Effects of habitual dart training on hemispheric lateralization in older adults: a cross-sectional study using functional near-infrared spectroscopy

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Abstract

Exercise training is one of the most effective ways of preventing dementia. In this study, we focus on exercise training using a dart game called Wellness Darts. Previous studies have shown that Wellness Darts is effective in preventing dementia through cognitive memory testing. However, the effects of continual Wellness Dart training on brain function are unclear. The purpose of this study was to elucidate the effects of sustained Wellness Darts practice on brain function in older adults. Here, we cross-sectionally compared the brain activity patterns between an expert older group who practiced darts continually against control groups of a non-expert older group and a younger group who had no experience with darts. Functional near-infrared spectroscopy (fNIRS) was used to measure brain activity, and their patterns were quantified by lateralization index (LI). The results showed that the younger group and the expert older group had significantly higher LI values than the non-expert older group and that these values did not differ between the expert older and younger groups. In addition, the accuracy of the dart-throwing test in the expert older group was positively correlated with the LI value. These results suggest that the Wellness Dart promotes hemispheric lateralization and has potential as exercise training in the prevention of dementia.

1 Introduction

Dementia is caused by a decline in cognitive function due to brain atrophy. When cognitive function deteriorates to the point where it interferes with daily life, it is called mild cognitive impairment (MCI). In the MCI stage, there are no problems in daily life, so the symptoms progress unnoticed,

and dementia develops. Therefore, early intervention at the MCI stage and prevention of MCI and thus, dementia, is very important.

Prevention of dementia requires, among other things, management of hypertension, i.e., the identification and control of risk factors for stroke and cardiovascular disease (Hanon et al., 2004; Román, 2005). However, although these measures can prevent hypertension-related dementia, they are ineffective in preventing dementia caused by other factors. Physical inactivity, diabetes mellitus, smoking, and depressive symptoms are also associated with the risk of developing Alzheimer's disease, the most common form of dementia. Among these, physical inactivity is one of the most preventable risk factors for Alzheimer's disease and higher levels of physical activity have been shown to reduce the risk of developing Alzheimer's disease (Meng et al., 2020). Therefore, promoting physical activity as a means of preventing dementia has received much attention. Physical activity associated with exercise training has shown to cause significant changes in brain health and cognitive performance, with potential effects on a wide range of cognitive functions, including memory, attention, and executive function (McGough et al., 2014). It has also been reported that executive functioning improves after low-intensity exercise, with increased activity in the dorsolateral prefrontal cortex (DLPFC) and frontal pole, brain regions associated with executive function (Byun et al., 2014).

In this study, we focused on exercise training using a darts game called Wellness Darts. Darts is one of the sports that seek fun and gameplay by subtracting the score obtained by the player from the points he or she has and reducing it to zero. Wellness Darts also has the unique feature of calculating scores by rote; patients with MCI and Alzheimer's disease are said to perform poorly on calculation tasks, especially subtraction and multiplication, and show this tendency from the MCI stage onwards (Martin., 2003). Wellness Darts is a sport that involves not only throwing darts, but also walking to pull them out of the board, memorizing the score, and subtracting it from the total score, thus allowing the performance of two tasks at the same time: exercise and calculation. Simultaneous performance of motor and cognitive tasks, each of which is effective in improving cognitive function as a single task, is more effective in increasing PFC activity and improving cognitive function than performing either task alone (Hermand et al., 2019). Takeda et al. (2017) conducted cognitive tests before, one month, and two months after an experiment on a Wellness Darts intervention group and a control group, both consisting of older adults. The results showed that the continuation of Wellness Darts increased the short-term memory test (STM test) scores of the older adults. Their results suggest that Wellness Darts is effective in preventing dementia. However, the impact of continual practice of Wellness Darts on brain function is unclear.

The purpose of this study is to elucidate the effects of continual Wellness Darts practice on brain function in older adults. In particular, the effects of the Wellness Darts intervention will be compared cross-sectionally among older adults who are proficient with darts, older adults who are inexperienced with darts, and younger adults who are inexperienced with darts. The Hemispheric Asymmetry Reduction in OLDer adults (HAROLD) model proposed by Cabeza et al. asserts that the degree of Frontal lobe (FL) lateralization seen in youth decreases with age (Cabeza et al., 2002; Cabeza et al., 2000; Mu□ller et al., 2014; Erickson et al., 2007; Cabeza et al., 2002; Reuter-Lorenz et al., 2000; Blum et al., 2021; Vermeij et al., 2014). In addition, Erickson et al. (2007) reported that when cognitive training was conducted on healthy older adults, an increase in lateralization was observed, bringing the brain activation pattern closer to that of younger adults (Erickson et al., 2007). On the other hand, brain regions such as the inferior frontal gyrus (IFG), superior frontal gyrus (SFG), middle frontal gyrus (MFG), (Verner et al., 2013), and DLPFC have been reported to be activated during mental calculation (Pfurtscheller et al., 2010). Furthermore, the inferior parietal

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lobule (IPL) in patients with cognitive decline such as MCI and Alzheimer's disease is reported to be less activated (Schroeter et al., 2009).

Based on these findings, we proposed the following three hypotheses: (1) older adults who practice Wellness Darts will show a level of hemispheric lateralization similar to that of younger people, with activation of the dorsal superior frontal gyrus (SFGdor) and MFG, which are known to be activated during mental arithmetic. (2) There is no difference in the level of IPL activation between older adults who continually practice Wellness Darts and younger inexperienced adults. (3) There is a positive correlation between the level of hemispheric lateralization in brain activity and the number of days of Wellness Dart experience. These three hypotheses were tested by measuring brain activity using functional near-infrared spectroscopy (fNIRS), a non-invasive functional brain imaging system robust to body movement.

2 Materials and Methods

2.1 Participants

Twenty-one healthy younger adults (13 males, 7 females; mean age: 22.5 ± 0.8 years) who had never played Wellness Darts, 21 healthy older adults (8 males, 13 females; mean age: 75.1 ± 4.3 years) who continually played Wellness Darts, and 21 healthy older adults (4 males, 17 females; mean age: 74.1 ± 4.5 years) who had never played Wellness Darts participated in the experiment. These three participant groups were referred to as the younger group, the expert older group, and the non-expert older group, respectively. The sample size for each group was determined with a significance level of 0.05 and a power of 0.8 to detect the effect size of Cohen's $d = 0.79$ reported in a previous study comparing the degree of hemispheric lateralization in the elderly using fNIRS (Yeung et al., 2020) (G*Power was used for the calculation).

2.2 Wellness Darts task

Wellness Darts is a darts game developed by the Japan Wellness Darts Association to enhance the efficacy of "dementia prevention," "nursing care prevention," and "functional recovery". The standard game of Wellness Darts is the "Zero One Game 251". In the game, each player is assigned a score of 251 and throws darts until the score reaches zero, subtracting the score of each dart throw from the holding points. The first player to reach a score of exactly 0 wins. Each player can throw darts three times in their turn (which is defined as one set), and the rule is that the score must always be exactly zero on the third throw. In addition, each player must subtract the number of points earned from their own score by themselves. These mental arithmetic operations, the planning of throws to reach zero as quickly as possible, and the exercise associated with throwing darts are important factors in the prevention of cognitive decline. However, since the official rules of Wellness Darts place a physical burden on the participants due to the long duration of the experiment, in this study, the initial score of the subjects was set at 128 points, and each subject played the game for a maximum of five sets. Furthermore, the game was terminated even if the score did not reach zero in the fifth set.

2.3 Procedure

Participants played up to five sets of Wellness Darts with a maximum of 128 holding points, while brain activity and head acceleration were simultaneously recorded. The accelerations were used to remove noise due to head movements, as described below. In each of the three throws in one set of the Wellness Darts game, the participants were instructed by the recorded voice prompts and the beep

cue from the experimental computer on when to hold the dart, throw, and start the calculation; the participants performed each action following the instructions.

During the planning block that was set at the beginning of each throwing session, participants were asked to determine in their mind where to hit (designate scoring points) within 5 s for the first throw and within 13 s for the remaining two throws. At the beginning of the second and third throwing sessions, they were provided an extra 8 s in the planning blocks to tally the points from the previous throws. Of note, we excluded the beginning 8 s and instead applied the later 5 s for the subsequent analyses because we assumed that the first throw did not involve the confirmation of the hit point and also employed different cognitive processes than those used in determining where to hit. The planning block was followed by dart-throwing within 3 s after the beep cue.

Following dart throwing, the participants were instructed to move their gaze away from the dartboard to the fixation point and not to think of anything in particular. This waiting block consisted of a random duration between 28 - 32 s to reduce the periodic effect. After completing the three throwing sessions, the participants commenced the calculation block where they were instructed to subtract the scores they received during the previous throws from the total score and write the remaining points on the scoring sheet. With the calculated results, they considered the throwing strategy for the next set during the calculation block. Then, they were asked to press a button to proceed to the 20 s rest block. During the rest block, they stayed the same as in the waiting block. This procedure was repeated for five sets. The overall procedure is illustrated in Figure 1.

All participants were informed of the methods and risks of the experiment and signed a written informed consent form. This study was conducted in accordance with the Research Ethics Committee of Doshisha University (Kyoto, Japan) (approval code: 20014). Prior to the experiment, participants completed a questionnaire, five cognitive tests: Simple Cognitive (SC) test, Computational Ability Test, Short-Term Memory (STM) Test, Trail Making Peg Test (TMPT), and CogEvo, and a darts performance test. Participants then performed one set of dart-throwing before being fitted with the fNIRS device in order to understand the experimental procedure.

2.4 fNIRS data acquisition

Changes in the concentration of oxy-hemoglobin (HbO), deoxy-hemoglobin (HbR), and total-hemoglobin (HbT) in the participants were measured using NIRSport2 (NIRx medical technologies, LLC). The sampling frequency was 4.36 Hz, and the wavelengths of the near-infrared light were 760 and 850 nm, respectively (Pereira et al., 2007). As shown in Figure 2 (b), 16 sources and 14 detectors were placed on the frontal, parietal, and temporal regions of the head. A pair of sources and detectors adjacent to each other at 30-mm intervals constituted one standard channel, and 44 standard channels were placed. In addition to these, a short-distance detector bundle (NIRx medical technologies, LLC) was placed to eliminate extra-cerebral blood flow alterations (Huppert et al., 2009; Tachtsidis et al., 2016). The signals obtained from the 16 short-distance channels were used to detect extracerebral signals and to remove the effect of skin blood flow in the signals measured by the standard channels. To remove noise from body motion, a six-axis accelerometer (NIRx medical technologies, LLC) was used to measure head acceleration at a sampling frequency of 4.36 Hz, the same frequency as the change in hemoglobin concentration (Lu□hmann et al., 2020). The accelerometer was placed at the top of the head as shown in Figure 2 (b). Presentation software (Neurobehavioral system Inc.) was used to control the presentation and timing of the recorded voice prompts and the beep cue during the experiment, and the signal measurement and execution of the experimental task were synchronized. The 3D coordinates of the light source and detection probe were measured using a 3D magnetic

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space digitizer (Fastrak, Polhemus, USA) to estimate the exact measurement position of the brain area for each individual. The measured 3D coordinates were entered into the ‘register2polhemus’ function and the 'depthmap' function implemented in the NIRS toolbox (Santosa et al., 2018), and the distance from each standard channel to the brain surface was calculated. On the basis of this distance, the regions of the brain defined by the automated anatomical labeling atlas corresponding to each standard channel were identified.

2.5 Cognitive tests

2.5.1 Simple Cognitive test

The Simple Cognitive (SC) test was used to verify that the participants' cognitive function had not declined. The SC test is a 50-point cognitive function test that can identify early cognitive decline that cannot be detected by the mini-mental state examination (MMSE), which is often used to examine dementia. A score of less than 20 points on the SC test is considered suspicious for cognitive decline. In this study, only participants with a score of 20 or higher were considered to have no cognitive decline and were used in subsequent analyses.

2.5.2 Computational ability test

The participants' computational abilities were measured by administering a test consisting of 30 subtraction problems between two digits, between three and two digits, and between three digits. Differences in mean scores on the computational ability test between the expert older group and the non-expert older group were *t*-tested ($p < .05$).

2.5.3 STM

To evaluate the short-term memory of the participants, the Short-Term Memory (STM) Test was conducted on a computer. After the instruction "Please memorize the numbers in order" was displayed on the monitor, nine disordered numbers were displayed on the screen one by one per second. The participants were then instructed to "write the numbers in order," and they wrote the memorized numbers on a piece of paper during a 20-s time frame. The difference in mean STM test scores between the expert older group and the non-expert older group was *t*-tested ($p < .05$).

