, Parkinson's disease and multiple sclerosis (Chen et al., 2009; Earhart et al., 2011; Feys et al., 2017; Wade, 1989). Interestingly, some studies reported correlations of the 9-HPT performance with cognitive variables. For instance, the 9-HPT score was found to worsen in multiple sclerosis with information processing speed and memory impairment (Leavitt et al., 2018). Also, worse 9-HPT was related to decreased resting-state connectivity in executive networks (Cordani et al., 2020),

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which are linked to working memory, decision making and problem-solving in the pursuit of goal-directed behavior (Menon, 2011).

Thus, notwithstanding manual dexterity is commonly addressed in the assessment of the sensorimotor domain, it could be considered more broadly, as it covers other domains, such as cognitive components that may rely on prefrontal circuits. Indeed, this is in line with an extensive definition of manual dexterity (Makofske, 2011), where the inclusion of different components related to sensorimotor and cognitive aspects is underlined. In fact, it refers to the ability to make coordinated hand and finger movements to grasp and manipulate objects and it requires the ability to cognitively plan and execute a task. In this vein, the 9-HPT can be considered an optimal tool for assessing manual dexterity, taking into account the cognitive component which coexists with and could overcome the sensorimotor one.

To disentangle sensorimotor from cognitive components in the 9-HPT, we proposed a novel active control condition called One-Hole Peg Test (1-HPT), which was based on the same type of action as the 9-HPT, but without having to choose one out of nine holes since only one hole was present on the board. With this approach, we had the possibility to assess the execution time of these two tests, with the hypothesis that the 9-HPT could require to develop a strategy, in terms of order of holes, to fill and empty the nine holes as fast as possible, differently from a pure sensorimotor strategy as in the case of the 1-HPT. This could help unravel an action requiring the planning of the movement based on a choice, from a condition in which the task was based on reaching, grasping, and positioning the peg inside the single hole.

Performing tasks requiring manual dexterity activates the prefrontal cortex and primary sensorimotor cortices in older adults (Naito et al., 2021; Ota et al., 2020; Seol et al., 2023; Sobinov and Bensmaia, 2021); whilst the manual dexterity task execution in healthy young subjects is mainly related to the activation of bilateral sensorimotor areas (Sarasso et al., 2018). These findings indicate again the contribution of cortical areas involved in both cognitive and sensorimotor tasks. However, not all subjects show a significant activation of prefrontal areas during a manual dexterity task. Then, why is the activation of prefrontal areas not elicited in all subjects? The use of behavioral tasks able to disentangle cognitive and sensorimotor components associated with neuroimaging could give an answer to our question. In this vein, we investigated cortical activity in areas known to have a role in sensorimotor and cognitive functions, i.e., in the sensorimotor and prefrontal areas, during the two tasks and to assess whether there was a difference in cortical activations between the two tasks. This was achieved by implementing a new study protocol based on functional near-infrared spectroscopy (fNIRS), an optical technique which allows the analysis of task-related activity of selected cortical areas during ecological movements overcoming the constraints induced by the magnetic resonance scanning environment (Ferrari and Quaresima, 2012). Indeed, although fMRI can be considered the gold standard for most of neuroimaging studies, fNIRS represents the ideal technique to investigate the neural substrates underlying manual dexterity, because of its added value in terms of ecological validity. In fact, the 9-HPT (and the 1-HPT) needs to be performed in a setting that satisfies some mandatory requirements: the participant must be seated on a chair in front of a desk, where the equipment for the test is positioned, with his/her hands on the desk.

Furthermore, we identified two sub-groups based on the median value of the difference in execution time between the 9-HPT and the 1-HPT in order to assess possible different strategies and related cortical activity in the participants showing greater difference with respect to those showing smaller difference between the two tasks. Our hypothesis was that a large difference in execution time could be found in participants developing a strategy to accomplish the test, likely involving cortical areas dealing with higher-order cognitive functions.

2. Materials and methods

2.1. Participants

Twenty-eight volunteers (age: mean ± SD = 28.39 ± 8.87 years; 17 females) were recruited for the study. All the participants were naive to the purpose of the experiment. They reported no previous history of neurological disorders or orthopedic problems of the upper limbs. They were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). The study was conducted in accordance with the 2013 revision of the Declaration of Helsinki on human experimentation. All participants gave informed consent for the participation in the study. The study was approved by the Regional Ethics Committee of Azienda Ospedaliera “San Martino”, Genoa, Italy (P.R. 271REG2017).

2.2. Behavioral task

Participants were seated on a chair, wearing the cap for fNIRS acquisition. A pegboard was positioned between their arms at their midline; the peg-filled lateral pegboard was oriented towards the right hand, as participants were asked to perform the tasks with their dominant (right) hand. They were asked to perform the classic Nine-Hole Peg Test (9-HPT) and, additionally, a control condition called One-Hole Peg Test (1-HPT) in which a paper mask of the same color as the board covered eight holes, leaving only the central hole visible. In the 9-HPT, the pegs were picked up one at a time from the lateral pegboard, transported and inserted into one of the holes of the medial pegboard and then returned likewise one by one to the lateral pegboard. In the 1-HPT, participants had to take one peg at a time among nine, place it into the hole, remove it and put it into a different container close to the board. The two conditions (9-HPT and 1-HPT) are represented in Fig. 1. The order of the conditions was randomized among participants, and the different conditions were presented three times each. The participants were instructed to perform both tests as quickly as possible. A brief familiarization phase was provided prior to timing the test to reduce possible practice effects. Notably, the 9-HPT is the gold standard for manual dexterity also because it has excellent test-retest reliability (Wang et al., 2011). Timing was performed with a stopwatch and recorded in seconds; the stopwatch was started when the participant touched the first peg and stopped when the participant placed the last peg in the container. The time needed to place and remove the 9 pegs was recorded and averaged over the three trials, separately for each condition.

