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Association between expertise in clinical skills and mental functions networking related to manual dexterity

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Abstract

Background Manual dexterity is key to clinical skill training. The networking between sensorimotor and visual-attention functions may be associated with the expertise of dental students. The study aims to investigate the pattern of networking between sensorimotor and visual-attention functions and related resting-state (rs) functional connectivity (FC).

Methods Twenty-six dental and 19 non-dental students completed visual-attention tests and psychomotor tests for manual dexterity and steadiness. Thirty participants also received structural and rs-functional magnetic resonance imaging.

Results Compared to non-dental students, dental students showed increased networking in performance between visual-attention tests and manual dexterity, increased rsFC between bilateral sensorimotor network (SMN) and the left middle frontal gyrus, and decreased rsFC between bilateral SMN and the left posterior insula. Better performance of manual dexterity was associated with increased rsFC between the left SMN and the right supramarginal gyrus.

Conclusions Dental skill training is associated with the networking of sensorimotor and visual-attention functions and coupled with increased rsFC of the SMN. In dental students, better manual dexterity is associated with the functional connectivity of the SMN.

Clinical trial number Not applicable.

Keywords Manual dexterity, Fine motor skill, Expertise, Dental skill training, Brain connectivity, Network analysis

Introduction

Clinical practice demands good coordination between perception and motor skills [1, 2]. In dental education, improving fine motor skills is the major goal of the training of dental students [3], and standardized tests have been used for assessing students' perceptual ability and psychomotor skills [4, 5, 6]. Manual dexterity, i.e., the skilled ability to make precise and flexible hand/finger movement [7], has been highlighted in dental skill training. Cumulating evidence has suggested that clinical skill training was related to the improvement of manual dexterity [1, 2, 8] and the performance of psychomotor

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tests was related to class performance [2, 4]. However, three key questions have remained unanswered: (a) How do other mental functions related to fine motor skills, e.g., visual attention and hand steadiness, network with manual dexterity? (b) Is the pattern of mental function networking associated with experience in clinical skill training? (c) What are the brain structural and functional features associated with the mental functions of clinical skill training?

In dental skill training, psychomotor tests are used to assess the ability of manual dexterity of fingers or using a tweezer, which plays a key role in manipulating dental instruments [1, 2, 9]. Notably, manual dexterity is associated with not only musculoskeletal features but also complex sensorimotor and visual-attention processing [7, 10]. For example, in dental students, abnormal stereoacuity was related to the worse performance of tooth preparation in dental students [11], and finger force generation was related to the posture of clinical practice [12]. In medical students, alertness and divided attention were associated with the performance of manual dexterity tests [13]. To investigate the networking between mental functions, a widely adopted strategy is to examine the pattern of cross-variable associations using network analysis [14]. For example, the pattern of networking between motor and cognitive factors was associated with the mental health of children [15], cognitive impairment [16], and the age-related difference in fine motor movement [17]. A network analysis may reveal the pattern of networking between mental functions, including visual attention, stereoacuity, hand steadiness, finger and tweezer dexterity, and finger force generation.

Recent neuroimaging evidence has suggested that the development of expertise, which requires training in perceptual and motor skills, such as musicians and surgeons, is associated with the sensorimotor network [18, 19, 20]. Furthermore, manual dexterity and force generation were associated with attention control, and the coupling between motor and visual attention was associated with the salience network [10]. Cumulating neuroimaging evidence has revealed the coupling between motor, cognitive, and sensory (including vision and proprioception) functions plays a key role in manual dexterity [7]. Therefore, if the pattern of mental function networking is associated with clinical skill training, such behavioral differences are associated with individual brain features, including the sensorimotor and salience networks.

At present, there have been studies investigating the performance of dental students in assessments of manual dexterity and the majority of the studies focused on the difference in testing performance between dental and non-dental professionals or different stages of dental training [1, 2, 4]. However, the association between performances from different assessments, which reflects the networking of mental functions, has remained unclear. Furthermore, the brain features associated with training in fine motor skills, e.g., playing musical instruments and painting, have been widely reported [21, 22]. However, the brain features related to dental skill training have not been systematically investigated.

This study aims to test the following hypotheses by investigating the pattern of mental function networking and related brain functional and structural features, focusing on the dental students, who received training in manual dexterity.

1. Do dental and non-dental students show a different pattern of networking between the sensorimotor and visual-attention functions? – The study tested the hypothesis *that in dental students, there is increased networking between the performance of manual dexterity and visual-attention tests, compared to non-dental students.*
2. Do dental and non-dental students show a different pattern of resting-state functional connectivity (rsFC) or difference in regional gray/white matter volume? – The study tested the hypothesis *that dental students and non-dental students differ in the rsFC or gray/white matter volume of the sensorimotor and salience networks.*
3. Is individual rsFC associated with the performance of manual dexterity tests in dental students? – The study tested the hypothesis *that rsFC of the sensorimotor network and the salience networks are significantly correlated with manual dexterity in dental but not in non-dental students.*

Materials and methods

Participants

Undergraduate students in their third to sixth year of study were recruited via an advertisement circulated on the university campus. The inclusion criteria for subject recruitment are: (a) able to conduct the written informed consent procedure independently, (b) aged between 20 and 35 years, and (c) a third-year (or above) student studying at National Yang Ming Chiao Tung University. The exclusion criteria are: (a) having a history of major neurological diseases, (b) having a history of major psychiatric diseases, (c) limited hand movement due to diseases or medical treatment, (d) limited visual function due to diseases or medical treatment, (e) having a history of brain injury of receiving cranial surgery, (f) unable to receive magnetic resonance imaging (MRI) scan due to metal implant installed, and (g) unable to receive MRI scan due to emotional disturbance about the context of scanning. The study has been approved by the Institutional Review Board (IRB) of National Yang Ming Chiao Tung University (IRB code: NYCU111187AE).

Study design

The participants were categorized into two groups: (a) the Dental group, consisting of undergraduate students for a DDS program in the Department of Dentistry, and (b) the Non-Dental group, consisting of undergraduate students from other health-related departments, including medicine, nursing, physical therapy, and pharmacology. Notably, the participants from the Dental group all have completed at least one of the courses of dental skill training, including tooth carving in *Dental Morphology* (the third year), using a dental handpiece in *Restorative Dentistry* (the fourth year), and tooth preparation in *Fixed Prosthodontics* (the fifth year). None of the participants in the Non-Dental group has received these courses. All the participants completed the same set of sensorimotor and visual-attention tests under standardized settings (Table 1) and were invited for resting-state functional magnetic resonance imaging (MRI) and structural MRI scans.

The sample size of this study was estimated based on a statistical power analysis, using G*Power ver. 3.1.9.4 [23]. We referred to the previous findings on the difference between the Purdue Pegboard Test using the dominant hand and the same test using the non-dominant hand, in dental students receiving skill training [2]. The effect size was calculated according to the published results (Lugassy et al., S3 Appendix [2]). A Wilcoxon signed-rank test was conducted to examine the difference between these two conditions due to the non-normal distribution of our scores (see 3. Results). The minimal sample size was estimated with Type I and Type II errors controlled at alpha = 0.05 and beta = 0.1, respectively. Based on the settings, at least 18 participants were required.