2.5.4 CogEvo

CogEvo was used to test the cognitive abilities of the participants; CogEvo is a computer-assisted cognitive function test that assesses disorientation, attention, memory, planning, and spatial awareness (Ichii et al., 2020). CogEvo can reportedly capture mild changes in cognitive function and is a simple and convenient ICT tool to assess cognitive changes over time in middle-aged and older adults, as well as during the preclinical stages of dementia (Ichii et al., 2020; Takechi et al., 2021). CogEvo has 12 different tasks; in this experiment, we selected flashlight, visual search, number step, and just fit as tasks related to Wellness Darts from the disorientation, attention, memory, planning, and spatial awareness components of CogEvo, respectively. The difference in mean CogEvo scores between the expert older group and the non-expert older group was *t*-tested ($p < .05$).

2.5.5 TMPT

The Trail making peg test (TMPT) was conducted to assess participants' cognitive functioning, particularly attentional function (Yoon et al., 2020). The TMPT is a peg-movement test that reflects cognitive function and provides elaboration, with elements of the trail-making test (TMT), a cognitive function assessment table focused on attentional function. In the TMPT, participants

quickly insert 25 cylindrical wooden sticks, called pegs, into numbered holes in numerical order. In the TMPT in our study, participants quickly inserted 25 pegs into the numbered holes, and the board containing the pegs and the board containing the holes were separated from each other. The difference in mean completion time was *t*-tested ($p < .05$).

2.6 Dart throwing performance test

To confirm that the dart-throwing skill of the expert older group was higher than that of the control groups, the dart-throwing performances of the three groups were tested. In this test, a target score of 65 points was set and participants were required to throw the darts 10 times and tally their scores to match the target score. The differences in total dart performance test scores between the expert and younger groups and between the expert and non-expert older groups were t-tested ($p < .05$). Furthermore, we assumed that dart proficiency can be assessed not only by the number of days of experience but also by dart throwing performance. Therefore, a positive correlation between the total dart performance test score and the degree of hemispheric lateralization of brain activity in the expert older group was also tested (uncorrelated test, $p < .05$).

2.7 Questionnaires

Participants were asked to respond to questions regarding their dominant hand, the number of days per week they practiced Wellness Darts, and the number of years they had been practicing. From these responses, the total number of days of experience for each participant was estimated. A positive correlation between the number of days of experience and the hemispheric lateralization level of brain activity was also tested (uncorrelated test, $p < .05$).

2.8 fNIRS data processing

2.8.1 Preprocessing

Previous studies have concluded that HbO in fNIRS is more strongly related to blood oxygenation level-dependent (BOLD) signals measured by functional magnetic resonance imaging (fMRI) than HbR (Strangmen et al., 2002; Cui et al., 2011; Huppert et al., 2006). The fMRI has better spatial resolution than fNIRS and has been used in many cognitive neuroscience studies. In this study, we used HbO to analyze brain activity. The fNIRS data were preprocessed using the NIRS toolbox (Santosa et al., 2018) to remove physiological noise such as skin blood flow, heart rate, and pulse rate. Optical intensity data acquired from the fNIRS system were converted to optical density (OD) data and then to Hb concentration data based on the modified Beer-Lambert law (Huppert et al., 2009). A bandpass filter (0.008-0.09 Hz) was applied to remove noise such as low-frequency drift and heartbeat (Huppert et al., 2006; Sasai et al., 2012).

2.8.2 Activation analysis

The level of task-induced brain activation for each individual was estimated using the iteratively reweighted least-squares model (AR-IRLS) with short separation (SS) and acceleration, a general linear model (GLM)-based analysis method implemented in the NIRS toolbox (Lu□hmann et al., 2020; Huo et al., 2021). In GLM, task-related brain activation was modeled by the hemodynamic response function (HRF). The measured brain activity, i.e., HbO signal, was regressed on the ideal task-related activity calculated from the HRF and a design matrix indicating the type of experimental task, and the partial regression coefficients were estimated by IRLS, a least-squares method. The AR-IRLS allows brain activation analysis to consider the effects of arbitrary confounding factors such as the SS signal measured with a short-distance channel, blood pressure, respiration, and acceleration on

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brain activity. In this study, we introduced the SS signal and acceleration data as physiological regressors of GLM to reduce the effects of skin blood flow and body motion on the HbO signal (Luhmann et al., 2020; Santosa et al., 2020).

For individual-level analysis, the following two contrasts were created for the HbO data of the younger group, the expert older group, and the non-expert older group: "rest vs. calculation" and "rest vs. planning". The β-values for each experimental condition and each channel were calculated. The statistical significance of the task-related brain activity was then verified by testing the null hypothesis that the estimated β coefficient was not significantly different from zero (*t*-test, $p < .05$). Note that multiple comparisons were corrected using the Benjamini-Hochberg method (Santosa et al., 2020) . In addition, to test the hypothesis that there is no difference in the level of IPL activation between older adults who continually practiced Wellness Darts and younger adults who were not experienced in Wellness Darts, β values of IPL were compared between the three groups (*t*-test, $p < .016$, Bonferroni corrected).

Next, for the group-level analysis, we constructed the most consistent contrast images of group-level brain activity using simultaneously the β values obtained from the individual-level analysis of all participants, based on Santosa et al. (2018). To estimate significant group-level activity, we used participants as random effects and conditions (planning, calculation, and rest blocks) as fixed effects. Finally, all participants were considered as a sample drawn from the population and a one-sample t-test was used to test if the population mean was greater than zero with respect to the *t*-value. The significance level was set at $p < .05$ (false discovery rate corrected at peak level), and the brain regions activated during the calculation and planning blocks were estimated.

2.8.3 Hemispheric lateralization analysis

The level of hemispheric lateralization was calculated from the lateralization index (LI) shown in Equation 1.

$$\boldsymbol{LI} = \frac{|\boldsymbol{AL}-\boldsymbol{AR}|}{|\boldsymbol{AL}|+|\boldsymbol{AR}|} \qquad \textbf{(1)}$$

where AL is the sum of β values in the regions of interest (ROIs) in the left hemisphere and AR is the sum of those in the right hemisphere (Seghier et al., 2008, Watanabe et al., 1998). We used absolute values for the LI values to allow for the fact that the dominant hemisphere differs depending on the dominant hand. The LI values were used to compare the degree of hemispheric lateralization among the three groups of participants (*t*-test, $p < .016$, Bonferroni corrected). In addition, we tested whether there was a positive correlation between the number of days of Wellness Dart experience and LI values in the expert older group (uncorrelated test, $p < .05$). We also tested whether there was a positive correlation between the total darts performance test score and the LI value in the expert older group (uncorrelated test, $p < .05$).

3 Results

3.1 fNIRS data

3.1.1 Hemispheric lateralization analysis

We hypothesized that the LI values of the younger group and the expert older group would be larger than those of the non-expert older group. LI values were calculated from the respective β values of the two task blocks (planning and calculation) for the three participant groups. The LI values in the

planning and calculation blocks of the younger group were 0.45 ± 0.34 and 0.49 ± 0.35, respectively. The LI values in the planning and calculation blocks of the expert older group were 0.53±0.38 and 0.61±0.35, respectively. Finally, for the non-expert older group, they were 0.23±0.18 and 0.50±0.38 in the planning and calculation blocks, respectively. The box plots of the LI values in the planning and calculation blocks for the three groups of participants are shown in Figure 3 (d) and Figure 4 (d), respectively. Furthermore, the β maps of the participants who showed the closest values to the median in the LI values for each group of participants are shown in Figure 3 (a)-(c) and Figure 4 (a)-(c).

There were no significant differences between the LI values of the younger group and the non-expert older group in the planning block (t = 0.6730, p = 0.504, d = 0.213). On the other hand, in the planning block, the LI values of the expert older group were significantly greater than those of the non-expert older group (t = 3.188, p = 0.003, d = 1.005). Furthermore, the LI values of the younger group were significantly greater than those of the non-expert older group in the planning block (t = 2.58, p = 0.014, d = 0.815).

In the calculation block, there were no differences in LI values between the younger group and the expert older group (t = 1.009, p = 0.319, d = 0.319). Similarly, there were no differences in LI between the expert older group and the non-expert older group (t = 0.828, p = 0.413, d = 0.262). There were also no differences in LI values between the younger group and the non-expert older group (t = 0.144, p = 0.886, d = 0.046).

We also hypothesized that the number of days of Wellness Dart experience in the expert older group would be positively correlated with LI values. The results of an uncorrelated test between the number of days of Wellness Dart experience and LI values showed no significant correlation for either the planning or the calculation block (planning block: r = -0.294, p = 0.195; calculation block: r = 0.179, p = 0.438, Figure 5).

To investigate the Wellness Dart experience of the expert older group in terms of skill, the mean darts performance test score (target score was 65 points; the closer the total score of 10 dart throws was to 65 points, the better the skill) was compared between the three participant groups. The mean scores for the younger group, the expert older group, and the non-expert older group were 39.3±13.4, 49.9±5.5, and 31.9±13.7, respectively. There were no participants who exceeded the 65 points. As shown in Figure 6, the expert older group showed better dart performance compared to the younger group (t = 3.247, p = 0.003, d = 1.022). Similarly, the expert older group showed better performance than the non-expert older group (t = 5.400, p = 0.00001, d = 1.700).

Furthermore, the uncorrelated test between the total dart performance test score and the LI value confirmed a positive correlation in the planning block (r = 0.463, p = 0.034, Figure 7 (a)). On the other hand, no such correlation was found in the calculation block (r = -0.289, p = 0.204, Figure 7 (b)).

3.1.2 Activation analysis

We hypothesized that there would be no difference in the IPL activation level in the younger group and in the expert older group. The activation analysis shown in Figure 8 indicates that in the planning block, there was no difference between the left and right IPL (IPL.L: t = 0.738, p = 0.466, d = 0.234. IPL.R: t = 0.134, p = 0.894, d = 0.043). Similarly, there was no difference between the expert older group and the non-expert older group (IPL.L: t = 0.042, p = 0.966, d = 0.014; IPL.R: t = 0.821, p =

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0.419, d = 0.257). Furthermore, there was no difference between the younger group and the non-expert older group (IPL.L: t = 0.711, p = 0.481, d = 0.226. IPL.R: t = 0.967, p = 0.343, d = 0.312).

In the calculation block, there was no difference between the left and right IPL (IPL.L and IPL.R) of the younger group and the expert older group (IPL.L: t = 1.211, p = 0.236, d = 0.381; IPL.R: t = 0.206, p = 0.838, d = 0.068). Similarly, there was no difference between the expert older group and the non-expert older group (IPL.L: t = 1.625, p = 0.115, d = 0.513; IPL.R: t = 1.642, p = 0.109, d = 0.523). There was no difference between the younger group and the non-expert older group (IPL.L: t = 2.176, p = 0.036, d = 0.688. IPL.R: t = 1.844, p = 0.074, d = 0.621).

Tables 1 to 6 summarize the results of individual-level analysis and show the regions of interest where the p-values are less than 0.05. Tables 7 to 9 summarize the results of group-level analysis and show only the ROIs. There was significant activation in the ROIs in the individual-level analysis in the expert older group, but no significant activation in the group-level analysis.

3.2 Cognitive tests

3.2.1 Computational ability test

The mean computational test scores for the younger group, the expert older group, and the non-expert older group were 24.0 ± 3.8, 20.8 ± 3.0, and 17.1 ± 5.5, respectively. As shown in Figure 9, the expert older group had higher scores on the computational skills test than the non-expert older group (t = 2.275, p = 0.029, d = 0.719).

3.2.2 STM test

The mean STM test scores of the younger group, the expert older group, and the non-expert older group were 74.6 ± 13.6, 57.1 ± 9.5, and 49.4 ± 9.9, respectively. As shown in Figure 10, the expert older group showed higher STM test scores than the non-expert older group (t = 2.475, p = 0.018, d = 0.792).

3.2.3 CogEvo

The scores of the five CogEvo tasks for each group of participants are summarized in Figure 11. In the expert older and non-expert older groups, there were no significant differences in the CogEvo scores (disorientation: t = 1.892, p = 0.067, d = 0.598, visual search: t = 1.435, p = 0.159, d = 0.454; flashlight: t = 1.386, p = 0.174, d = 0.438; number step: t = 1.722, p = 0.093, d = 0.550; just fit: t = 0.625, p = 0.534, d = 0.198).

3.2.4 TMPT

The mean TMPT completion times for the younger, expert older, and non-expert older groups were 41.1 ± 4.5, 58.1 ± 8.5, and 58.9 ± 9.2, respectively. There was no significant difference in TMPT completion time between the older and non-expert older groups (t = 0.272, p = 0.787, d = 0.086).

4 Discussion

We proposed three hypotheses in the present study: (1) Older adults who continue to play Wellness Darts show hemispheric lateralization in brain activity patterns in FL with activation of SFGdor and MFG, which are known to be activated during mental calculation, similar to those in younger adults. (2) The degree of activation of the IPL in the elderly who continue to play Wellness Darts is similar to that seen in the young. (3) There is a positive correlation between the degree of hemispheric

lateralization in brain activity and history of Wellness Dart experience. In this section, the results of the hypotheses testing are discussed.