2.3. fNIRS acquisition and analysis

To investigate cortical activity related to the 9-HPT and the 1-HPT, changes in the concentration of oxy- and deoxy- hemoglobin (HbO and HbR, respectively) were measured by a portable NIRS system (NIRSport, NIRx Medical Technologies, Berlin, Germany) equipped with 16 sources and 16 detectors. Particularly, two 8 × 8 devices were used to record cortical signals in tandem mode, with sources operating at 760 nm and 850 nm. The total array was composed of 40 standard channels with a source-detector distance of 3 cm and 8 short-separation (SS) channels. Standard channels were arranged to cover prefrontal and sensorimotor cortical areas. The sampling rate was set to 3.47 Hz. A block-designed paradigm was adopted, with alternating periods of task (i.e., 9-HPT or 1-HPT) and rest (the participants stayed still, with the two hands on the table) (Fig. 1). Every participant had to wait for an acoustic “go” signal delivered by the PC and start performing the test as quickly as possible (at own pace, only once per “task” block). The test was repeated three times, with a rest interval between two successive trials. The same protocol was adopted for the control condition we proposed (1-HPT). The time was recorded by the experimenter (expert for this task and the same for the whole study) with a stopwatch.

More in detail, the beginning of each trial was synchronized with the

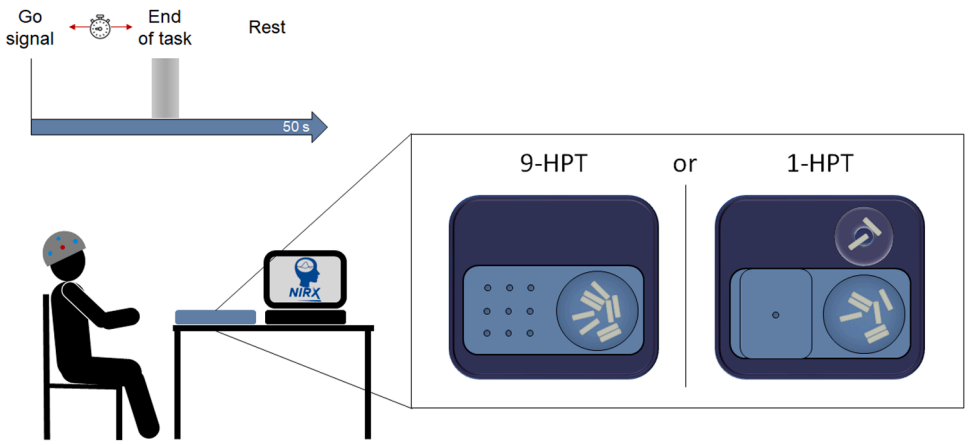

Fig. 1. Experimental set-up. Participants performed the standard 9-HPT and the control condition (1-HPT) with the right (dominant) hand, with simultaneous fNIRS recording. Execution time was recorded and averaged on three trials, separately for each condition. The shaded grey bar corresponds to the end of the task, which was variable among participants.

fNIRS signal using direct event synchronization between NIRStar and NIRStim co-existing on the same PC. An auditory "go" signal was delivered through NIRStim by the PC every 50 s notifying the participant to proceed with the trial, while a trigger signal was simultaneously transmitted to NIRStar; in this way, a marker was set on the recording trace indicating the beginning of the task. Thus, we synchronized the "go" signal with the recording of the fNIRS signal through software, and very shortly the participant started the task and the experimenter started the stopwatch (when the participant touched the first peg, as from 9-HPT guidelines). The stopwatch was stopped when the last peg hit the container. fNIRS data pre-processing was performed in MATLAB (MathWorks, MA, USA) through in-house scripts and some of the Homer3 NIRS processing package functions (Huppert et al., 2009). For each participant, all channels with a low signal-to-noise ratio were discarded (SNR<2). Then, the intensity data of the remaining channels were converted to optical density changes. Motion artifacts were identified by applying the Homer3 function *hmrR_MotionArtifactByChannel* on changes in optical density data (AMPthresh = 0.5; STDEVthresh= 12; tMotion=0.5; and tMask=1) and corrected by applying a combination (Brigadoi et al., 2014; Di Lorenzo et al., 2019) of spline (p = 0.99) (Scholkmann et al., 2010; Yücel et al., 2014) and wavelet (iqr=0.5) (Molavi and Dumont, 2012) motion correction techniques. Then, the identification of motion artifacts was repeated to detect residual motion artifacts. A band-pass filter (0.01–1.5 Hz) was applied to remove slow drifts, and high frequencies components. Then, trials falling within the time points identified as residual motion artifacts were discarded from hemodynamic response function (HRF) calculation. An age-dependent differential pathlength factor was computed for each participant (Scholkmann and Wolf, 2013), and then the HbO concentration changes were computed through the modified Beer-Lambert law (Delpy et al., 1988). To calculate the mean HRF for each block, participant, and channel, a General Linear Model (GLM) was applied. Iterative weighted least squares were used to solve the GLM (Barker et al., 2013). A set of a consecutive sequence of gaussian functions with a spacing and standard deviation of 2 s was used as temporal basis functions for HRF. The statistical analysis related to the fNIRS signal was then conducted by considering the marker on the fNIRS trace (corresponding to the "go" signal) and the return of the HbO concentration values to the baseline. Convergence between HbO and HbR activity in the hemodynamic response profiles (i.e., HbO increase coupled with HbR decrease, and vice versa) was assessed by visual inspection. This approach is supported by a recent review of fNIRS studies (Kinder et al., 2022), showing that reporting only HbO response is the most common procedure given the lower signal-to-noise-ratio of HbR signal.