Sensorimotor and visual-attention tests

The participants were asked to complete three visual-cognitive tests and five sensorimotor tests with a fixed sequence, as listed in Table 1. The visual-attention tests are the Visual Search Task (VST), the Sustained Attention Response Task (SART), and the Random Dot 2 Stereo Acuity Test (SAT) [24]. The sensorimotor tests are the Hand Steadiness Test-Groove Type (HST-G) as well as Hole Type (HST-H), the O'Connor Tweezer Dexterity Test (TDT), the Purdue Pegboard Test (PPT), and an assessment of finger pinch force (FPF). All the tests were conducted under the instruction of the same researcher with standardized instruments (Table 1). The SART assessment was performed using the online toolbox PsyToolkit (v. 3.4.4) [25, 26]. The HST-G, HST-H, TDT, and PPT were conducted using standardized test devices (Lafayette Instrument, Lafayette, U.S.A.). SAT, HST, TDT, PPT, FPF were conducted based on standard protocols according to the instructions from the official manuals provided by the manufacturers.

Notably, some tests consisted of different variations and score items. Three variations of the VST were conducted for increasing difficulty: a simple VST (VST-S) with fewer distractors, a complex VST (VST-C) with more distractors, and a VST with background distraction (VST-B) that mimics the background of human tissue. Three score items were collected for the SART: the accuracy for Go trials (SART-G), the accuracy for NoGo trials (SART-NG), and the total accuracy (SART-T) [27]. Four variations of the PPT were conducted: the performance for the dominant hand (PPT-D), the non-dominant hand (PPT-ND), two hands (PPT-2), and a test of assembling tools (PPT-A) [2, 9]. Two score items were collected for the FPF, respectively, for the dominant hand (FPF-D) and the non-dominant hand (FPF-ND). Additionally, we calculated two derivative indices:

(A) The index ΔTDT denoted the gain of speed during the TDT. The overall process of the TDT, i.e., to complete inserting 100 pins, was evenly split into five batches (e.g., inserting the first 20 pins, inserting pins #21 to #40, and inserting the pins (#41 to #60, etc.). Among the five batches, the maximal and minimal time to complete was selected, and ΔTDT = (the maximal time - the minimal time) / Total TDT time.
(B) The index ΔPPT denoted the relative difference in performance between dominant and non-dominant hands, i.e., ΔPPT = (PPT-D - PPT-ND) / PPT-ND.

In total, 18 test variables were collected (Table 2) and analyzed for the following analysis.

Acquisition of imaging data

Thirty participants also received structural and resting-state functional MRI. All MRI scans were conducted at the 3 T MRI Laboratory of National Yang Ming Chiao Tung University with a 3 Tesla Siemens MRI scanner (Siemens Magnetom Tim Trio). A resting-state functional MRI was acquired using a gradient echo planar imaging T2* weighted sequence with the following parameters: repetition time ([TR]) = 2000 ms, echo time ([TE]) = 20 ms, matrix size = $64 \times 64 \times 40$, voxel size = $3.4 \times 3.4 \times 3.4$ mm^3. The participants were asked to relax, open their eyes, and fix their sight on a crosshair shown on a screen during scanning, which lasted for six minutes. T1-weighted MRI was acquired with a ^{3}2-channel head coil using the magnetization-prepared rapid gradient-echo (MPRAGE) sequence ([TR] = 2530 ms, [TE] = 3.03 ms, flip angle = 7°, matrix size = $256 \times 256 \times 192$, voxel size = $1 \times 1 \times 1$ mm3).

Pre-processing of imaging data

Analyses of seed-based connectivity (SBC) and voxel-based morphometry (VBM) were conducted,

Table 1 Summary of the sensorimotor and visual-attention tests in the study

Mental functions	Name	Procedure	Scoring
Visual search	Visual search task (VST)	Participants are asked to visually search the location of a grey circle (i.e., the target) surrounded by distractors (see below) and point to its location on a computer screen. Each of the following tests consists of three trials.	
	Simple (VST-S)	Distractors consisting of 16 grey squares and 16 black circles	The time (sec) to correctly point to the target
	Complex (VST-C)	Distractors consisting of 32 grey squares and 32 black circles	
	Background (VST-B)	Same as VST-C but the background is filled with mesh dots	
Sustained attention	Sustained attention to response task (SART)	Participants are asked to respond to a series of 120 numbers (1–9) sequentially displayed on a computer screen by pressing 'space', except for the number '3', upon which they need to halt pressing.	
	Accuracy of 'Go' trials (SART-G)		The proportion of correct response (i.e., to press 'space' upon the presence of numbers (1–2, 4–9)
	Accuracy of 'NoGo' trials (SART-NG)		The proportion of correct response (i.e., to halt pressing 'space') upon the presence of number '3'
	Accuracy of all trials (SART-T)		The proportion of correct response for both Go and NoGo trials
Stereopsis	Random Dot 2 Stereo Acuity Test (SAT)	Participants are asked to wear a pair of polaroid glasses and look at 12 sets of random dots pictures sequentially. The 12 sets differ in visual disparities from 400 to 12.5 s arc. Each set consists of three pictures and participants need to correctly identify the one showing stereoscopic form.	The number of sets that one can identify a stereoscopic form
Hand steadiness	Hand Steadiness Test (HST)	Participants are asked to manipulate a metal stylus without touching the surrounding metal sides.	
	Groove-Type (HST-G)	Moving a stylus along a gradually narrowing groove (25 cm)	The time (sec) to complete moving through the groove successfully
	Hole-Type (HST-H)	Inserting the metal stylus into a set of holes in gradually smaller hole sizes sequentially	The number of holes to insert successfully
Manual (tweezer) dexterity†	O'Connor Tweezer Dexterity Test (TDT)	Participants are asked to insert pins in a testing board of 100 holes (10 rows X 10 columns) sequentially using a tweezer.	The total time (sec) to complete inserting 100 pins
Manual (finger) dexterity	Purdue Pegboard Test (PPT)	Participants are asked to insert a pin into a hole of the pegboard sequentially as fast as possible.	
	Dominant hand (PPT-D)	Inserting the pins using the dominant hand within 30 s	The number of pins inserted successfully
	Non-dominant hand (PPT-ND)	Inserting the pins using the non-dominant hand within 30 s	
	Both hands (PPT-2)	Inserting the pins using both hands within 30 s	
	Assembly (PPT-A)	Assembling a pin, a collar, and two washers into a set, using both hands, within 60 s	The number of pieces (pin, collar, or washer) assembled successfully
Finger force generation	Finger pinch force (FPF)	Participants are asked to hold the pinch force tester and press the testing button using the thumb with maximal force repeatedly until the maximal force is reached.	
	Dominant hand (FPF-D)	Holding the tester and pressing using the dominant hand	The maximal force (kg) is recorded as the maximal performance in consecutive tests
	Non-dominant hand (FPF-ND)	Holding the tester and pressing using the non-dominant hand	