4.1 Hypothesis 1

As seen in the results of the individual-level analysis in Tables 1-6, we were able to confirm the activation of SFGdor and MFG in the three participant groups. However, there was no significant activation of these regions in the group-level analysis. This may be because the mean activation level was estimated to be lower after averaging the results of the group as the individual activated areas varied even in the same region due to the distinct differences in the arrangement of measurement channels in the fNIRS device.

On the other hand, Figure 3 (d) shows that the LI values of the younger group and the expert older group were significantly higher than those of the non-expert older group in the planning block. In addition, there was no difference in LI values between the younger group and the expert older group. This indicates that the brain activation patterns of participants in the younger group and the expert older group are hemispherically lateralized during the planning of dart-throwing and while determining where to hit. The β-map in Figure 3 (a)-(c) also shows that the activation levels in the younger and expert older groups were higher in one hemisphere, while the non-expert older group showed no hemispheric difference. In the non-expert older group, there is no difference between the hemispheres, and bilateral activation levels of SFGdor and MFG are high. This result is consistent with a previous study in which left-right hemispherical asymmetry increased when cognitive training was performed in healthy older adults (Erickson et al., 2007). In summary, although SFGdor and MFG were not significantly activated in the expert older group in group-level analysis, Hypothesis 1 was established during the planning of dart throwing, suggesting that continual Wellness Dart training promotes hemispheric lateralization in brain activity in older adults.

4.2 Hypothesis 2

Figure 8 indicates that there were no significant differences in the β-values of the left and right IPL between the younger group and the expert older group. Further, there was no significant difference in the β-values of the left and right IPL between the younger and non-expert older groups, and between the expert and non-expert older groups. However, in the three participant groups in the present study, the IPL activation was comparable, suggesting that there was no difference in IPL activation between the older groups. The previous study to which the hypothesis refers involved healthy subjects and patients with MCI and Alzheimer's disease (Schroeter et al., 2009). The participants in the present study were only healthy adults, suggesting that the difference in cognitive function between the older groups and the younger group did not affect IPL activation.

4.3 Hypothesis 3

As shown in Figure 5, there was no correlation between the number of days of Wellness Dart experience and the LI value of the expert older group; therefore, Hypothesis 3 was not confirmed. The present study was a cross-sectional study to investigate the current cognitive status of participants who practiced Wellness Darts. However, the number of days of Wellness Dart experience, which was obtained from the participants' self-reports, was not accurate. On the other hand, in Figure 6, dart performance of the expert older group was higher than that of the other two groups. In addition, Figure 7 shows a positive correlation between dart performance and LI value in the planning block. The total score of our dart performance test indicates the accuracy of dart throwing, which is improved by the number of days of experience. Therefore, the results of Figures 6

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and 7 may contribute to the validity of Hypothesis 3. Future longitudinal controlled studies of the Wellness Darts intervention that measure dart performance levels can be expected to verify the increase in LI values promoted by Wellness Dart training.

4.4 Cognitive tests

In addition to hypotheses testing, the results of three cognitive function tests to determine the impact of Wellness Darts on cognitive function are also discussed.

4.4.1 Computational ability test

The score of the expert older group was significantly higher than that of the non-expert older group. In other words, the expert older group had better computational ability than the non-expert older group. According to previous studies, cognitive function, particularly for high-load tasks, declines as the brain deteriorates with age (Bierre et al., 2017). Therefore, the results of the computational ability test in this study suggest that continual practice of Wellness Darts can reduce the decline of calculation ability due to aging.

4.4.2 STM test

The STM test scores of the expert older group were higher than that of the non-expert older group, and the difference was significant. Fandakova et al. (2014) have shown that short-term memory capacity declines with age. Therefore, our results indicate that constant training with Wellness Darts can reduce the age-related decline in short-term memory capacity.

4.4.3 CogEvo

No significant differences were found in the scores between the expert older group and the non-expert older group on the five CogEvo tasks. Although CogEvo has been reported to be able to significantly distinguish between Alzheimer's disease, MCI, and cognitively normal groups of older adults (Ichii et al., 2020; Takechi et al., 2021), our results showed that the expert older group and the non-expert older group did not differ significantly in their scores on the five CogEvo tasks. In fact, our results indicated that the expert older and non-expert older groups had similar cognitive levels. In other words, the older groups in our experiment had normal levels of cognitive function or the differences in cognitive function were at levels that were undetectable by CogEvo. Another explanation could be that the older groups were unfamiliar with the operation of CogEvo as it was conducted using a tablet device.

4.4.4 TMPT

As seen in Figure 12, there was no significant difference in the completion time of TMPT between the expert older and the non-expert older groups. TMPT requires skill from the participant as a component of physical function. We expected that participants engaged in ongoing Wellness Darts exercise would demonstrate improved skillfulness; however, in this cross-sectional study, no differences were observed between the expert older and non-expert older groups. A previous longitudinal study that divided older adults into a dual-task (DT) exercise group and a control group observed a significant difference in TMPT before and after intervention in the DT exercise group, but no significant difference was identified in TMPT between the two groups (Yoon et al., 2020). Therefore, future longitudinal controlled studies of the Wellness Darts intervention can be expected to validate the reduction in TMPT completion time.

4.5 Strengths of the current study and future direction

The purpose of this study was to elucidate the effects of continual Wellness Darts practice on brain function in the elderly through a cross-sectional comparison of brain activity patterns and cognitive test results among an expert older group, a non-expert older group, and a younger group. Here, three hypotheses were formulated: (1) Older adults who continually play Wellness Darts show hemispherically lateralized brain activity patterns in FL with activated SFGdor and MFG, which are known to be active during memorization, similar to that in younger adults. (2) The degree of activation of the IPL in the elderly who continually practice Wellness Darts is similar to that of the young. (3) There is a positive correlation between the degree of hemispheric lateralization in brain activity and history of Wellness Dart experience. Based on our findings, hypothesis 1 was confirmed in the planning of dart throwing and in determining where to hit. Hypothesis 2 could not be substantiated in this study, as there was no difference in IPL activation levels between the three groups. Although hypothesis 3 was not confirmed due to the inaccuracy in the number of days of Wellness Dart experience reported by the participants, a positive correlation was observed between dart performance and degree of hemispheric lateralization, suggesting a relationship between dart-throwing proficiency and hemispheric lateralization. These results suggest that older adults with Wellness Dart experience have a higher tendency toward hemispheric lateralization than those with no experience and that the Wellness Darts intervention may be effective. In the future, longitudinal randomized controlled trials should be conducted to explore the effects of continual Wellness Dart training on brain functions, including hemispheric lateralization.

5 Data availability statement

The datasets generated for this study are available on request to the corresponding author.

6 Ethics statement

Studies involving human participants were reviewed and approved by the Research Ethics Committee of Doshisha University, Kyoto, Japan (approval code: 20014). The individuals provided written informed consent to participate in the study.

7 Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

8 Funding

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11 Figure legends

Figure 1. Overview of the experiment. A. The experimental procedure. B. The experimental setup.

Figure 2. Probe displacement of fNIRS. (a) Monte-Carlo simulation results over the frontal cortex, temporal cortex, and parietal cortex. Red dots represent emitters, blue dots represent detectors, and yellow lines represent measurement channels, respectively (created using Homer 2 AtlasViewer; v2.8, p2.1: https://www.nitrc.org/frs/shownotes.php?release_id=3956). The color bar represents the spatial sensitivity of fNIRS measurements. (b) The two-dimensional fNIRS montage using the International 10-20 measurement system as reference is presented.

Figure 3. βmaps and LI values in the planning block. (a)-(c) βmaps of participants with LI values close to the median in younger, expert older, and non-expert older groups are shown, respectively. (d) Distribution of LI values for the three participant groups. *p < .016. βmaps were visualized using the xjView toolbox and BrainNet viewer.

Figure 4. βmaps and LI values in the calculation block. (a)-(c) βmaps of participants with LI values close to the median in the younger, expert older, and non-expert older groups are shown, respectively. (d) Distribution of LI values for the three participant groups. *p < .016. βmaps were visualized using the xjView toolbox and BrainNet viewer.

Figure 5. Correlation between the number of days of Wellness Dart experience and LI values in the expert older group. (a) planning block. (b) calculation block.

Figure 6. Dart performance level in the younger, expert older, and non-expert older group. *p<.05.

Figure 7. Correlation between darts performance level and LI value in the expert older group. (a) planning block. (b) calculation block.

Figure 8. β values of IPL in the younger, expert older, and non-expert older group.

Figure 9. Computational ability test scores for the younger, expert older, and non-expert older group. *p <.05.

Figure 10. STM test scores for the younger, expert older, and non-expert older group. *p <.05.

Figure 11. Scores on five different CogEvo tasks for the three groups of participants. (a) Orientation. (b) Visual search. (c) Flashlight. (d) Number step. (e) Just Fit.

Figure 12. TMPT completion time for the younger, expert older, and non-expert older group.

12 Tables

Table 1. Brain regions that showed task-related activation for each individual in the planning block (younger group). Only regions of interest that showed p < 0.05 (FDR corrected at peak level) are shown.

Partic	Anatomical	t-	p-value	Partic	Anatomical	t-	p-value

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ipant	Region	value	(FDR-corrected)	ipant	Region	value	(FDR-corrected)
1	IPL.L	3.765	5.76E-04	11	MFG.L	5.449	2.54E-07
	MFG.L	4.408	4.06E-05		MFG.R	8.413	8.76E-16
	MFG.R	10.33	5.57E-23		SFGdor.L	6.024	1.12E-08
	SFGdor.L	7.434	1.48E-12		SFGdor.R	8.779	5.39E-17
	SFGdor.R	9.248	9.70E-19	12	MFG.L	4.957	1.77E-06
2	IPL.R	-4.224	3.05E-04		MFG.R	5.836	2.56E-08
	MFG.L	2.498	0.038		SFGdor.L	6.686	1.67E-10
	MFG.R	-2.941	0.012		SFGdor.R	5.824	2.63E-08
	SFGdor.R	-2.978	0.012	13	IPL.L	-2.443	0.035
3	IPL.R	3.342	0.002		MFG.L	5.219	1.93E-06
	MFG.R	6.801	1.32E-10		SFGdor.L	5.193	2.03E-06
	SFGdor.R	5.896	2.37E-08	14	MFG.R	7.688	3.71E-13
4	IPL.L	-3.846	1.84E-04		SFGdor.R	6.225	2.75E-09
	IPL.R	-4.344	2.73E-05	15	IPL.L	-3.952	2.21E-04
	MFG.L	-6.759	7.67E-11		MFG.R	8.127	8.13E-15
	MFG.R	-	0.028		SFGdor.R	9.337	7.87E-19

		2.298					
	SFGdor,L	-4.55	1.07E-05	16	IPL.L	-6.443	3.36E-09
	SFGdor.R	-2.273	0.029		MFG.R	2.473	0.026
5	MFG.L	8.83	9.44E-18	17	IPL.L	-4.459	9.81E-05
	MFG.R	6.576	2.80E-10		SFGdor.L	-2.842	0.02
	SFGdor.L	19.18	2.87E-77	18	IPL.L	-9.742	1.12E-20
	SFGdor.R	7.335	1.45E-12		MFG.L	-3.147	0.005
6	IPL.R	6.645	3.50E-10		MFG.R	-3.923	3.48E-04
	SFGdor.L	-4.996	2.78E-06		SFGdor.L	-5.72	7.17E-08
	SFGdor.R	2.399	0.028		SFGdor.R	-4.389	5.23E-05
7	IPL.L	2.771	0.008	19	IPL.L	6.362	7.05E-10
	IPL.R	4.191	6.82E-05		MFG.L	7.276	2.11E-12
	MFG.R	4.289	4.64E-05		MFG.R	7.561	3.03E-13
	SFGdor.L	4.583	1.38E-05		SFGdor.L	6.035	4.98E-09
	SFGdor.R	4.365	3.38E-05		SFGdor.R	10.65	3.69E-24
8	IPL.L	4.411	1.56E-05	20	MFG.R	4.538	1.88E-05

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	IPL.R	4.257	3.09E-05		SFGdor.R	4.636	1.26E-05
	MFG.L	5.811	1.70E-08	21	IPL.L	2.346	0.033
	MFG.R	5.317	2.31E-07		MFG.L	3.582	9.94E-04
	SFGdor.L	9.745	5.83E-21		MFG.R	12.54	9.28E-34
	SFGdor.R	6.694	7.43E-11		SFGdor.L	4.791	5.92E-06
10	IPL.L	3.432	0.002		SFGdor.R	12.01	3.62E-31
	MFG.L	3.113	0.004				
	MFG.R	4.145	1.42E-04				
	SFGdor.R	3.909	3.05E-04				

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 2. Brain regions that showed task-related activation for each individual in the calculation block (younger group). Only regions of interest that showed $p < 0.05$ (FDR corrected at peak level) are shown.