Since all participants completed the tests in less than 20 s, the interval for the block average was set at −5 to 40 s from stimulus onset. As an additional regressor in the GLM, the average signal of all SS channels was added. The SS channel regression led to the reduction of the physiological noise.

2.4. Cognitive tests

Within one week from the experimental procedure, a cognitive assessment was performed. All participants underwent neuropsychological tests addressing processing speed and motor speed with the Symbol Digit Modalities Test (SDMT) (Ebaid et al., 2017), planning ability and visuospatial working memory with the Tower of London (ToL) (Shallice, 1982) and the Corsi Supraspan Learning test (SUPRASPAN) (Spinnler and Tognoni, 1987). These tests were chosen because it is reasonable to conceive that the underlying abilities needed to perform them in an optimal way could be relevant for the 9-HPT and 1-HPT as well. Scores of the neuropsychological tests were corrected for age, gender and schooling.

2.5. Statistical analysis

Normality of data distribution was checked for all variables with Shapiro-Wilk tests; then, parametric or non-parametric tests were applied accordingly.

A paired t-test was adopted to compare the execution time (averaged on the three trials) of the 9-HPT with respect to the 1-HPT. Pearson's correlation coefficient between the execution time of the 9-HPT and that of the 1-HPT, averaged on the three trials, was calculated.

The difference in the execution time of the two tests (9-HPT − 1-HPT) was also calculated (hereafter ΔHPT). Consequently, the whole group of participants was divided into two groups of 14 participants each, according to the median value of the distribution of this difference. Hence, we obtained: the High Difference (HD) group, including the participants showing ΔHPT above the median of the distribution, and the Low Difference (LD) group, including the participants showing ΔHPT below the median of the distribution. Raw performances were analyzed with a 2 × 2 mixed ANOVA with TASK (9-HPT, 1-HPT) as within-subject factor and GROUP (HD, LD) as between-subject factor. Significant effects in the ANOVA were followed by post-hoc LSD test. Pearson's correlation coefficients between the execution times of the two tasks (9-HPT and 1-HPT) averaged on the three trials were separately calculated in the two groups (HD and LD).

Then, a regression linear relationship was generated for both HD and LD groups and described by regression equations consisting of a regression constant (intercept) and a regression coefficient (slope). To

compare the intercepts and slopes of the HD and LD regression lines, a *t*-test with hypothesis tests for comparing regression constants and coefficients was used (Armitage et al., 2002).

For each participant, channel, and task, the average of the HbO mean hemodynamic responses in the range between −5 to 40 s after stimulus onset was computed and chosen as a metric for statistical analyses.

The analysis of fNIRS data was characterized by a two-step nature. First, we identified the active channels by a channel-wise series of t-tests; crucially, this series of t-tests was corrected using Bonferroni method, allowing us to reliably identify the active channels in the task. All the following ANOVAs were restricted to the group of channels found to be active in the first step of the analysis procedure. Specifically, active channels were selected by performing a paired *t*-test for each channel to detect different changes in HbO concentration during the task with respect to zero and then corrected for multiple comparisons with Bonferroni correction (critical value: α/n channels). For the whole group, statistical analysis was performed on the channels found to be active in at least one condition. When separate groups were considered, statistics were applied to channels active in at least one group and condition. HbO concentration changes were analyzed to test differences in cortical activation between the two tasks in the whole group of participants by means of two-way repeated measures ANOVA with TASK (9-HPT, 1-HPT) and CHANNEL as within-subject factor. Then, the analysis was performed considering the group division identified on the basis of ΔHPT. Hence, a mixed ANOVA was performed with TASK (9-HPT, 1-HPT) and CHANNEL as within-subject factors and GROUP (HD, LD) as between-subject factor. To evaluate a possible relationship between activity of the cortical areas corresponding to the channels found to be significantly different between groups and behavioral performance, correlations between changes in HbO concentration and ΔHPT were assessed. Further, to investigate relationships of cognitive assessment scores with cortical activity and behavioral performance, Pearson's correlation coefficients were calculated for the SDMT, the ToL and the SUPRASPAN scores with HbO concentration changes and with ΔHPT.

3. Results

3.1. Behavioral data

Participants showed a significant difference in execution time between the two tasks, with the execution of the 9-HPT being significantly slower than that of the 1-HPT (mean ± SE: 9-HPT = 17.18 ± 0.27 s; 1-HPT = 16.36 ± 0.25 s; $t_{(27)} = 3.89$, $p < 0.001$, Cohen's $d = 0.55$) (Fig. 2A).