†The overall performance of the TDT is the time to complete inserting 100 pins. Additionally, to evaluate the speed for inserting pins, the time intervals for the following conditions were collected separately: the time to complete the first 20 pins, the time to complete the second 20 pins (i.e., #21 to #40), the time to complete the third 20 pins (i.e., #41 to #60), the time to complete the fourth 20 pins (i.e., #61 to #80), and the time to complete the last 20 pins (i.e., #81 to #100)

respectively, to assess the difference in functional and structural brain features between the Dental and the Non-Dental groups. The SBC analyses were conducted using the default procedure of the CONN toolbox [28] based on Statistical Parametric Mapping (SPM12) (Wellcome Department of Cognitive Neurology, U.K.). The following pre-processing steps were conducted:

(A) slice-timing correction,
(B) realignment of the images and estimation of head motion,
(C) image registration to the Montreal Neurologic Institute (MNI) template,
(D) outlier detection using artifact detection tools [28],

Table 2 Results of descriptive analyses of tests

Non-Dental (*n* = 19)	**Mean**	**Median**	**SD**	**MIN**	**MAX**	**IQR**	**Normality**†	
VST-S	4.7	4.6	1.0	3.3	6.7	1.5	0.12	
VST-C	5.9	5.6	1.6	3.5	10.1	1.8	0.22	
VST-B	5.7	5.4	1.5	4.1	9.3	1.8	0.00	
SART-NG	0.78	0.82	0.18	0.23	1.00	0.14	0.00	
SART-G	1.00	1.00	0.00	0.99	1.00	0.00	0.00	
SART-T	0.98	0.98	0.02	0.91	1.00	0.00	0.00	
SAT	6.5	7.0	2.1	3.0	10.0	4.0	0.11	
TDT	315	312	46	232	401	47	0.71	
ΔTDT	0.06	0.06	0.02	0.02	0.12	0.03	0.40	
HST-H	5.0	5.0	1.1	3.0	7.0	2.0	0.08	
HST-G	8.4	7.0	4.2	3.0	18.0	4.0	0.02	
PPT-D	16.5	17.0	1.9	13.0	20.0	3.0	0.84	
PPT-ND	14.3	15.0	1.7	11.0	18.0	2.0	0.17	
PPT-2	12.5	13.0	2.2	9.0	16.0	2.0	0.12	
PPT-A	38.5	37.0	5.8	30.0	48.0	9.0	0.14	
ΔPPT	0.13	0.12	0.09	0.00	0.28	0.15	0.13	
FPF-D	7.5	7.4	2.5	3.2	12.7	3.2	0.85	
FPF-ND	7.7	7.6	2.9	3.7	15.2	3.8	0.20	
Dental (*n* = 26)	**Mean**	**Median**	**SD**	**MIN**	**MAX**	**IQR**	**Normality**†	***p***††
VST-S	5.1	4.9	1.2	3.4	8.3	1.4	0.08	0.290
VST-C	5.9	6.0	1.5	3.7	9.4	2.2	0.45	*0.945*
VST-B	6.1	6.0	1.7	2.9	10.4	2.0	0.93	0.223
SART-NG	0.69	0.74	0.24	0.14	1.00	0.28	0.03	0.115
SART-G	1.00	1.00	0.01	0.97	1.00	0.00	0.00	0.519
SART-T	0.97	0.97	0.03	0.90	1.00	0.03	0.01	0.063
SAT	7.7	7.0	2.4	3.0	12.0	4.0	0.15	*0.074*
TDT	330	320	52	246	474	79	0.31	*0.307*
ΔTDT	0.06	0.06	0.02	0.02	0.09	0.02	0.03	0.520
HST-H	4.5	5.0	1.2	3.0	7.0	2.0	0.01	0.235
HST-G	8.6	8.0	4.3	2.0	18.0	5.5	0.11	0.826
PPT-D	15.3	15.0	1.6	12.0	19.0	2.3	0.40	*0.022*
PPT-ND	14.2	14.0	1.5	12.0	17.0	2.3	0.05	0.806
PPT-2	12.7	13.0	2.3	8.0	18.0	3.0	0.25	*0.851*
PPT-A	40.0	40.0	4.5	28.0	48.0	6.0	0.67	*0.344*
ΔPPT	0.07	0.07	0.11	-0.08	0.25	0.21	0.03	0.117
FPF-D	8.3	7.7	3.4	4.3	16.9	4.1	0.00	0.671
FPF-ND	7.4	6.9	2.6	3.3	12.8	3.4	0.03	0.791

Notes: IQR, interquartile range; MAX, maximal value; MIN, minimal value; SD, standard deviation

†The *p* values denote the results from Shapiro-Wilk test

††The *p* values denote the results of between-group comparison based on independent t-test (in the italic font) and Mann-Whitney U test (in the regular font)

(E) spatial smoothing with a Gaussian kernel of 8 mm full-width-half-maximum (FWHM),
(F) correction for physiological noise using the a CompCor method [29], and.
(G) signals filtered by bandpass frequency between 0.008 Hz and 0.09 Hz.

Individually, the SBC maps of the following seed regions were constructed: the bilateral sensorimotor network (SMN) and the bilateral anterior insula (AIns) of the salience network [28].

The VBM analyses were conducted using the default procedure of the Computational Anatomy Toolbox (CAT12) [30] based on SPM12, including the segmentation of gray and white matter areas using the tissue probability maps of SPM12, registration to the MNI template, and spatial smoothing with a Gaussian kernel of 8 mm FWHM.

Statistical analysis

Analysis of descriptive statistics

We first conducted the analyses on the descriptive statistics, respectively, for the Dental and the Non-Dental groups. The distribution of all variables was examined using the Shapiro-Wilk test. The null hypothesis of the Shapiro-Wilk test suggests that the scores follow a normal distribution. Therefore, we considered that the p-value < alpha (here 0.1) rejects the null hypothesis, i.e., the scores do not follow a normal distribution. Between-group difference was investigated using an independent t-test and Mann-Whitney U test, respectively for normally and non-normally distributed scores. The difference between the variations of each test (i.e., VST-S vs. VST-C vs. VST-B, SART-G vs. SART-NG, PPT-D vs. PPT-ND vs. PPT-2, and FPF-D vs. FPF-ND) was investigated using paired t-test and Wilcoxon signed-rank test, respectively for normally and non-normally distributed scores.

Analysis of the first hypothesis

To investigate the pattern of mental networking between the sensorimotor and visual-attention functions related to manual dexterity, we first conducted graph-based analyses, respectively, for Dental and Non-Dental groups. An undirectional weighted network was constructed, with 16 vertices (nodes) that represent the 16 test variables (see Methods 2.3 and Table 2). The edges (links) between each pair of nodes are defined as the absolute value of correlation coefficients between each pair of test variables. Because individual age and sex may be associated with test performance, we quantified the strength of cross-variable association using partial correlation analysis, controlled for age and sex. In total 120 edges were quantified for each network.