Participant	Anatomical Region	t-value	p-value (FDR-corrected)	Participant	Anatomical Region	t-value	p-value (FDR-corrected)
1	MFG.R	7.509	2.55E-12	11	IPL.L	-3.342	0.002
	SFGdor.L	4.194	2.04E-04		MFG.L	5.89	1.75E-08
	SFGdor.R	5.533	7.67E-05		MFG.R	6.951	2.72E-11
2	IPL.R	-8.217	1.51E-14		SFGdor.L	6.464	6.57E-10

	MFG.R	-3.969	8.20E-04		SFGdor.R	8.092	8.43E-15
	SFGdor.R	-5.505	7.29E-07	13	IPL.L	-2.444	0.035
3	IPL.L	-5.429	8.59E-07		MFG.L	5.219	1.93E-06
	MFG.R	5.85	8.88E-08		SFGdor.L	5.193	2.03E-06
	SFGdor.R	2.523	0.023	14	MFG.L	3.061	0.004
4	IPL.L	-8.516	7.35E-17		MFG.R	7.079	9.36E-12
	IPL.R	-9.993	1.64E-22		SFGdor.L	3.61	6.08E-04
	MFG.L	-2.591	0.011		SFGdor.R	6.778	6.56E-11
	MFG.R	-2.234	0.029	15	MFG.R	7.157	1.92E-11
	SFGdor.L	-5.707	2.23E-08		SFGdor.R	8.688	2.59E-16
	SFGdor.R	-4.508	9.39E-06	16	IPL.L	-6.433	2.05E-09
5	IPL.L	-3.004	0.007	17	IPL.L	-6.99	4.20E-11
	MFG.L	6.701	1.05E-10		MFG.L	-7.918	5.44E-14
	MFG.R	2.79	0.013		SFGdor.L	-8.635	2.21E-16
	SFGdor.L	15.94	2.31E-54		SFGdor.R	-	0.006

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		9				3.074	
	SFGdor.R	2.956	0.008	18	IPL.L	-4.03	1.73E-04
6	IPL.R	3.981	2.01E-04		MFG.L	-5.082	2.31E-06
	MFG.R	3.87	2.90E-04		MFG.R	-3.547	9.51E-04
	SFGdor.L	-5.067	2.42E-06		SFGdor.L	-6.342	2.48E-09
	SFGdor.R	4.977	3.63E-06		SFGdor.R	-4.291	6.13E-05
7	IPL.L	3.011	0.009	19	IPL.L	3.566	6.62E-04
	IPL.R	4.247	1.77E-04		IPL.R	-2.674	0.011
8	IPL.L	3.933	1.30E-04		MFG.L	4.345	3.13E-05
	IPL.R	3.329	0.001		MFG.R	7.278	1.86E-12
	MFG.L	5.935	7.59E-09		SFGdor.L	4.855	3.25E-06
	MFG.R	2.072	0.044		SFGdor.R	11.48	2.56E-28
	SFGdor.L	8.248	2.22E-15	20	IPL.L	-5.517	6.64E-08
	SFGdor.R	2.922	0.004		MFG.L	-2.113	0.042
9	IPL.L	-3.998	1.99E-04		MFG.R	4.332	2.16E-05
	IPL.R	-5.626	1.14E-07		SFGdor.R	3.732	2.57E-04

	MFG.L	-3.412	0.001	21	MFG.L	3.828	3.12E-04
					MFG.R	14.12	6.09E-42
					SFGdor.L	3.692	4.94E-04
					SFGdor.R	12.36	3.38E-33

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 3. Brain regions that showed task-related activation in the planning block for each individual (expert older group). Only regions of interest with $p < 0.05$ (FDR corrected at peak level) are shown.

Participant	Anatomical Region	t-value	p-value (FDR-corrected)	participant	Anatomical Region	t-value	p-value (FDR-corrected)
1	IPL.R	4.418	4.97E-05	12	MFG.L	-5.516	1.33E-06
	MFG.R	-4.478	3.88E-05		MFG.R	-4.304	3.30E-04
2	IPL.L	5.142	1.98E-06	13	MFG.L	6.548	1.97E-10
	IPL.R	4.167	1.24E-04		MFG.R	3.212	0.002
	MFG.L	-4.8	9.13E-06	14	MFG.L	5.044	3.19E-06
	SFGdor.L	-3.54	0.001		MFG.R	6.031	2.05E-08
3	MFG.L	-7.369	1.65E-12		SFGdor.L	4.537	2.84E-05
	SFGdor.L	-4.309	4.51E-05		SFGdor.R	2.859	0.009
4	IPL.R	-	1.03E-06	15	IPL.L	6.276	3.28E-09

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		5.123					
	MFG.L	4.82	4.32E-06		IPL.R	7.845	1.55E-13
5	IPL.R	2.806	0.01		MFG.L	4.419	3.04E-05
	SFGdor.L	-3.32	0.002		MFG.R	5.777	6.03E-08
6	MFG.L	-2.802	0.014		SFGdor.R	4.734	8.11E-06
7	MFG.L	4.296	1.29E-04	16	IPL.R	-4.795	2.22E-05
	SFGdor.L	3.352	0.003	17	IPL.L	-4.806	5.20E-06
8	IPL.L	-4.035	2.56E-04		MFG.L	-2.944	0.006
	SFGdor.R	-2.635	0.02	19	MFG.L	-2.989	0.007
9	IPL.L	3.995	4.11E-04		MFG.R	-5.129	1.74E-06
	SFGdor.L	3.754	9.62E-04		SFGdor.L	-4.712	1.02E-05
10	IPL.L	-3.172	0.007		SFGdor.R	-2.744	0.012
	IPL.R	7.868	2.43E-13	20	MFG.L	2.756	0.023
	MFG.R	2.39	0.049		SFGdor.L	3.671	0.001
11	MFG.R	7.11	3.42E-11	21	MFG.R	3.168	0.005
	SFGdor.R	4.948	1.11E-05		SFGdor.R	5.267	1.52E-05

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 4. Brain regions that showed task-related activation for each individual in the calculation block (expert older group). Only regions of interest with $p < 0.05$ (FDR corrected at peak level) are shown.

Participant	Anatomical Region	t-value	p-value (FDR-corrected)	Participant	Anatomical Region	t-value	p-value (FDR-corrected)
1	IPL.R	4.418	4.97E-05	13	MFG.L	5.359	2.13E-07
	MFG.R	-4.478	3.88E-05		MFG.R	5.988	6.77E-09
2	IPL.L	5.142	1.98E-06		SFGdor.L	3.457	9.19E-04
	IPL.R	4.167	1.24E-04		SFGdor.R	3.344	0.001
	MFG.L	-4.8	9.13E-06	14	MFG.R	3.831	4.78E-04
	SFGdor.L	-3.54	0.001	15	IPL.L	8.888	1.50E-17
3	MFG.L	-7.369	1.65E-12		IPL.R	7.401	1.02E-12
	SFGdor.L	-4.309	4.51E-05		MFG.L	6.731	8.57E-11
4	IPL.R	-5.123	1.03E-06		MFG.R	8.754	3.76E-17
	MFG.L	4.82	4.32E-06		SFGdor.L	5.877	1.52E-08
5	IPL.R	2.806	0.01		SFGdor.R	7.612	2.69E-13
	SFGdor.L	-3.32	0.002	16	MFG.R	8.742	5.85E-17
6	MFG.L	-2.802	0.014		SFGdor.L	4.577	2.61E-05
7	MFG.L	4.296	1.29E-04		SFGdor.R	9.739	1.51E-20
	SFGdor.L	3.352	0.003	17	IPL.L	-3.792	3.28E-04

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8	IPL.L	-4.035	2.56E-04		MFG.R	4.375	3.15E-05
	SFGdor.R	-2.635	0.02	18	IPL.L	-2.839	0.012
9	IPL.L	3.995	4.11E-04		MFG.L	4.933	6.41E-06
	SFGdor.L	3.754	9.62E-04		SFGdor.L	3.433	0.002
10	IPL.L	-3.172	0.007	19	SFGdor.R	3.007	0.013
	IPL.R	7.868	2.43E-13	20	MFG.L	-11.83	5.34E-31
	MFG.R	2.39	0.049		MFG.R	-14.5	1.92E-45
11	MFG.R	7.11	3.42E-11		SFGdor.L	-68.23	0
	SFGdor.R	4.948	1.11E-05		SFGdor.R	-93.95	0
12	MFG.L	-5.55	5.50E-07	21	IPL.R	3.885	2.64E-04
	MFG.R	-4.926	1.23E-05		MFG.L	-4.797	6.94E-06
					MFG.R	4.554	2.01E-05
					SFGdor.L	-21.789	4.15E-98
					SFGdor.R	7.121	1.20E-11

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 5. Brain regions that showed task-related activation for each individual in the planning block (non-expert older group). Only regions of interest with $p < 0.05$ are shown.

Participant	Anatomical Region	t-value	p-value (FDR-corrected)	Participant	Anatomical Region	t-value	p-value (FDR-corrected)
1	IPL.L	4.003	3.30E-04	13	IPL.L	-6.647	1.57E-10
	MFG.R	2.857	0.013		IPL.R	-8.842	2.49E-17
2	IPL.L	-4.04	9.84E-04		MFG.L	6.663	1.48E-10
3	MFG.L	-4.888	1.43E-05		MFG.R	3.744	3.67E-04
	MFG.R	-4.201	1.22E-04		SFGdor.R	5.344	3.00E-07
	SFGdor.L	-4.201	1.22E-04	14	IPL.L	2.801	0.009
	SFGdor.R	-4.027	2.30E-04		IPL.R	2.918	0.006
4	MFG.L	-5.972	2.00E-08		MFG.L	-1.914	0.078
	MFG.R	-2.455	0.028		SFGdor.L	-2.504	0.019
	SFGdor.L	-5.021	2.74E-06	15	IPL.L	4.378	4.65E-05
	SFGdor.R	-3.152	0.004		MFG.R	-3.081	0.005
5	MFG.L	4.23	2.98E-04	16	IPL.L	-3.582	0.004
	MFG.R	3.643	0.002		MFG.L	-3.388	0.006
	SFGdor.R	5.05	1.69E-05		SFGdor.R	-	0.031

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						2.628	
7	MFG.R	-3.466	0.002	17	IPL.L	-3.349	0.002
	SFGdor.L	-4.202	2.30E-04		MFG.L	-2.394	0.027
8	MFG.L	4.709	3.04E-05		SFGdor.L	-9.055	2.14E-18
	MFG.R	2.838	0.014		SFGdor.R	-7.301	1.48E-12
	SFGdor.R	3.386	0.003	18	IPL.L	14.66	4.98E-46
9	IPL.L	6.602	2.53E-09		MFG.L	5.508	1.02E-07
	SFGdor.L	-3.184	0.008		SFGdor.L	4.667	7.56E-06
10	IPL.L	2.37	0.04		SFGdor.R	5.935	8.93E-09
	MFG.L	7.529	8.86E-13	19	IPL.L	8.061	2.25E-14
	MFG.R	5.415	3.04E-07		SFGdor.L	3.538	8.87E-04
	SFGdor.L	7.37	2.32E-12		SFGdor.R	3.536	8.87E-04
	SFGdor.R	6.141	5.18E-09	20	IPL.L	-2.806	0.018
11	MFG.L	-4.217	1.30E-04		IPL.R	-3.373	0.004
	SFGdor.L	-3.748	6.50E-04		MFG.L	-8.005	7.56E-14
	SFGdor.R	-2.585	0.023		SFGdor.L	-2.431	0.046
				21	MFG.L	-	0.024

		2.649	

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 6. Brain regions that showed task-related activation for each individual in the calculation block (non-expert older group). Only regions of interest with $p < 0.05$ are shown.

Participant	Anatomical Region	t-value	p-value (FDR-corrected)	Participant	Anatomical Region	t-value	p-value (FDR-corrected)
1	IPL.L	3.241	0.003	13	IPL.L	-8.63	1.57E-16
	SFGdor.L	-2.994	0.006		IPL.R	-8.138	4.42E-15
2	IPL.L	-7.816	7.98E-13		MFG.L	5.221	5.11E-07
	MFG.L	-3.72	0.002		MFG.R	3.503	9.32E-04
3	IPL.L	-2.901	0.008		SFGdor.R	5.609	6.61E-08
	IPL.R	-2.726	0.013	15	IPL.R	-2.658	0.025
	MFG.L	-5.086	1.88E-06		MFG.L	-4.417	8.75E-05
	SFGdor.L	-2.479	0.024	16	IPL.L	-4.386	4.12E-05
	SFGdor.R	8.724	4.59E-17		IPL.R	-3.726	5.33E-04
4	MFG.L	-3.32	0.01		MFG.L	-6.352	2.58E-09
5	IPL.R	2.419	0.032		MFG.R	-	1.22E-05

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						4.675	
	MFG.L	7.139	3.06E-11		SFGdor.L	-2.931	0.007
	MFG.R	6.862	1.73E-10		SFGdor.R	-6.661	5.64E-10
	SFGdor.L	3.649	9.31E-04		IPL.L	-5.71	7.40E-08
	SFGdor.R	8.793	1.29E-16	17	SFGdor.L	-4.989	2.74E-06
7	SFGdor.L	-2.798	0.011		SFGdor.R	-2.72	0.014
	MFG.L	10.47	7.82E-24		IPL.L	8.34	3.71E-16
8	MFG.R	5.262	7.12E-07	18	MFG.R	-2.519	0.017
	SFGdor.R	5.782	5.24E-08		SFGdor.L	7.127	3.42E-12
9	IPL.L	10.99	1.15E-25		SFGdor.R	5.032	9.95E-07
	SFGdor.L	-3.241	0.003		IPL.L	7.062	2.39E-11
	MFG.L	4.3	6.68E-05	19	MFG.R	-3.826	3.31E-04
10	MFG.R	2.867	0.011		IPL.L	3.576	0.001
	SFGdor.L	5.681	9.16E-08		IPL.R	4.542	2.56E-05
	MFG.L	-4.033	2.33E-04		MFG.L	9.534	1.23E-19
11	SFGdor.L	-2.915	0.009	20	MFG.R	3.608	0.001
	SFGdor.R	-2.952	0.008		SFGdor.L	4.643	1.73E-05
12	MFG.R	-2.837	0.013		SFGdor.R	5.79	9.68E-08

	SFGdor.R	-2.926	0.01	21	MFG.L	-3.354	0.003
					MFG.R	-2.275	0.044
					SFGdor.R	-2.226	0.049

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 7. Task-related activation in the region of interest revealed by group-level analysis (younger group).