Then, the whole group of participants was divided into two groups of 14 participants each, according to the median value of the distribution of ΔHPT (HD and LD groups). ANOVA showed a significant main effect of TASK ($F_{(1, 26)} = 39.60$; $p < 0.001$, $\eta^2 = 0.60$) and a significant interaction TASK * GROUP ($F_{(1, 26)} = 44.49$; $p < 0.001$, $\eta^2 = 0.63$). Post-hoc analysis showed longer execution time of the 9-HPT (17.75±0.34 s) performed by the HD group with respect to the 1-HPT (16.19±0.31 s) of the same group ($p < 0.001$) and with respect to both the 9-HPT (16.70 ±0.28 s; $p = 0.047$) and the 1-HPT (16.74±0.26 s; $p = 0.049$) of the LD group. In contrast, in the LD group, there was no statistical difference between the execution time of the two tasks ($p = 0.79$). Moreover, the execution time of the 1-HPT was not significantly different between the two groups ($p = 0.29$) (Fig. 2B).

Correlation analysis between the execution time of the 9-HPT and of the 1-HPT showed a significant positive correlation in the whole group ($r = 0.73$; $p < 0.001$) (Fig. 3A). Also, significant positive correlations were found in both HD and LD groups when evaluated separately ($r = 0.81$; $p < 0.001$ and $r = 0.94$; $p < 0.001$, respectively) (Fig. 3B).

The intercepts of the regression lines were significantly different between the two groups ($t_{(1-25)} = 7.56$; $p < 0.001$). Interestingly, the slopes of the two regression lines of the HD and the LD groups were comparable ($t_{(1-24)} = 0.42$; $p = 0.68$), indicating a significant positive shift on the vertical axis of the HD regression line with respect to the LD one.

3.2. fNIRS data

From the analysis of hemodynamic responses with respect to zero, 11 channels, mainly corresponding to sensorimotor areas, were found to be active at least for one task (see Table 1 and Fig. 4).

Exploring differences in cortical activities (i.e., changes in HbO concentration) in these channels between the tasks, a significant main effect of the CHANNEL factor ($F_{(10, 270)} = 3.39$; $p < 0.001$, $\eta^2 = 0.11$) was found. The effect of the TASK factor ($p = 0.24$) and the TASK*-CHANNEL interaction ($p = 0.71$) were not significant.

By analyzing HbO concentration changes during the two tasks in the HD and LD groups, 11 channels were found to be significantly active (Table 2). When the two groups were considered separately, cortical activity during the 9-HPT and the 1-HPT of the two groups showed a significant effect of the CHANNEL factor ($F_{(10, 260)} = 7.91$; $p < 0.001$, $\eta^2 = 0.23$) and a significant CHANNEL * GROUP interaction ($F_{(10, 260)} = 2.8$; $p < 0.01$, $\eta^2 = 0.09$). No significant effects were found for the TASK factor ($p = 0.17$). Post-hoc analysis revealed a significant difference between the two groups in channels 36 and 46, corresponding to Brodmann's areas (BA) 10 and 11 respectively, with higher activity in the HD group than in the LD group (channel 36: 0.07 vs. −0.15 μM, $p < 0.001$; channel 46: 0.17 vs. 0.01 μM, $p = 0.02$) (Fig. 5).

HbO concentration changes of the whole group in channel 36 averaged on the two tasks were significantly and positively correlated with ΔHPT ($r = 0.57$; $p = 0.0014$) (Fig. 6A), whilst no significant correlation was found when considering channel 46 ($p = 0.14$).

SDMT scores resulted to be not significantly correlated with ΔHPT

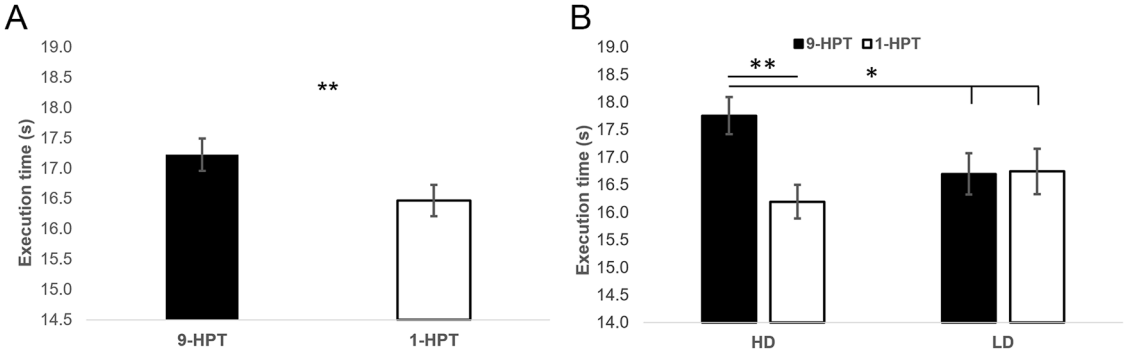

Fig. 2. (A) the averaged execution time required to complete the Nine-Hole Peg Test (9-HPT) and the control task with one peg (1-HPT) in the whole group; (B) the averaged time occurred to complete the 9-HPT and the 1-HPT in the High Difference (HD) and Low Difference (LD) groups. The error bars refer to the standard error of the mean. **indicates $p < 0.01$, *indicates $p < 0.05$.