To test our first hypothesis that *in the dental students, there is increased networking between the performance of manual dexterity and visual-attention tests, compared to non-dental students*, we examined the edges showing a statistically significant correlation. The edges common to both groups and specific to each group were calculated. Furthermore, an analysis of modularity was conducted to investigate the community structure of the node. The nodes differentiated into the same module showed stronger intra-modular connections but weaker inter-modular connections. Finally, we investigated the eigenvector centrality [31], a topological metric that reflects the impact of a node in a network for all nodes. The graph-based analysis was conducted using the Brain Connectivity Toolbox [32]. The networks were displayed using BrainNet Viewer v.1.7 [33].

Analysis of the second hypothesis

To test our second hypothesis that *dental students and non-dental students differ in the rsFC or gray/white matter volume of the sensorimotor and salience networks*, comparisons in functional and structural brain features were conducted between the Dental and Non-Dental groups using SPM12. In terms of rsFC, the between-group comparison was conducted for four SBC maps, respectively, in which the bilateral SMN and the AIns were the seed regions. The general linear models (GLM) were established with individual sex and age as the nuisance regressors. In terms of structural features, the between-group comparison was conducted for gray matter volume (GMV) and white matter volume (WMV), respectively. The GLMs were established with individual sex, age, and total intracranial volume (TICV) as the nuisance regressors.

All the imaging results were thresholded with the following level of significance: uncorrected $p < 0.001$ for intensity and $p < 0.05$ corrected for familywise error (FWE), according to the suggestion by previous research [34].

Analysis of the third hypothesis

To test our third hypothesis that *rsFC of the sensorimotor network and the salience networks are significantly correlated with manual dexterity in dental but not in non-dental students*, we focused on the performance of bimanual dexterity of tool assembling, PPT-A, which showed a greater number of associations with other mental functions in the Dental group (see Results and Fig. 1B). We investigated the association between the PPT-A score and the SBC of the lateral SMN, which showed increased connectivity in the Dental group, compared to the Non-Dental group (Fig. 2A; Table 3). A regression model was established to investigate the brain regions where connectivity with the SMN was positively correlated with the PPT-A score, with individual sex and age as the nuisance regressors.

Results

Analysis of descriptive statistics

The results of descriptive analyses are shown in Table 2. In general, the results of sensorimotor tests are consistent with previous findings of psychomotor tests in standardized testing conditions. For example, the scores of manual dexterity tests are consistent with the findings (PPT-D: 15.71 ± 1.89, PPT-ND: 14.58 ± 1.90) from previous research of dental students [35]. Notably, while some psychomotor tests (e.g., the PPT) revealed normally distributed scores, the scores from visual-attention tests revealed a non-normal distribution (Table 2). The between-group analysis showed no significant difference for all the test variables, except for the score of

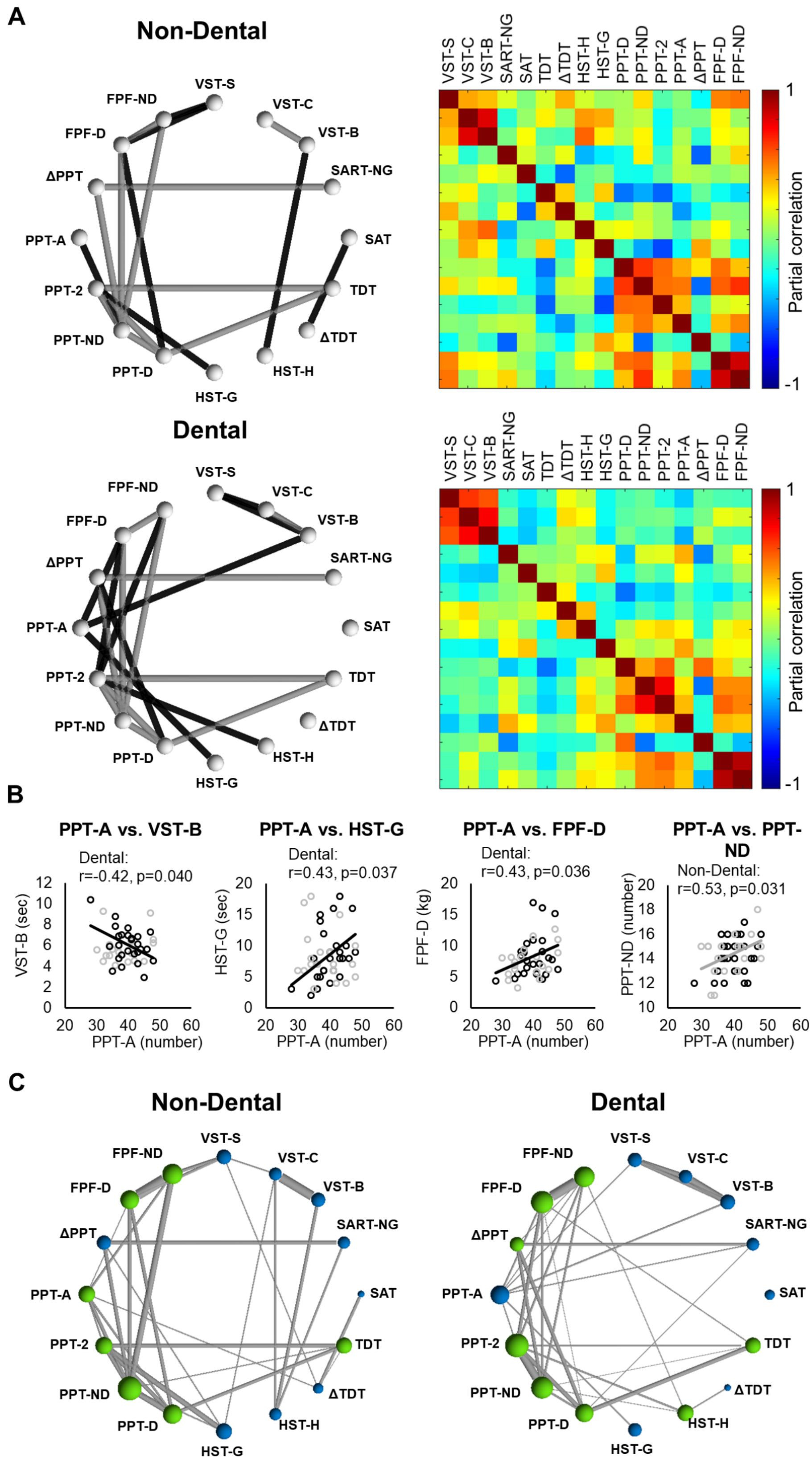

Fig. 1 (See legend on next page.)

(See figure on previous page.)

Fig. 1 Results of graph-based network analyses. (**A**) The networks represent the mental networking of 16 test variables for the Non-Dental and Dental groups, respectively. The edges represented by a gray line denote significant cross-variable correlations common to both groups. The edges represented by a black line denote the significant cross-variable correlations specific to each group. The right panel shows the adjacent matrices that reveal the coefficients of partial correlation controlled for sex and age of each pair of variables. (**B**) The scatter plots of the correlation between the PPT-A and the VST-B, the HST-G, the FPD-D, and the PPT-ND, respectively for the Dental group (the black circle) and the Non-Dental group (the gray circle). The r value and p value of partial correlation (controlled for sex and age) are reported. (**C**) The analysis of modularity reveals different community structures of the 16 test variables between the groups, with the PPT-A forming a module (the blue nodes) with the visual-attention tests in the Dental group. The size of each node represents the eigenvector centrality of the node. Only the edges with the top 25% highest correlation are displayed. For the abbreviations of the 16 test variables, please refer to Table 1

PPT-D, which showed a lower number in the Dental group (15.3 ± 1.6), compared to the Non-Dental group (16.5 ± 1.9) (two-tailed independent t-test, $p = 0.022$).