Condition	Anatomical Region	t-value	p-value (FDR-corrected)
planning	IPL.L	0.15	0.909
	MFG.L	1.931	0.186
	MFG.R	3.321	0.022
	SFGdor.L	3.155	0.022
	SFGdor.R	3.822	0.012
calculation	IPL.L	0.139	0.454
	MFG.L	3.321	0.022
	MFG.R	3.321	0.022
	SFGdor.L	2.866	0.052
	SFGdor.R	5.847	5.72E-05

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Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 8. Task-related activation in the region of interest revealed by group-level analysis (expert older group).

Condition	Anatomical Region	t-value	p-value (FDR-corrected)
planning	IPL.L	0.127	0.988
	IPL.R	1.706	0.548
	MFG.L	-0.163	0.988
	MFG.R	1.238	0.709
	SFGdor.L	0.343	0.988
	SFGdor.R	1.04	0.817
calculation	IPL.L	0.545	0.723
	IPL.R	0.367	0.82
	MFG.L	0.999	0.495
	MFG.R	1.542	0.289
	SFGdor.L	1.115	0.272
	SFGdor.R	0.989	0.495

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

Table 9. Task-related activation in the region of interest revealed by group-level analysis (non-expert older group).

Condition	Anatomical Region	t-value	p-value (FDR-corrected)
planning	IPL.L	2.282	0.385
	MFG.L	0.446	0.943
	MFG.R	-0.928	0.794
	SFGdor.L	-0.331	0.943
	SFGdor.R	-0.684	0.904
calculation	IPL.L	1.234	0.525
	MFG.L	0.309	0.876
	MFG.R	-1.118	0.54
	SFGdor.L	-0.496	0.803
	SFGdor.R	-0.469	0.815

Abbreviations: IPL: Parietal Inf lobule; MFG: middle frontal gyrus; SFGdor: dorsal superior frontal gyrus; R: right; L: Left.

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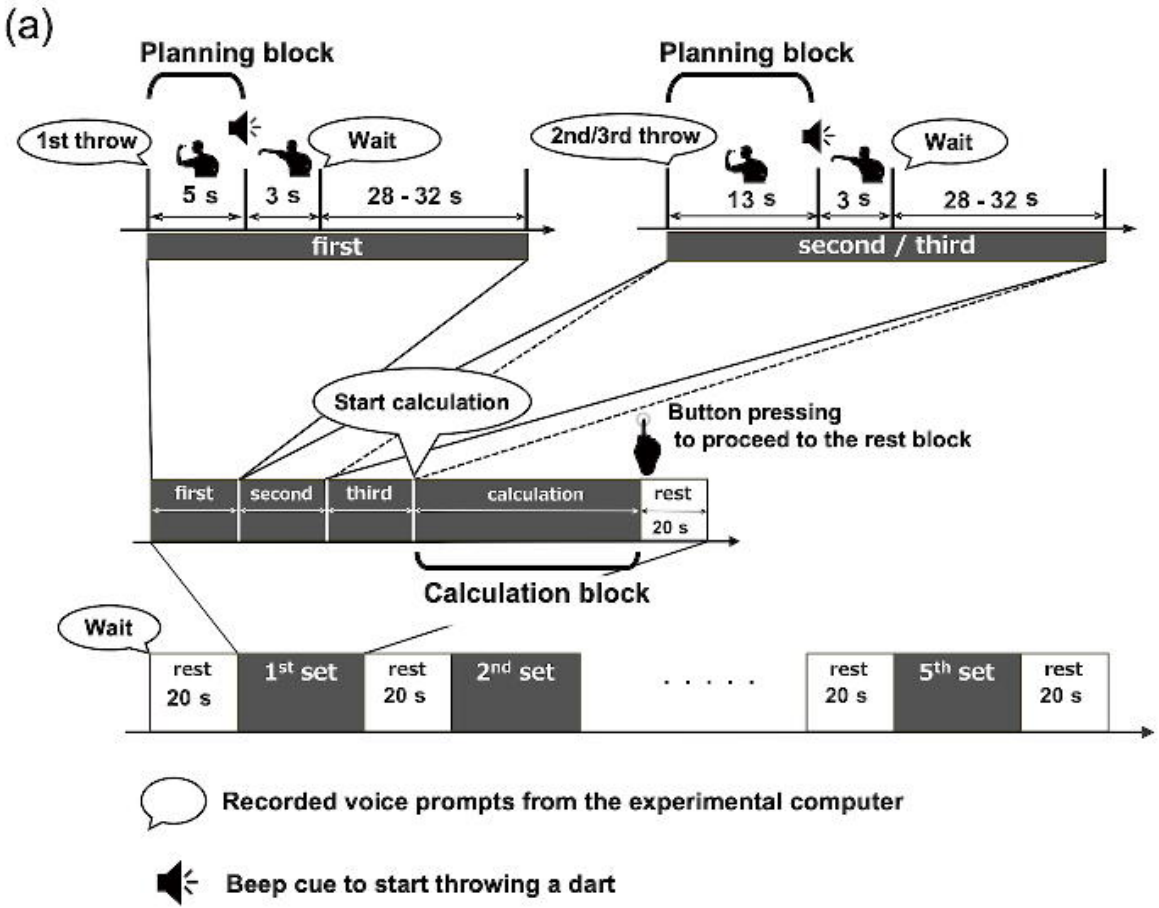
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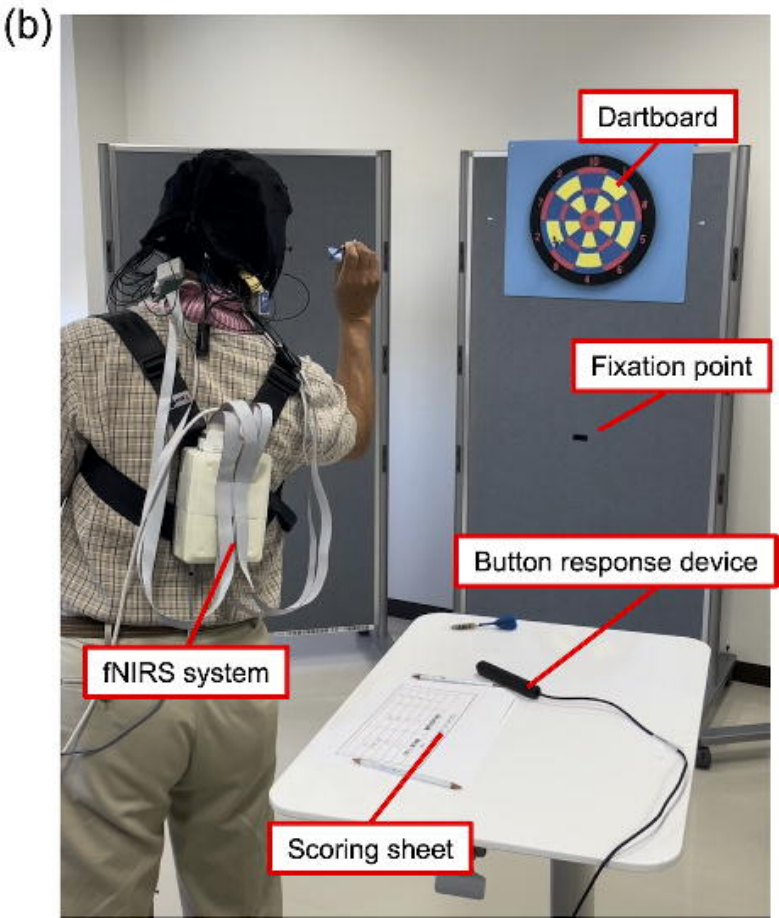
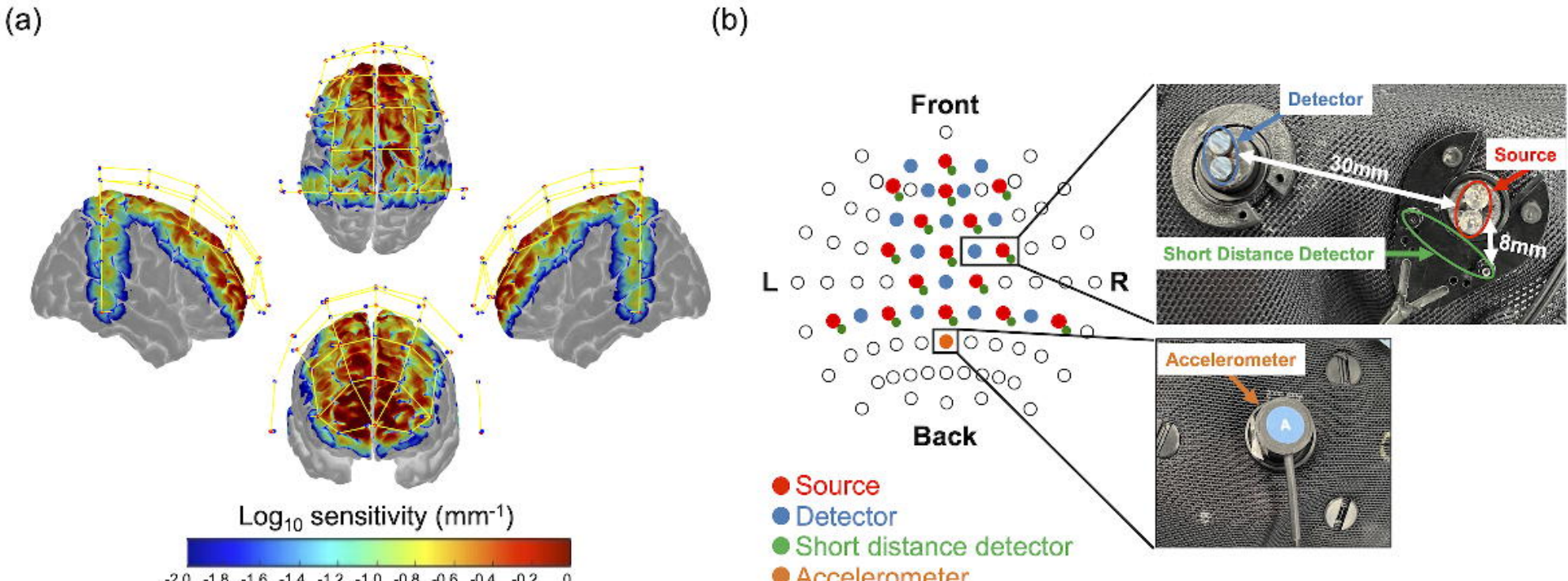
Planning block
Planning block
1st throw
Wait
2nd/3rd throw
Wait
5 s
3 s
28 - 32 s
13 s
3 s
28 - 32 s
first
second / third
Start calculation
Button pressing
to proceed to the rest block
first
second
third
calculation
rest
20 s
Calculation block
Wait
rest
20 s
1st set
rest
20 s
2nd set
. . . . .
rest
20 s
5th set
rest
20 s
Recorded voice prompts from the experimental computer
Beep cue to start throwing a dart