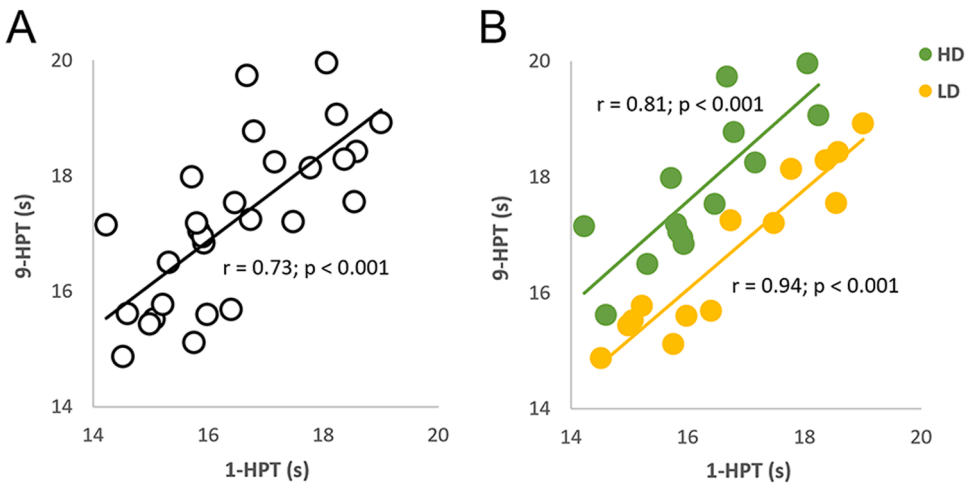

Fig. 3. Linear relationships between the execution time of the 9-HPT and the 1-HPT in: A) the whole group ($y = 0.76x + 4.78$) and B) the High (HD, $y = 0.90x + 3.24$) and Low (LD, $y = 0.86x + 2.27$) Difference groups, separately.

Table 1
Description of the fNIRS channels (source-detector pair) found to be activated in the whole group during at least one of the two tasks (9-HPT or 1-HPT): location of source and detector in the 10–10 international system, MNI coordinates and the corresponding left or right (L or R) Brodmann's Area.

Channel ID	Label source	Label detector	x	y	z	Brodmann's Area
1	C1	FC1	−38.47	8.63	84.60	6 L
3	C1	C3	−57.08	−9.56	77.44	4 L
5	FC3	C3	−67.50	6.48	58.07	6 L
6	FC3	FC5	−71.84	22.12	37.64	44 L
7	CP3	CP1	−56.07	−49.12	80.67	40 L
8	CP3	C3	−72.34	−29.62	65.52	40 L
9	C5	C3	−80.05	−11.79	44.03	3 L
10	C5	FC5	−81.34	2.61	21.62	43 L
11	C2	FC2	37.49	9.94	84.65	6 R
13	C2	C4	55.86	−8.63	78.22	4 R
21	F3	F5	−58.80	54.14	23.51	45 L

and HbO concentration changes in channels 36 and 46 ($p = 0.21$, $p = 0.91$, $p = 0.66$, respectively). ToL scores showed a significant positive correlation with HbO concentration changes in channel 46 ($r = 0.50$; $p = 0.007$) (Fig. 6B) and not in channel 36 ($p = 0.56$). No significant correlation was found between ToL and ΔHPT ($p = 0.47$).

No significant correlation of the SUPRASPAN test was found with ΔHPT and HbO concentration changes in channels 36 and 46 ($p = 0.41$, $p = 0.65$, $p = 0.20$, respectively).

4. Discussion

In this work, for the first time, we showed cortical activations elicited by the execution of the 9-HPT, which is a standard test used for the assessment of manual dexterity. Further, we tried to discern between aspects dealing with the sensorimotor and cognitive domains in manual dexterity by introducing a novel active control condition. Specifically, we compared the 9-HPT with a new test we called 1-HPT, where it is not necessary to choose among the various holes, but the pegs must be placed and taken out of the same single hole.

Behaviorally, we showed a significant, positive, linear relationship between the time employed by a participant to complete the 9-HPT and that required for the 1-HPT, indicating that the participant's characteristics in performing the 1-HPT were similar to those shown during the 9-HPT. This finding could suggest that the sensorimotor component related to the phases of reaching, grasping and positioning the peg in the hole, as occurring in the 1-HPT, already outlined a profile of the participant when he/she was asked to perform a more complex manual dexterity task, such as the 9-HPT.

The strong linear relationship between the 9-HPT and the 1-HPT was mirrored by a similar cortical activation observed in the two tasks by means of fNIRS. In particular, the cortical network which was activated during the execution of the 1-HPT and the 9-HPT was the same, and included sensorimotor areas belonging to the network controlling reaching and grasping movements (Caliandro et al., 2021; Ranzini et al., 2022). Further, ipsilateral premotor and motor areas were found to be active, in line with previous works showing an active role of the ipsilateral hemisphere in planning and executing unilateral limb movements (Bundy and Leuthardt, 2019).

Interestingly, when we considered two distinct groups based on the difference between the execution time of the 9-HPT and the 1-HPT (named ΔHPT), we observed that the group showing lower difference (LD group) replicated the behavioral effects found in the total group, i.e., a strong, positive, linear relationship between the execution time of the 9-HPT and the execution time of the 1-HPT with similar values for both tasks.