Between the variations of each test, we found increased time (i.e., decreased performance) for VST-C and VST-B, compared to VST-S (Wilcoxon signed-rank test, two-tailed $p < 0.001$ and $p < 0.001$, respectively). The performance between VST-C and VST-B did not significantly differ. We also found decreased accuracy for SART-NG, compared to SART-G (Wilcoxon signed-rank test, two-tailed $p < 0.001$), decreased performance for PPT-2 compared to PPT-ND (paired t-test, two-tailed $p < 0.001$) and for PPT-ND compared to PPT-D (paired t-test, two-tailed $p < 0.001$). The difference between FPF-D and FPD-ND did not significantly differ (Wilcoxon signed-rank test, two-tailed $p = 0.06$).

Analysis of the first hypothesis

The networks of cross-variable association of the Dental and the Non-Dental groups are shown in Fig. 1A. In both groups, there were significant correlations between the following 11 pairs of test variables: VST-C and VST-B, SART-NG and ΔPPT, TDT and PPT-D, TDT and PPT-2, PPT-D and PPT-ND, PPT-D and PPT-2, PPT-ND and PPT-2, PPT-ND and ΔPPT, PPT-ND and FPF-D, PPT-ND and FPF-ND, and FPF-D and FPF-ND. Notably, some correlations were identified specifically to each group: In the Dental group, the three sub-variables of VST were coupled mutually, and the PPT-A was correlated with VST-B, HST-G, and FPF-D. In contrast, PPT-A was associated with PPT-ND in the Non-Dental group (Fig. 1B).

The graph-based analysis revealed that the networks differed between the groups in community structure. As shown in Fig. 1C, an analysis of modularity revealed that the psychomotor tests, i.e., PPT-D, PPT-ND, PPT-2, and TDT, showed a stronger connection among one another. Specifically, in the Dental group, there was a stronger connection between the PPT-A and the VST. In contrast, the PPT-A showed a stronger connection with other psychomotor tests in the Non-Dental group (Fig. 1C). The findings suggested a unique role of the PPT-A, which showed a closer connection with the visual-attention function in the Dental group.

Analysis of the second hypothesis

Seventeen participants from the Dental group and 13 participants from the Non-Dental Group have received MRI scans. Using the left SMN as the seed, we found increased rsFC at the right middle frontal gyrus ([32, 4, 46], size = 545 voxels, $p_{\mathrm{FWE-corrected}}$<0.001) and decreased rsFC at the left posterior insula (PIns) ([-34, -12, 22], size = 192 voxels, $p_{\mathrm{FWE-corrected}}$=0.009) in the Dental group compared to the Non-Dental Group (Fig. 2A). Using the right SMN as the seed, we found increased rsFC at the right middle frontal gyrus ([34, 8, 46], size = 213 voxels, $p_{\mathrm{FWE-corrected}}$=0.006) and decreased rsFC at the left posterior insula (PIns) ([-36, -20, 6], size = 267 voxels, $p_{\mathrm{FWE-corrected}}$=0.002) in the Dental group compared to the Non-Dental Group (Table 3A and Fig. 2A).

Using the left AIns as the seed, we did not find an above-threshold cluster for the comparison between the Dental and the Non-Dental groups. Finally, using the right AIns as the seed, we found decreased rsFC at the left superior frontal gyrus ([-10, 22, 54], size = 268 voxels, $p_{\mathrm{FWE-corrected}}$=0.001), the right temporal pole ([52, 18, -28], size = 188 voxels, $p_{\mathrm{FWE-corrected}}$=0.010), and the anterior cingulate cortex ([-2, 52, 4], size = 161 voxels, $p_{\mathrm{FWE-corrected}}$=0.021) in the Dental group compared to the Non-Dental Group (Table 3A and Fig. 2A).

The VBM analysis did not reveal any above-threshold cluster for an increased GMV in the Dental, compared to the Non-Dental group. We found increased GMV in the Non-Dental, compared to the Dental group, at the left primary motor cortex ([-50, 0, 38], size = 635 voxels, $p_{\mathrm{FWE-corrected}}$=0.042) (Table 3B and Fig. 2B). No above-threshold cluster was found in the difference of WMV.

Analysis of the third hypothesis

In the Dental group, we found a significantly positive correlation between the PPT-A score and the rsFC between the left SMN and the right supramarginal gyrus (SMG) ([60, -30, 40], size = 127 voxels, $p_{\mathrm{FWE-corrected}}$=0.021). We found a significantly negative correlation between the PPT-A score and the rsFC between the left SMN and the cerebellum ([6, -50, -44], size = 118 voxels, $p_{\mathrm{FWE-corrected}}$=0.029) (Table 3C and Fig. 2C). No above-threshold cluster was found for the Dental group when the right SMN was the seed.