(b)
Dartboard
Fixation point
Button response device
fNIRS system
Scoring sheet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Log10 sensitivity (mm-1)
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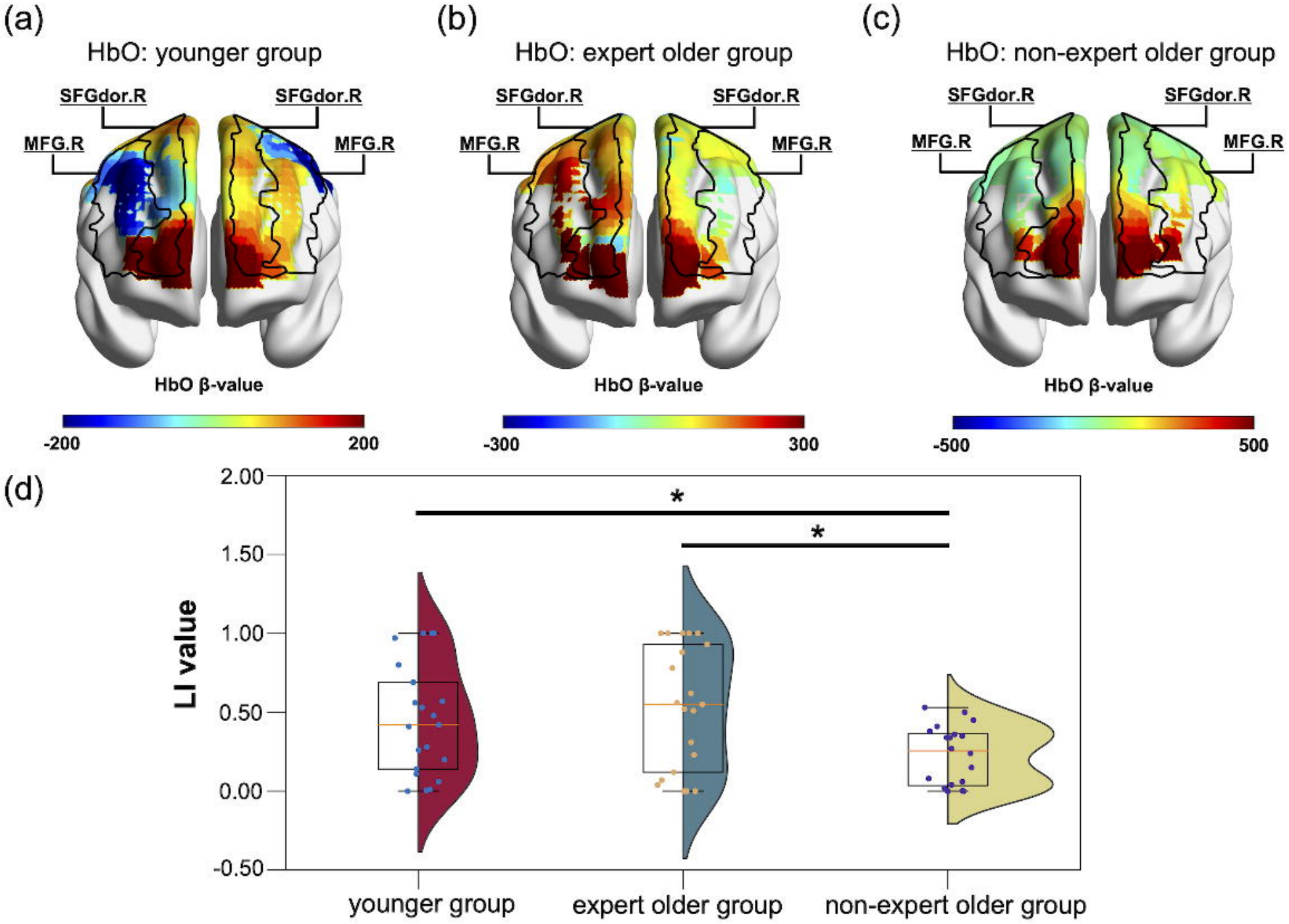
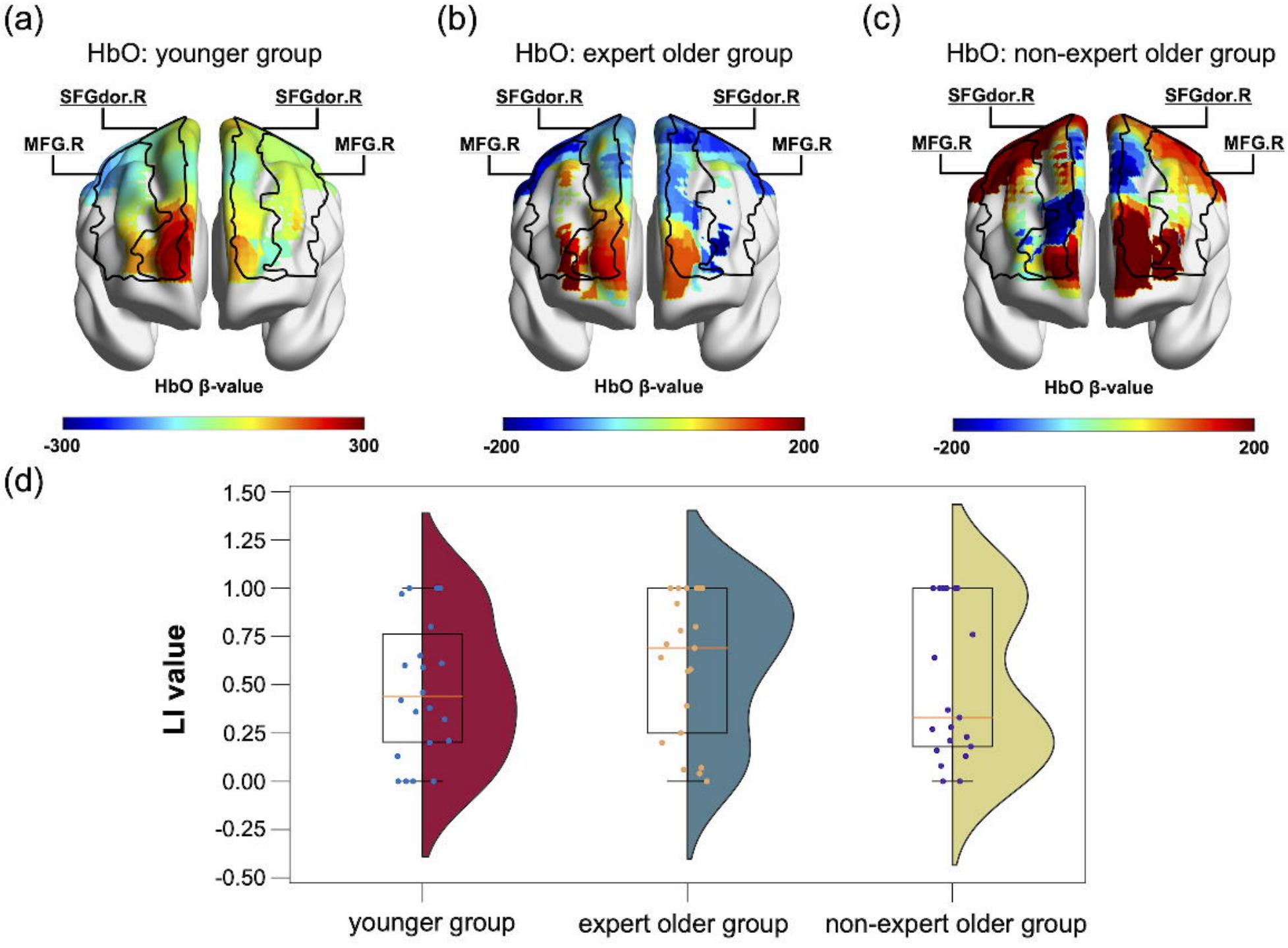
(b)
Front
L
R
Back
Source
Detector
Short distance detector
Accelerometer
Detector
Source
30mm
8mm
Short Distance Detector
Accelerometer


(a)
HbO: younger group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-200
200
(b)
HbO: expert older group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-300
300
(c)
HbO: non-expert older group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-500
500
(d)
LI value
2.00
1.50
1.00
0.50
0.00
-0.50
*
*
younger group
expert older group
non-expert older group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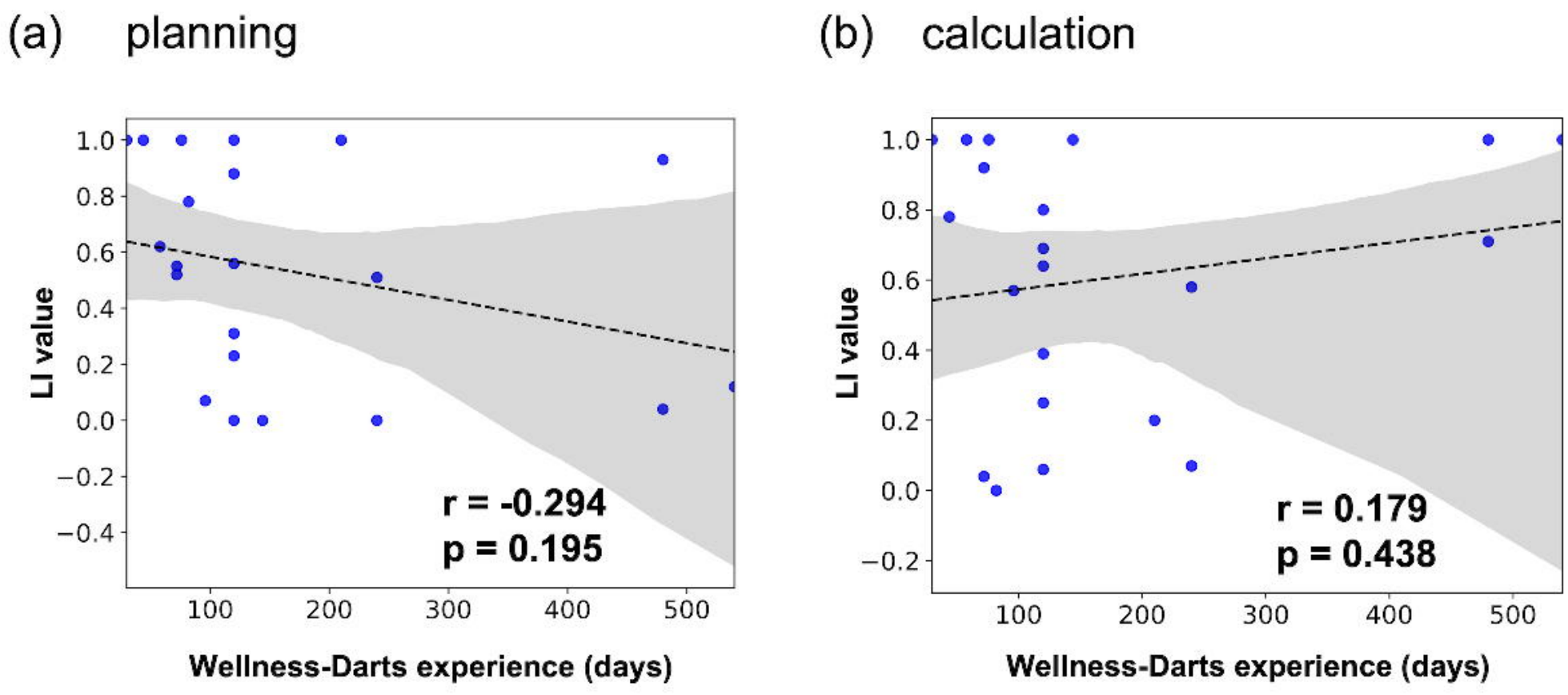
HbO: younger group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-300
300
(b)
HbO: expert older group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-200
200
(c)
HbO: non-expert older group
SFGdor.R
SFGdor.R
MFG.R
MFG.R
HbO β-value
-200
200
(d)
LI value
1.50
1.25
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
younger group
expert older group
non-expert older group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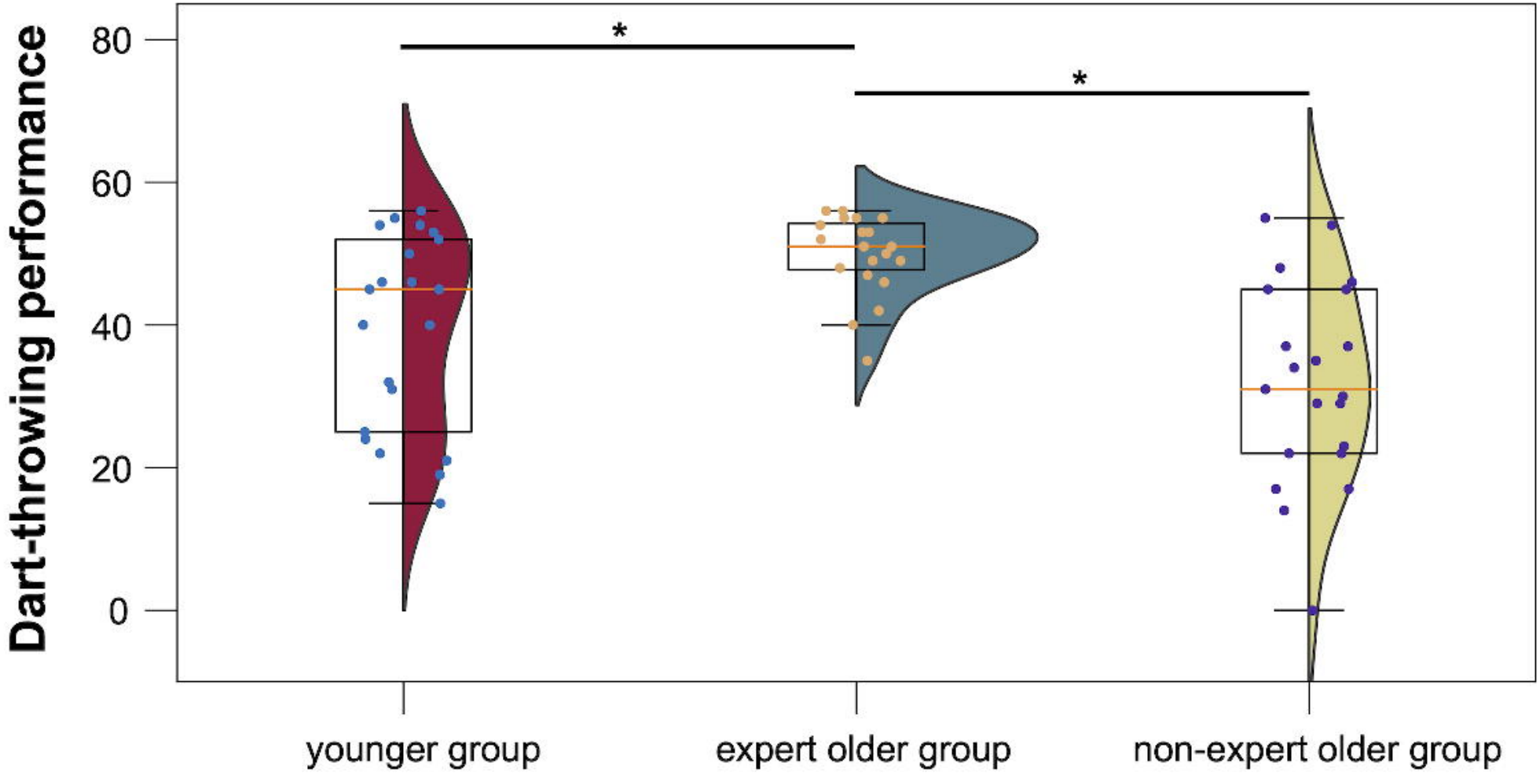
0.6
0.4
0.2
0.0
−0.2
−0.4
r = -0.294
p = 0.195
100
200
300
400
500
Wellness-Darts experience (days)
(b) calculation
LI value
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
r = 0.179
p = 0.438
100
200
300
400
500
Wellness-Darts experience (days)