In particular, the intercept of the regression function of the HD group was significantly higher than that of the LD group, but the slopes of the two linear relationships were comparable between the two groups. Therefore, the HD group showed the same trend of the LD group with an almost constant "vertical offset" (for both the slower and the faster participants) between the 9-HPT and the 1-HPT values. These findings suggest that the LD group can be thought as including participants who exploit the sensorimotor domain to perform both tasks, whereas the HD group as including participants who could also exploit higher-order components in accomplishing the 9-HPT which can be time-consuming (Sobinov and Bensmaia, 2021).

When we analyzed cortical activity separately for the two groups, we found that the cortical areas belonging to the network controlling reaching and grasping movements were still significantly active; however, the HD group showed significantly higher activation in two channels located in prefrontal cortical areas corresponding to the BA10 and BA11. Noteworthy, this prefrontal cortical activity was similar, from a statistical point of view, during the performance of the 9-HPT and the 1-HPT, suggesting that the observed prefrontal activity was not due to the task difficulty, but to the approach used in tackling these manual dexterity tasks, whether they are simple or complex. On the other hand, in the LD group no significant activation was found in prefrontal cortical areas, and in the BA10, on the contrary, there was a deactivation with respect to the baseline, underlining that in this case probably the prefrontal component more associated with higher functions is used less compared to the other group.

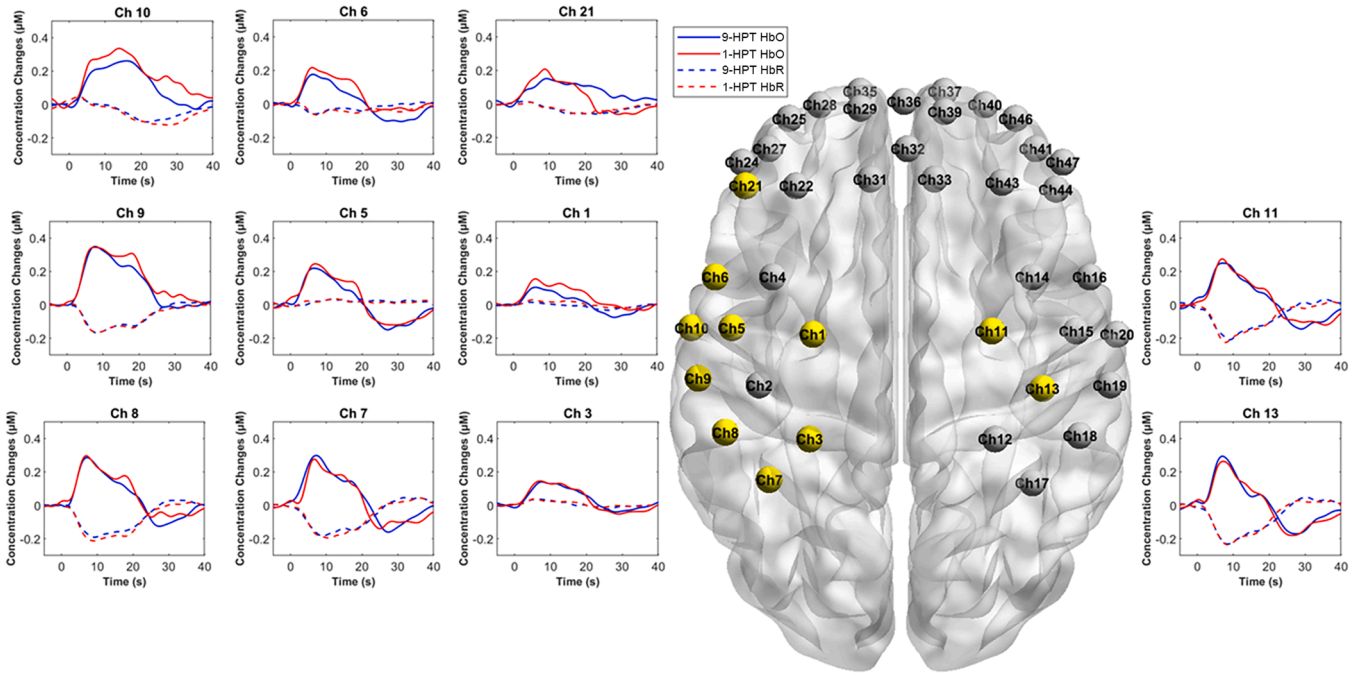

Fig. 4. The circles represent the acquisition channels in correspondence of bilateral prefrontal and sensorimotor cortices, used for fNIRS recording. Active channels are shown in yellow. The boxes show variations in Oxy- and Deoxy- hemoglobin concentrations (HbO and HbR are displayed with continuous and dashed lines, respectively) in the 9-HPT and 1-HPT (blue and red lines, respectively).

Table 2
Description of the fNIRS channels (source-detector pair) found to be activated at least in one group (HD or LD) analyzed separately during at least one of the two tasks (9-HPT or 1-HPT): location of source and detector in the 10–10 international system. MNI coordinates and the corresponding left or right (L or R) Brodmann's Area.