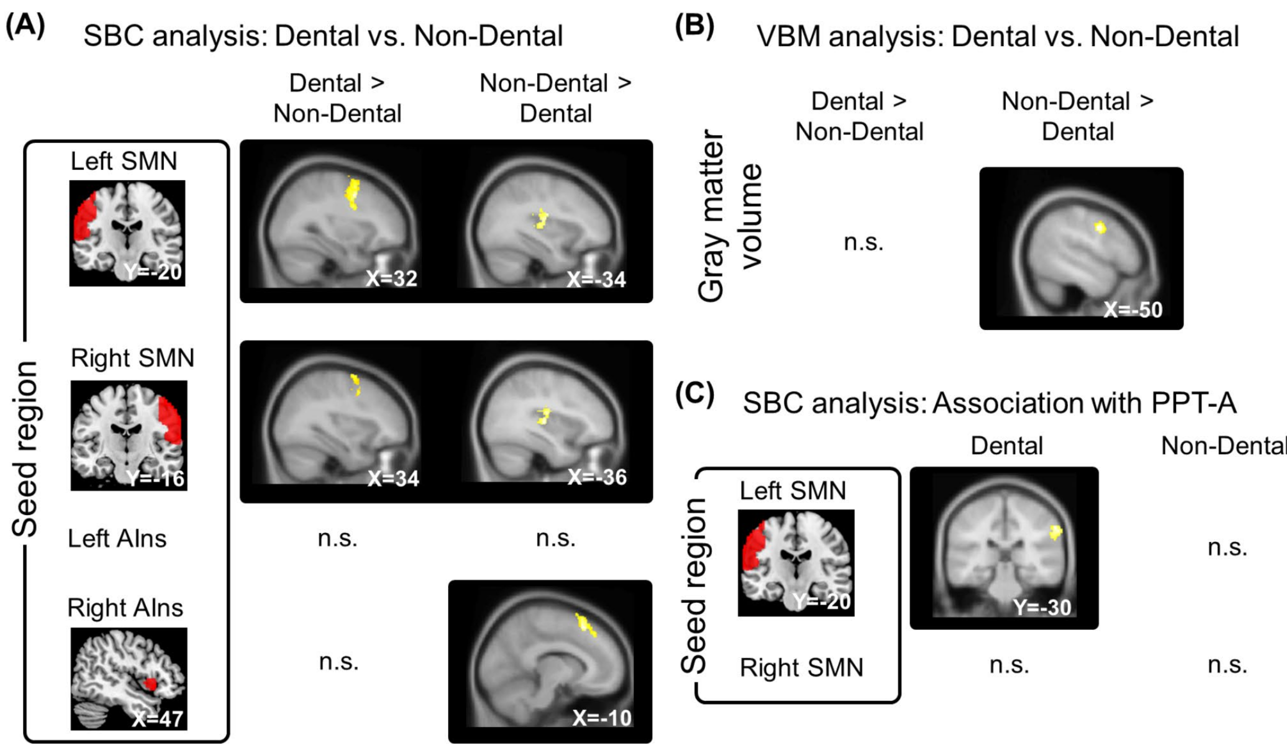

Fig. 2 Results of functional and structural features related to expertise of dental training. (**A**) The results of seed-based connectivity (SBC) analyses with the bilateral sensorimotor network (SMN) and the anterior insula (AIns) as the seed. Increased resting-state functional connectivity (rsFC) is identified between bilateral SMN and the right middle frontal gyrus in the Dental group, compared to the Non-Dental group. In contrast, increased rsFC is identified between bilateral SMN and the left posterior insula (PIns) in the Non-Dental group, compared to the Dental group. Additionally, increased rsFC is identified between right AIns and the left superior frontal gyrus in the Non-Dental group, compared to the Dental group. (**B**) The results of voxel-based morphometry (VBM). Increased gray matter volume is identified at the left primary motor cortex in the Non-Dental group, compared to the Dental group. (**C**) The association between rsFC and manual dexterity. Positive correlation is identified between the score of Purdue Pegboard Test-Tool Assembly (PPT-A) and the rsFC between the left SMN and the right supramarginal gyrus in the Dental group. All the clusters are thresholded by peak intensity $p_{\mathrm{uncorrected}}$<0.001 and cluster size $p_{\mathrm{FWE-corrected}}$<0.05

Discussion

Summary of the major findings

The current study presented novel findings regarding the mental networking and brain mechanisms related to manual dexterity. The major findings include:

1. The performance of manual dexterity of tool assembling (PPT-A) was associated with visual search, hand steadiness, and finger force generation, only in the Dental group, supporting our first hypothesis that different pattern of mental networking was associated with expertise in dental training.
2. We found increased rsFC between the bilateral SMN and the right middle frontal gyrus, decreased rsFC between the bilateral SMN and the left PIns, decreased rsFC between the right AIns and the left superior frontal gyrus, and decreased GMV at the left primary motor cortex, in the Dental group, compared to the Non-Dental group. The findings supported our second hypothesis that expertise in dental training was associated with functional and structural brain features.
3. We found a positive correlation between the PPT-A score and the rsFC between the left SMN and the right SMG. The findings partially supported our third hypothesis that manual dexterity was associated with the SMN but not the salience network.

Mental networking of manual dexterity is associated with expertise in dental skill training

Across the sensorimotor and visual-attention tests, our findings did not reveal an overall difference between the Dental and the Non-Dental groups (Table 2). In this study, the Non-Dental group consisted of students from other clinical fields (e.g., nursing, medicine, and physical therapy), and these participants also received skill training on manual manipulation. It is not surprising that the Non-Dental group showed equal or even superior ability in psychomotor tests (e.g., PPT-D), compared to the Dental group. Nevertheless, the network analysis revealed the pattern of mental function networking differed between the groups (Fig. 1A). Among the sensorimotor tests,

Table 3 Results of functional and structural brain features

(A) Between-group difference in seed-based connectivity								
	cluster size (voxel)	**cluster$p_{FWE-corrected}$**	**MNI coordinates**			***Z***	**Region**	
			x	**y**	**z**			
Seed: Left SMN								
D > ND	545	< 0.001	32	4	46	4.5	R	Middle frontal gyrus
			36	4	30	4.3	R	Primary motor cortex
			30	6	54	3.9	R	Middle frontal gyrus
ND > D	192	0.009	-32	-18	14	4.0	L	Posterior insula
			-38	-28	22	4.0	L	
			-34	-12	22	3.8	L	
Seed: Right SMN								
D > ND	213	0.006	28	4	40	4.6	R	Middle frontal gyrus
			34	8	46	4.2		
			34	0	68	4.0	R	Superior frontal gyrus
ND > D	267	0.002	-36	-20	6	4.1	L	Posterior insula
			-38	-18	18	3.9		
			-46	-14	20	3.8	L	Secondary somato sensory cortex
Seed: Left AIns								
D > ND	n.s.							
ND > D	n.s.							
Seed: Right AIns								
D > ND	n.s.							
ND > D	268	0.001	-10	22	54	4.5	L	Superior frontal gyrus
			-12	34	46	3.8		
	188	0.010	52	18	-28	4.1	R	Temporal pole
			42	20	-32	3.9		
			34	18	-28	3.2		
	161	0.021	-2	52	4	3.6	L	Anterior cingulate cortex
			-4	50	12	3.6		
			8	52	-6	3.5	R	Medial prefrontal cortex
(B) Between-group difference in gray matter volume								
	cluster size (voxel)	**cluster$p_{FWE-corrected}$**	**MNI coordinates**			***Z***	**Region**	
			x	**y**	**z**			
D > N	n.s.							
ND > D	653	0.042	-50	0	38	4.5	L	Primary motor cortex
			-59	-9	48	3.5	L	Primary somato sensory cortex
			-59	2	21	3.4		
(C) Association between the PPT-A score and seed-based connectivity								
	cluster size (voxel)	**cluster$p_{FWE-corrected}$**	**MNI coordinates**			***Z***	**Region**	
			x	**y**	**z**			
Seed: Left SMN								
Positive correlation								
D	127	0.021	60	-30	40	3.9	R	Supramarginal gyrus
			58	-32	32	3.6		
Negative correlation								
D	118	0.029	6	-50	-44	4.4	R	Cerebellum lobule 9
			0	-52	-50	4.1		
			-8	-40	-46	3.9	L	

Notes: AIns, anterior insula; D, the Dental group; L, the left hemisphere; ND, the Non-Dental group; PPT-A, the Purdue Pegboard Test for assembling tools; R, the right hemisphere; SMN, sensorimotor network

some test variables were highly correlated due to the coordination between the dominant and non-dominant hands (e.g., FPF-D vs. FPD-ND and PPT-D vs. PPT-ND), consistent with previous findings [2]. Increased finger force was associated with better performance of the PPT (e.g., FPF-ND vs. PPT-ND), and the performance of similar tests also showed a strong association (e.g., PPT-2 vs. TDT), consistent with previous findings [2].