Dart-throwing performance
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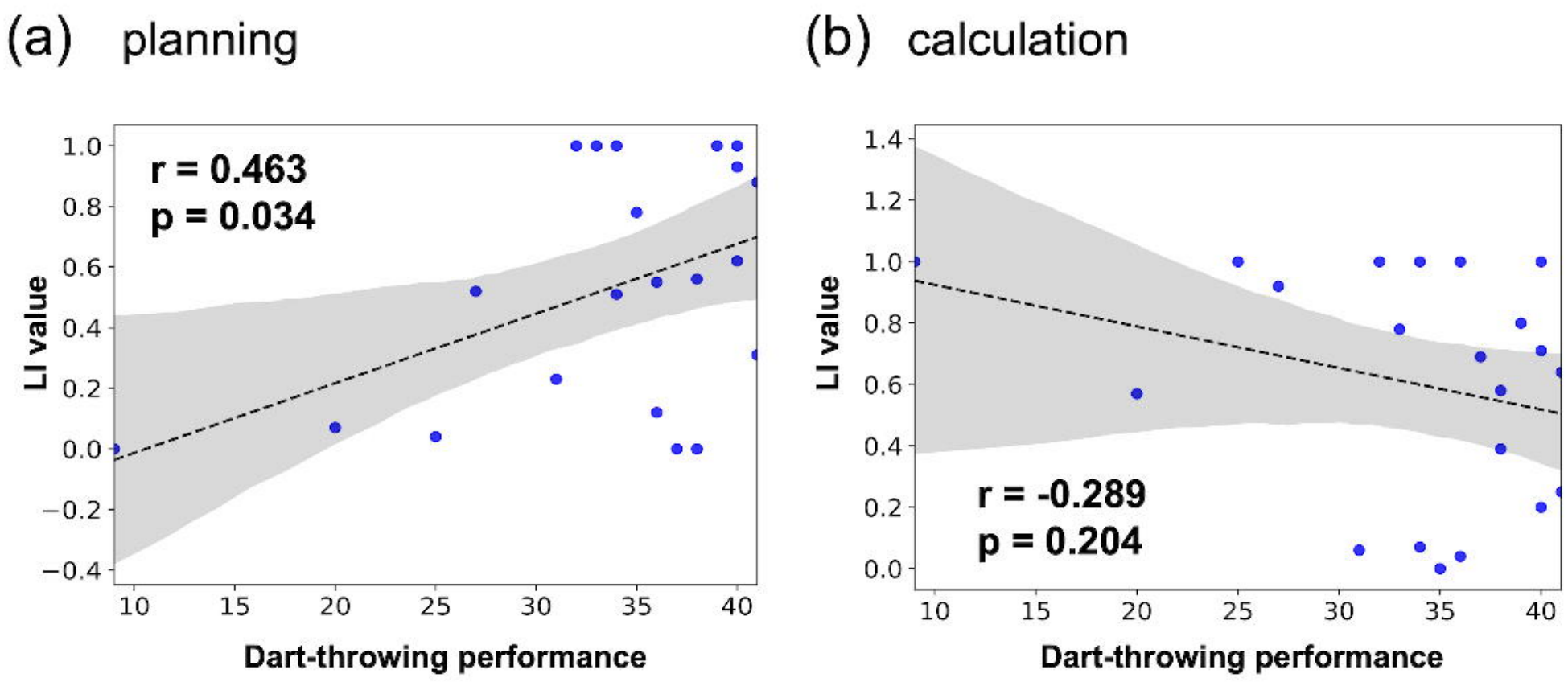
60
40
20
0
*
*
younger group
expert older group
non-expert older group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p = 0.034
LI value
Dart-throwing performance
(b) calculation
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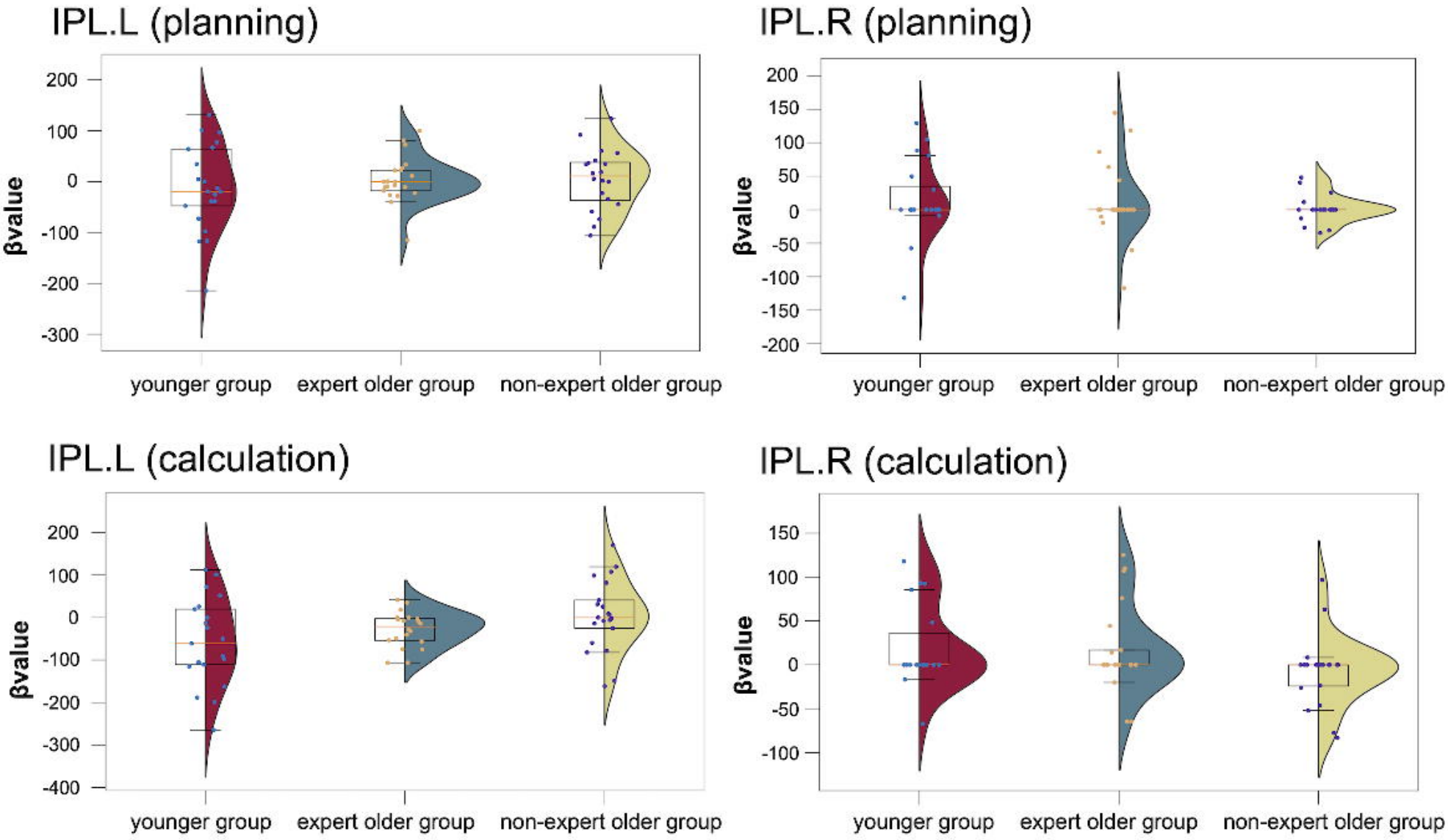
p = 0.204
LI value
Dart-throwing performance


IPL.L (planning)
IPL.R (planning)
IPL.L (calculation)
IPL.R (calculation)
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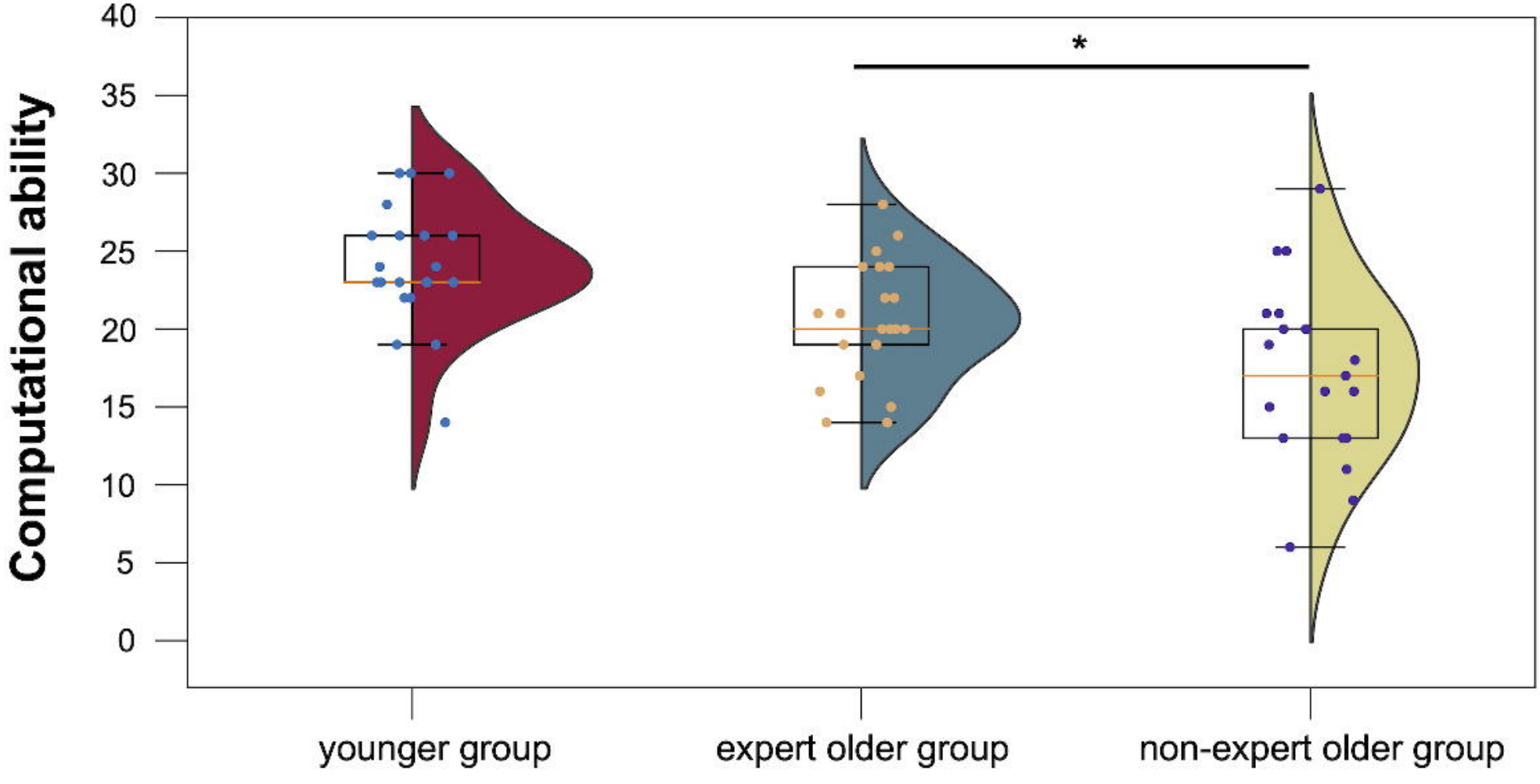
100
0
-100
-200
-300
150
50
-50
-150
-400
younger group
expert older group
non-expert older group