Channel ID	Label Source	Label Detector	x	y	z	Brodmann's Area
1	C1	FC1	−38.47	8.63	84.60	6 L
3	C1	C3	−57.08	−9.56	77.44	4 L
6	FC3	FC5	−71.84	22.12	37.64	44 L
8	CP3	C3	−72.34	−29.62	65.52	40 L
9	C5	C3	−80.05	−11.79	44.03	3 L
10	C5	FC5	−81.34	2.61	21.62	43 L
11	C2	FC2	37.49	9.94	84.65	6 R
13	C2	C4	55.86	−8.63	78.22	4 R
21	F3	F5	−58.80	54.14	23.51	45 L
36	FPz	AFz	0.08	87.75	11.95	10 R
46	AF8	FP2	42.85	77.84	−15.34	11 R

Furthermore, we observed a positive linear relationship between ΔHPT and right BA10 activity, i.e., the higher the difference in the execution times between the 9-HPT and the 1-HPT, the higher the oxyhemoglobin concentration changes in the right BA10 during task performance. On the other hand, BA10 activity was not correlated with the participants' score of the ToL test. This result deserves further investigation, including a larger number of participants in future studies. Interestingly, right BA11 activity significantly, positively, correlated with the participants' score of the ToL test, indicating that higher values of oxyhemoglobin concentration changes in the right BA11 during tasks performances were found in those participants with a good capacity in cognitive planning, able to formulate, evaluate and select a sequence of thoughts and actions to achieve a desired goal (Shallice, 1982). These findings can be, at a first glance, seen as a paradox, i.e., participants belonging to the HD group, performing the 9-HPT slower than the LD group, were those participants recruiting cortical areas related to cognitive planning. This would suggest that the HD group used a different approach from a cognitive standpoint in performing manual dexterity tasks than the LD group. Nevertheless, our findings showed that this approach was not efficient and, instead, increased the time to accomplish a manual dexterity task. Higher execution times might reflect a strategy that reduced their performance speed, especially during the 9-HPT possibly due to the search of "better" ways not to hinder and speed up the insertion and removal of the pegs (no instruction was given concerning the order of the holes). In addition, if we inspect the regression lines shown in Fig. 3B, we can speculate that the extra-time observed in HD participants is likely to be caused by a larger amount of time spent during movement planning. This hypothesis is corroborated by two key elements: the slopes of the two regression lines for HD and LD participants are almost identical, but there is a sizeable difference in their offset, because the HD line had a vertical shift (i.e., higher intercept) with respect to the LD line.

Furthermore, since the HD group had a similar cortical activation during the 9-HPT and the 1-HPT, we could think that the high task load could not be related to the complexity of the task, but rather to the use of a common approach requiring higher attentional and control processes with respect to the LD group. Taken together, these results provide an intriguing suggestion: spending extra time in planning execution in the 9-HPT does not necessarily translate into a better performance (i.e., faster execution time). In the light of our findings, participants exploiting higher-order domains showed longer execution time and therefore worse performance.

Interestingly, this picture is complementary to what happens in the ToL test, where participants who produce an active effort in planning usually perform better. On the contrary, the lack of advantage by planning in the 9-HPT indicates that the 9-HPT is not directly related to motor planning skills. Unfortunately, this interpretation is limited by the fact that we could not collect planning times in the present experiment; more detailed behavioral information might be collected in the following studies. The same line of reasoning can be applied to brain activity: although one could expect an improvement in performance (i.e., a reduction of execution time), when cortical areas involved in executive function are active, this is not what we observed in the 9-HPT. It should also be noted that we did not find any relationship between

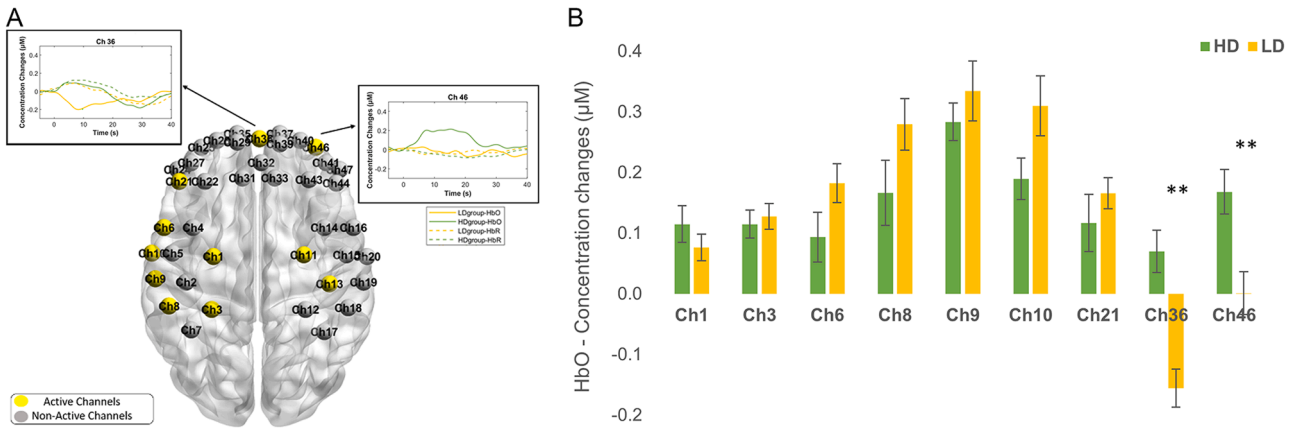

Fig. 5. (A) Arrangement of all channels (grey); active channels are shown in yellow. The boxes show the hemodynamic response of the channels found to be significantly different between groups (namely, Ch36 and Ch46). Continuous lines correspond to changes in Oxy-hemoglobin concentration and dashed lines correspond to variations in Deoxy-hemoglobin concentration. Green lines refer to the HD group, yellow lines refer to the LD group. (B) Histograms show the changes in Oxy-hemoglobin concentration in the active channels in two groups. Green bars refer to the HD group and yellow bars refer to the LD group. The error bars represent the standard error of the mean. ** indicates $p < 0.01$.