Specifically, the Dental group showed stronger connections among the VST tests, a pattern not displayed in the Non-Dental group. Furthermore, while the pattern of connections for PPT-D and PPT-ND are similar between the Dental and the Non-Dental groups, the PPT-A, which requires complex bimanual coordination for tool assembling, showed a greater number of connections with other tests in the Dental group (Fig. 1A and B). Bimanual manipulation, such as using a mouth mirror and an explorer to examine a dental cavity, is a key feature specific to dental skill training [36]. Therefore, it should be considered as 'precision finger movement', requiring fingers to move independently [37]. The association between visual attention and fine motor skills – including finger dexterity and force generation – has been highlighted in recent studies. For example, in aged individuals, distraction was associated with decreased performance of a hand-tracking task and grip force generation [10]. The change in visualization condition of psychomotor tests, i.e., reflecting the testing condition via a mirror, also influenced the performance of manual dexterity [9]. Consistently, our findings revealed that the PPT-A shared the same module with the test items demanding increased attention (e.g., the VST, the SART-NG, and the HST-G), suggesting that the high demand for attention processing is related to the expertise of dental training.

Brain features associated with expertise in dental skill training

To our knowledge, the current study provided the first neuroimaging evidence of the difference in rsFC and GMV between the Dental and the Non-Dental groups. We reasoned the difference may be associated with the expertise of dental skill training, which requires increased efforts in sensorimotor and visual-attention processing. Changes in rsFC of the SMN have been reported in other expertise that requires similar mental networking of manual dexterity, including musicians [19] and surgeons [18]. Notably, we found increased rsFC between the bilateral SMN (which encompasses the finger region of motor homunculus, see Fig. 2A) and the middle frontal gyrus, which overlaps with the premotor cortex, a key region for motor learning [38]. Research on the bimanual coordination of surgeons has revealed the connectivity of the premotor and prefrontal regions seed connectivity is associated with motor skill learning [39]. Interestingly, our findings also revealed decreased rsFC and GMV in the Dental group, compared to the Non-Dental group (Fig. 2; Table 3). Recent findings also reported that better manual dexterity was associated with decreased connectivity in the motor cortex [40]. The decreased rsFC in dental students may also reflect the nature of their skill learning, i.e., using both hands independently for precise movement [37].

Notably, in the current study, either the Dental or the Non-Dental group was not selected by their manual dexterity in their entrance examination, which reduces the confounding effect on the rs-FC findings. However, the cultivation of art or music skills is associated with changes in structural and functional brain features [21, 22]. In the students, early experiences of learning art or music skills (before the undergraduate programs) may be associated with their performance in manual dexterity. The cross-talk between prior experience in art/music performance and clinical skill learning would require further investigation.

Limitation of the study and further considerations

The results of this study should be cautiously interpreted considering the following limitations. First, the study presents data from a cross-sectional study with a comparison between participants of different expertise. The findings may imply the neuroplastic effect of dental skill training on brain features but the cause-effect relationship between brain and behavior should be asserted by further longitudinal research, which should focus on the comparison between pre-training and post-training conditions [41]. Second, the sample size of the study is relatively small because all participants were recruited voluntarily. While voluntary participation guaranteed no coercion or conflict of interests between teachers and students, there exists the risk of sampling bias – i.e., the participants who volunteered in the study were more confident in their fine motor skills. Finally, in the study, the sensorimotor and visual-attention tests were conducted under the same standard settings as psychological and clinical research. However, the perceptual demands and manual manipulation in real dental practice can be more complicated than the simplified settings. For example, dentists need to inspect very small lesions and manipulate them inside the oral cavity, and such a limited space of operation cannot be reflected by the standard test settings. Therefore, one should be careful about generalizing the test scores to actual performance in clinical settings.

Implications in medical education of clinical skill learning

The novel findings from this current study help to elucidate the mental function networking of manual dexterity dental students. Furthermore, the findings highlight new directions in training clinical skills in medical/dental students, especially for the following aspects.

(A) The findings from the mental function network revealed a connection between visual-attentional performance and sensorimotor performance, suggesting the importance of practice in visual search and sustained attention in dental skill training.

(B) In the Dental group, better performance of PPT-A (tool assembling) and PPT-2 (two-hands) – which all require bimanual manipulation – was associated with better performance in other assessments. The findings highlight the importance of bimanual coordination in dental skill training.

(C) Previous studies have shown that changes in brain features (e.g., increased functional connectivity) are associated with skill training in playing music and painting. Our findings of brain features may suggest such a 'neuroplastic' effect of dental skill learning on the brain.

(D) Our results of the visual-attentional performance, which are novel in the literature, help the design of digital devices (e.g., augmented reality and virtual reality-based) to assist dental skill training.

Conclusion

Dental skill training is associated with the networking of sensorimotor and visual-attention functions and coupled with increased rsFC of the SMN. In dental students, better manual dexterity is associated with the functional connectivity of the SMN.

Author contributions
C-S Lin led the project, designed the study, executed the study, analyzed data, and wrote the initial draft; T-I Chen executed the study; C-C Yang initiated the project and designed the study.

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Data availability
Data in this study are available upon request.

Code availability
Not applicable.