Computational ability
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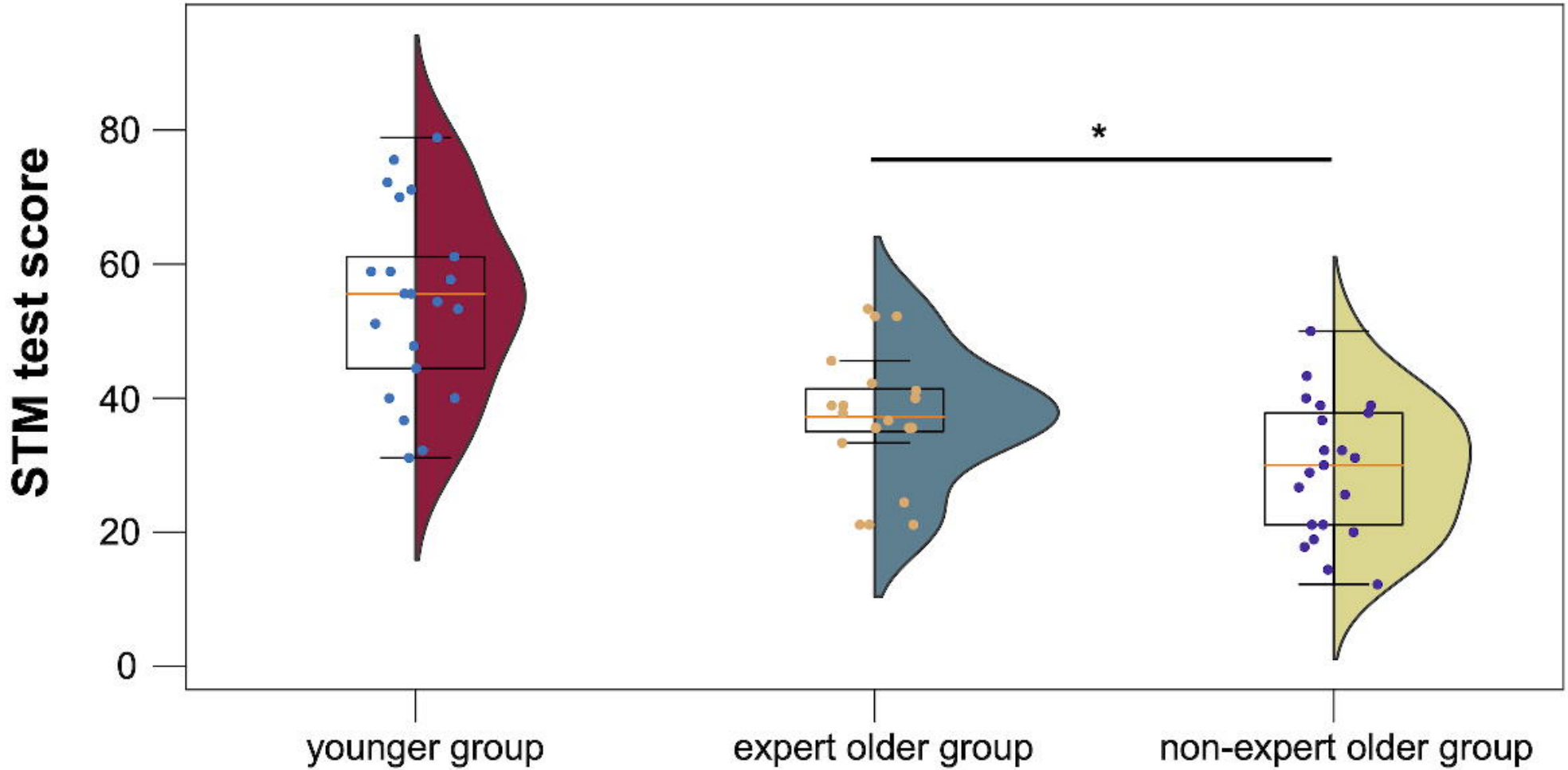
35
30
25
20
15
10
5
0
*
younger group
expert older group
non-expert older group


STM test score
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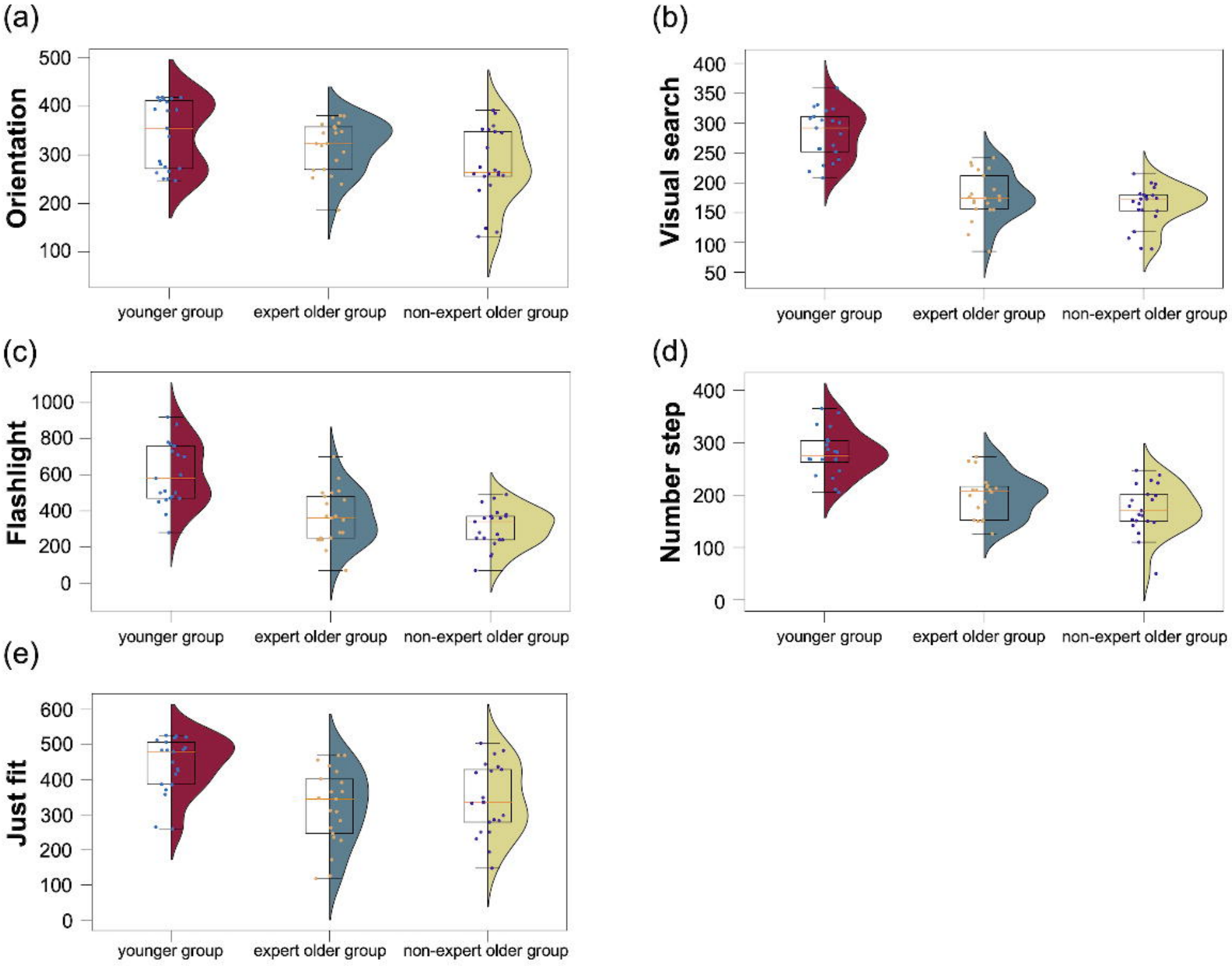
60
40
20
0
*
younger group
expert older group
non-expert older group


(a)
Orientation
500
400
300
200
100
younger group
expert older group
non-expert older group
(b)
Visual search
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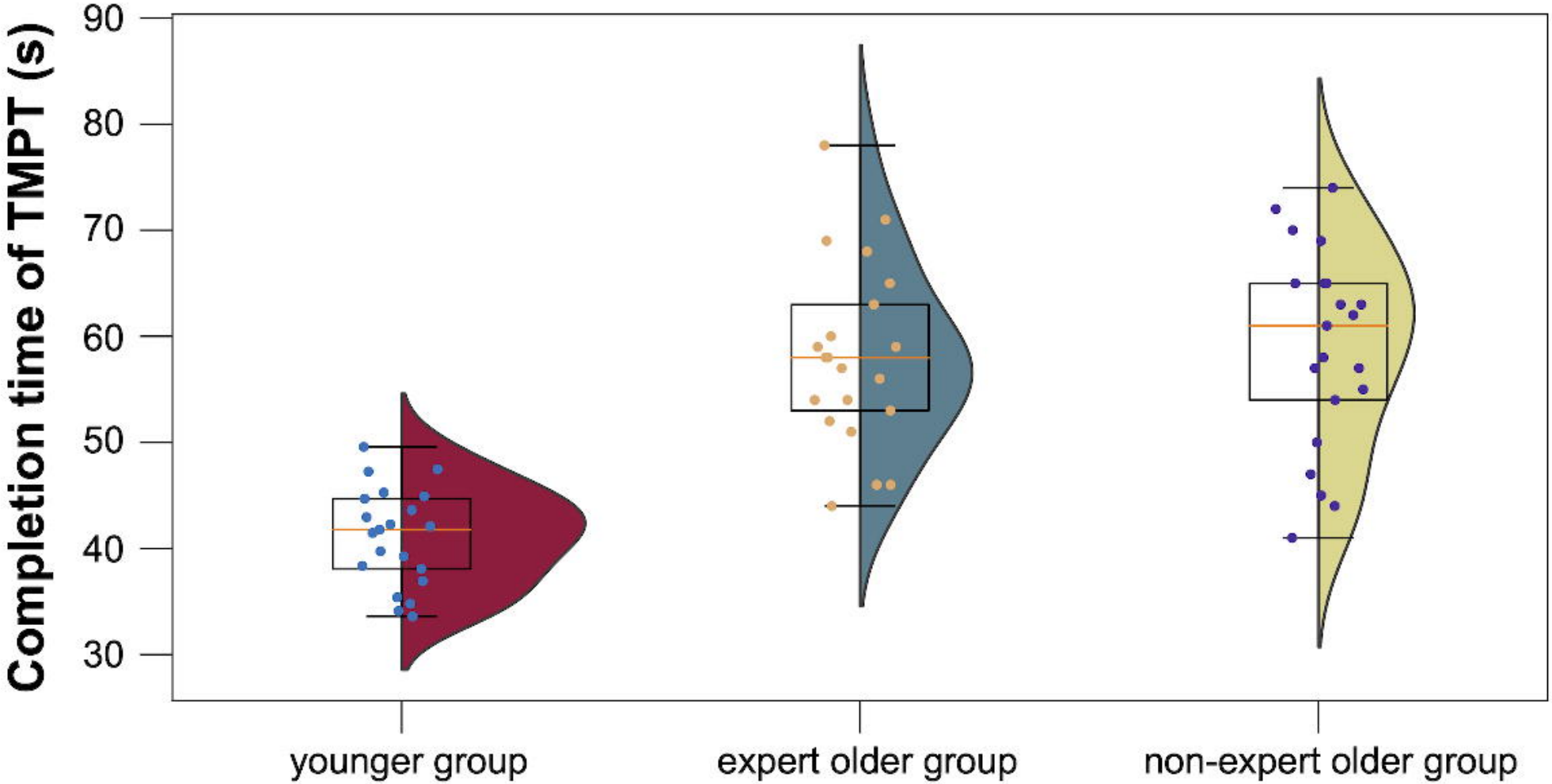
350
300
250
200
150
100
50
younger group
expert older group
non-expert older group
(c)
Flashlight
1000
800
600
400
200
0
younger group
expert older group
non-expert older group
(d)
Number step
400
300
200
100
0
younger group
expert older group
non-expert older group
(e)
Just fit
600
500
400
300
200
100
0
younger group
expert older group
non-expert older group


Completion time of TMPT (s)
90
80
70
60
50
40
30
younger group
expert older group
non-expert older group