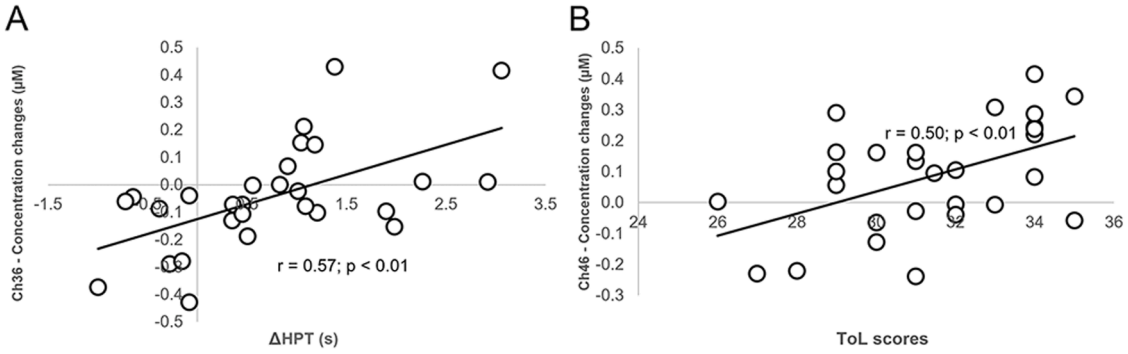

Fig. 6. Pearson's correlation between: (A) Oxy-hemoglobin concentration changes in channel 36, averaged on the tasks, and ΔHPT; (B) Oxy-hemoglobin concentration changes in channel 46, averaged on the tasks, and Tower of London scores.

prefrontal cortical activity and scores obtained at the SDMT, which is a measure of processing speed or efficiency, suggesting that these areas do not directly influence the performance level based on time. On the other hand, prefrontal cortical activity (right BA11) correlated with the scores obtained at the ToL test, which is used to assess executive functioning specifically related to planning: participants activating more this area performed better at the ToL test. This difference might be rooted in two different types of planning required by the two tasks: BA10 might be involved in motor planning, whereas ToL test might rely on a more abstract type of planning. This interpretation is consistent with previous neuroimaging evidence: BA11 is typically involved in cognitive tasks (Hubert et al., 2007) and it is typically recruited in ToL test (Jaspers-Fayer et al., 2022), whereas BA10 has been found to be involved in motor imagery (van der Meulen et al., 2014) and during intentional and imitative motor acts (e.g., Babiloni et al., 2008). In future studies, it would be helpful to include cognitive measures of visuo-spatial attention, such as the Posner cueing paradigm (Posner, 1980), and measures of the ability to cope with distractors, such as in the Flanker task (Eriksen and Eriksen, 1974). The present results gave us reason to believe that these abilities might be more relevant for the optimal execution of 9-HPT and 1-HPT than planning skills. For instance, the ability to efficiently shift visual attention to different spatial locations throughout the task would reasonably concur in yielding shorter execution times, as well as the ability to inhibit the other pegs while dealing with the placement of a single piece.

In conclusion, all these results point to the existence of different cortical circuits involved in 9-HPT performance: one more related to brain areas which are active during a reaching and grasping motor task, and another including also prefrontal areas, which are mainly involved in executive functions dedicated to cognitive planning. Therefore, the participants performing the 9-HPT more slowly than the 1-HPT recruited prefrontal areas implicitly exploiting the cognitive skills of planning, perhaps in search of a motor strategy to solve the test activating attentional and cognitive control processes, but this solution resulted not efficient and instead increased the time to accomplish a manual dexterity task.

Thanks to the present results, we demonstrated for the first time that the cortical activation during 9-HPT execution is similar to that observed in reaching and grasping movements, which is more related to sensorimotor and associative areas. However, by introducing the 1-HPT condition, it was possible to extract a group of participants showing a motor behavior significantly different between a simple and a more complex manual dexterity task corresponding to an activation in prefrontal areas related to cognitive functions. All these findings suggest that the use of the 1-HPT, and the comparison of the performance of the 9-HPT with this control test, could help identify subjects showing a more cognitive approach to manual dexterity tasks. This should be taken into account in clinical settings testing manual dexterity, particularly when considering diseases in which the cognitive functions could be altered or prefrontal areas could be over-active.

Ethics statement

The study was conducted in accordance with the 2013 revision of the

Declaration of Helsinki on human.

CRediT authorship contribution statement

Laura Bonzano: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft. **Monica Biggio:** Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Sabrina Brigadoi:** Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. **Ludovico Pedullà:** Conceptualization, Investigation, Writing – review & editing. **Monica Pagliai:** Investigation, Writing – review & editing. **Costanza Iester:** Investigation, Visualization, Writing – review & editing. **Giampaolo Brichetto:** Conceptualization, Writing – review & editing. **Simone Cutini:** Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Marco Bove:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that there are no relevant financial or non-financial competing interests to report.

Data availability

Data will be made available on request.

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