Declarations

Ethics approval and consent to participate
The study was approved by the Institutional Review Board (IRB) of National Yang Ming Chiao Tung University (IRB code: NYCU111187AE). Informed consent was obtained from all subjects before they participated the study. The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Luck O, Reitemeier B, Scheuch K. Testing of fine motor skills in dental students. Eur J Dent Educ. 2000;4:10–4. https://doi.org/10.1034/j.1600-0579.2000.040103.x.
2. Lugassy D, et al. Predicting the clinical performance of dental students with a manual dexterity test. PLoS ONE. 2018;13:e0193980. https://doi.org/10.1371/journal.pone.0193980.
3. El-Kishawi M, Khalaf K, Winning T. How to improve fine motor skill learning in dentistry. Int J Dent. 2021;2021(6674213). https://doi.org/10.1155/2021/6674213.
4. Novack R, Turgeon DP. Investigating dental aptitude test (DAT) results as predictors for preclinical and clinical scores in dental school. J Dent Educ. 2020;84:1254–61. https://doi.org/10.1002/jdd.12331.
5. Spratley M. Aptitude testing and the selection of dental students. Aust Dent J. 1990;35:159–68.
6. Segura C, Halabi D, Navarro N. Design and validation of a basic dental psychomotor skills test for novice dental students. J Dent Educ. 2018;82:1098–104. https://doi.org/10.21815/JDE.018.111.
7. Sobinov AR, Bensmaia SJ. The neural mechanisms of manual dexterity. Nat Rev Neurosci. 2021;22:741–57. https://doi.org/10.1038/s41583-021-00528-7.
8. Giuliani M, et al. Is manual dexterity essential in the selection of dental students? Br Dent J. 2007;203:149–55. https://doi.org/10.1038/bdj.2007.688.
9. Levanon Y, et al. Assessment of the modified O'Connor tweezer dexterity and Purdue pegboard test for use among dental students. J Dent Educ. 2022. https://doi.org/10.1002/jdd.13137.
10. Rinne P, et al. Motor dexterity and strength depend upon integrity of the attention-control system. Proc Natl Acad Sci U S A. 2018;115:E536–45. https://doi.org/10.1073/pnas.1715617115.
11. Al-Amad SH, Alhammouri QM, Jaser S, Inshasi FK. Association between stereoacuity and simulated clinical performance among dental students: an exploratory investigation. J Dent Educ. 2024;88:418–24. https://doi.org/10.1002/jdd.13429.
12. Dong H, Barr A, Loomer P, Rempel D. The effects of finger rest positions on hand muscle load and pinch force in simulated dental hygiene work. J Dent Educ. 2005;69:453–60.
13. Strenge H, Niederberger U, Seelhorst U. Correlation between tests of attention and performance on grooved and Purdue pegboards in normal subjects. Percept Mot Skills. 2002;95:507–14. https://doi.org/10.2466/pms.2002.95.2.507.
14. Borsboom D, et al. Network analysis of multivariate data in psychological science. Nat Reviews Methods Primers. 2021;1:58.
15. Felin Fochesatto C, et al. A network analysis involving mental difficulties, cognition, physical fitness, 24-hour movement components, fatness, and sociodemographic factors in children. J Exerc Sci Fit. 2023;21:416–23. https://doi.org/10.1016/j.jesf.2023.10.001.
16. Nevado A, Del Rio D, Pacios J, Maestu F. Neuropsychological networks in cognitively healthy older adults and dementia patients. Neuropsychol Dev Cogn B Aging Neuropsychol Cogn. 2022;29:903–27. https://doi.org/10.1080/13825585.2021.1965951.
17. Bondi D, Robazza C, Lange-Kuttner C, Pietrangelo T. Fine motor skills and motor control networking in developmental age. Am J Hum Biol. 2022;34:e23758. https://doi.org/10.1002/ajhb.23758.
18. Andersen AG, Riparbelli AC, Siebner HR, Konge L, Bjerrum F. Using neuroimaging to assess brain activity and areas associated with surgical skills: a systematic review. Surg Endosc. 2024;38:3004–26. https://doi.org/10.1007/s00464-024-10830-x.
19. Criscuolo A, Pando-Naude V, Bonetti L, Vuust P, Brattico E. An ALE meta-analytic review of musical expertise. Sci Rep. 2022;12:11726. https://doi.org/10.1038/s41598-022-14959-4.
20. Fasano MC, et al. Inter-subject similarity of brain activity in expert musicians after multimodal learning: A behavioral and neuroimaging study on learning to play a piano sonata. Neuroscience. 2020;441:102–16. https://doi.org/10.1016/j.neuroscience.2020.06.015.
21. Bolwerk A, Mack-Andrick J, Lang FR, Dorfler A, Maihofner C. How Art changes your brain: differential effects of visual Art production and cognitive Art evaluation on functional brain connectivity. PLoS ONE. 2014;9:e101035. https://doi.org/10.1371/journal.pone.0101035.
22. Palomar-Garcia MA, Zatorre RJ, Ventura-Campos N, Bueicheku E, Avila C. Modulation of functional connectivity in Auditory-Motor networks in musicians compared with nonmusicians. Cereb Cortex. 2017;27:2768–78. https://doi.org/10.1093/cercor/bhw120.

23. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39:175–91. https://doi.org/10.3758/bf03193146.
24. Deepa BMS, Valarmathi A, Benita S. Assessment of stereo acuity levels using random Dot stereo acuity chart in college students. J Family Med Prim Care. 2019;8:3850–3. https://doi.org/10.4103/jfmpc.jfmpc_755_19.
25. Stoet G. PsyToolkit: a software package for programming psychological experiments using Linux. Behav Res Methods. 2010;42:1096–104. https://doi.org/10.3758/BRM.42.4.1096.
26. Stoet G, PsyToolkit. A novel web-based method for running online questionnaires and reaction-time experiments. Teach Psychol. 2017;44:24–31.
27. Carter L, Russell PN, Helton WS. Target predictability, sustained attention, and response Inhibition. Brain Cogn. 2013;82:35–42. https://doi.org/10.1016/j.bandc.2013.02.002.
28. Whitfield-Gabrieli S, Nieto-Castanon A. Conn: a functional connectivity toolbox for correlated and anticorrelated brain networks. Brain Connect. 2012;2:125–41. https://doi.org/10.1089/brain.2012.0073.
29. Behzadi Y, Restom K, Liau J, Liu TT. A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. NeuroImage. 2007;37:90–101. https://doi.org/10.1016/j.neuroimage.2007.04.042.
30. Gaser C et al. CAT–A computational anatomy toolbox for the analysis of structural MRI data. *biorxiv*, 2022.2006. 2011.495736 (2022).
31. Lohmann G, et al. Eigenvector centrality mapping for analyzing connectivity patterns in fMRI data of the human brain. PLoS ONE. 2010;5:e10232. https://doi.org/10.1371/journal.pone.0010232.
32. Rubinov M, Kötter R, Hagmann P, Sporns O. Brain connectivity toolbox: a collection of complex network measurements and brain connectivity datasets. NeuroImage 47, S169 (2009).
33. Xia M, Wang J, He Y. BrainNet viewer: a network visualization tool for human brain connectomics. PLoS ONE. 2013;8:e68910. https://doi.org/10.1371/journal.pone.0068910.
34. Woo CW, Krishnan A, Wager TD. Cluster-extent based thresholding in fMRI analyses: pitfalls and recommendations. NeuroImage. 2014;91:412–9. https://doi.org/10.1016/j.neuroimage.2013.12.058.
35. Saeed M, et al. Comparative analysis of manual dexterity of dental students at Ajman university following one academic year of preclinical training sessions: A longitudinal cohort study. Eur J Dent. 2023;17:1179–88. https://doi.org/10.1055/s-0042-1758793.
36. Kaluschke M, Yin MS, Haddawy P, Suebnukarn S, Zachmann G. The effect of 3D stereopsis and hand-tool alignment on learning effectiveness and skill transfer of a VR-based simulator for dental training. PLoS ONE. 2023;18:e0291389. https://doi.org/10.1371/journal.pone.0291389.
37. Dietz V. Neural coordination of bilateral power and precision finger movements. Eur J Neurosci. 2021;54:8249–55. https://doi.org/10.1111/ejn.14911.
38. Dayan E, Cohen LG. Neuroplasticity subserving motor skill learning. Neuron. 2011;72:443–54. https://doi.org/10.1016/j.neuron.2011.10.008.
39. Andreu-Perez J, Leff DR, Shetty K, Darzi A, Yang GZ. Disparity in frontal lobe connectivity on a complex bimanual motor task aids in classification of operator skill level. Brain Connect. 2016;6:375–88. https://doi.org/10.1089/brain.2015.0350.
40. Maddaluno O, et al. Encoding manual dexterity through modulation of intrinsic alpha band connectivity. J Neurosci. 2024;44. https://doi.org/10.1523/JNEUROSCI.1766-23.2024.
41. Bezzola L, Mérillat S, Jäncke L. Motor training-induced neuroplasticity. Gero-Psych (2012).

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