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Original Article

Effects of a dual task and different levels of divided attention on motor-related cortical potential

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Abstract. [Purpose] The aim of this study was to investigate the effect of divided attention on motor-related cortical potential (MRCP) during dual task performance while the difficulty of the secondary task was altered. [Participants and Methods] Twenty-two right-handed healthy volunteers participated in the study. MRCPs were recorded during two tasks, a single task (ST) and a simple (S-DT) or complex dual task (C-DT). The ST involved a self-paced tapping task in which the participants extended their right index finger. In the dual task, the participants performed the ST and a visual number counting task simultaneously. [Results] The amplitude and integral value of MRCP from electroencephalography electrode C3 was significantly higher in the S-DT than in the ST, whereas they were similar between the C-DT and the ST. Medium-load divided attention (i.e., S-DT) led to significantly more changes in the MRCP magnitude than did low-load divided attention (i.e., ST). However, the MRCP of high-load divided attention (i.e., C-DT) was similar to that of low-load divided attention. [Conclusion] These results suggest that MRCP reflects the function of or network between the supplementary motor area and the dorsolateral prefrontal cortex, and may serve as a marker for screening the capacity of individuals to perform dual tasks.
Key words: MRCP, Bereitschaftspotential, Dual-task interference

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INTRODUCTION

In daily life, humans commonly perform not only one task but also two tasks (dual tasks) or multiple tasks (multi tasks) simultaneously, e.g., walking and talking, driving and using a cell phone, or talking while cooking at the same time. The incidence of falls or accidental injuries associated with multi tasks has been increasing[1)]. The use of cell phones in motor vehicles can increase the risk of a collision when the driver is distracted for a brief period while attending to a call[2)]. These effects reported in the above studies can be explained by dual-task interference, which is a reduction in the performance of one or both individual tasks that are performed concurrently[3)]. However, the mechanisms underlying dual-task interference are still unclear. A specific dual-task locus in the brain cannot be concluded from the overall current literature. It is important for therapeutic rehabilitation to reduce or predict risks or mistakes in dual-task or multi-task situations; therefore, we have focused on the neural bases of motor preparation to predict and prevent the risk and occurrence of mistakes in humans.

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The neural bases of action motor preparation have been studied using motor-related cortical potential (MRCP)[4–7]. MRCP is known as readiness potential or Bereitschaftspotential and is a slow cortical potential that is associated with voluntarily executed or self-paced movements. The magnitude and time course of MRCP are influenced by various factors such as the level of intention, preparatory state, movement selection, learning, praxis movement, force, speed, precision, discreteness, complexity, parkinsonism, cerebellar lesion, dystonia, recovery from hemiparesis, or mirror movements[4–7]. These factors are included as not only motor processes but also non-motor processes.

While there is a consensus that attention is not a unitary process, there is no agreement on the typologies and taxonomies describing the range of attentional processes[8]. Loetscher et al. considered the following attentional components: alertness/arousal, selective attention, sustained attention (vigilance), and divided attention[8]. The difficulty of performing a dual task is determined by the level of divided attention. The levels of load of a dual task affect the MRCP features of a motor task. High-load divided attention leads to a reduction in specific features of MRCP[9, 10]. For example, in stroke patients, the negativity of MRCP decreases, while pre-phase variability increases[11].

In daily life, humans are required to perform movements at a specific frequency, such as movement timing or inter-response or inter-trial intervals, as well as cue-based motions under dual- or multi-task conditions. Patients with schizophrenia or stroke exhibit impairment in interval timing[12, 13]. Furthermore, exercise feedback is effective in noticing the correct exercise, correcting the exercise, and enhancing motivation during rehabilitation intervention, constant movements, or stable life. However, the relationship between the difficulty of dual tasks and movement frequency with feedback in MRCP has not been investigated sufficiently.

Therefore, the purpose of the present study was to quantify the effects of dual task complexity and movement frequency, which relies on an internal pacemaker and feedback, and the accuracy of a cognitive task on MRCP. We selected a finger movement task as the motor task since finger movements are used frequently during normal daily tasks, such as writing, typing, or eating a meal. A visual number counting task was used as the cognitive task since there are many situations in which numbers are a visually understood quantity, such as on a clock. We assessed dual-task interference in this study according to the frequency of finger tapping and the accuracy of the visual number counting task. We hypothesized that MRCP magnitude would be reduced with increasing load in the divided attention tasks if the corresponding pre-movement neural activity relies on the engagement of divided attention. The results of the present study will have important implications as MRCP may serve as a marker for screening the safety of dual or multi tasks in real life settings, since the modulation of cortical plasticity is known to be affected by attention[14–16].

PARTICIPANTS AND METHODS

Twenty-two right-handed healthy volunteers (7 females; 15 males; average age ± standard deviation, 20.82 ± 1.18 years; range, 19–22 years) participated in the study. They were subdivided into 2 groups of 11 participants. Handedness was assessed by the Edinburgh Handedness Inventory[17]. This study was approved by the institutional ethics committee of the International University of Health and Welfare, Japan (approval no. 16-Io-198). Written informed consent was obtained from all participants prior to their participation in the study.

Each participant was seated in a comfortable chair located 60–70 cm away from a digital computer monitor and their right and left forearms were placed on a table. A surface electromyography electrode (DL-141; S&ME, Tokyo, Japan) was placed on the right extensor digitorum muscle of the index finger to determine movement onset. Two monopolar electroencephalogram channels were recorded using an active electroencephalogram electrode system (DL-160B; S&ME, Tokyo, Japan) from C3 and C4, according to the standard international 10–20 system. The reference electrode was placed on Fz and the ground was placed on the left and right earlobes. The recorded data were analyzed using a Multi-Analyzer system (Medical Try System, Tokyo, Japan).

The participants performed two tasks: a single task (ST) and a dual task (DT) consisting of a simple dual task (S-DT) or complex dual task (C-DT) (Fig. 1). The ST and DT (S-DT and C-DT) were defined as low-, medium-, and high-load divided attention tasks, respectively. The paradigm used here is similar to that employed in previous studies[9–11]. This paradigm can reduce the effects of mental or cognitive fatigue[18, 19]. The ST was a motor task that involved self-paced tapping with the extended right index finger at a frequency of 5 s. The intervals were displayed on a monitor as feedback to the participants. In the DT, the participants performed the ST and a visual number counting task simultaneously. For the visual number counting task, the X-type Continuous Performance Test in the Clinical Assessment for Attention (Japan Society for Higher Brain Dysfunction, Tokyo, Japan) was used. For the visual number counting task, a random series of numbers (from 1 to 9) were presented on a screen and the participants were required to identify the number of times a specified target number appeared. The numbers were presented at an irregular interval of 1–2 s. In the S-DT, the participants were asked to count the number of sevens appearing among a random series of predominantly distractor numbers. In the C-DT, the participants were asked to count the number of threes and sevens. Each task contained 3 blocks with 30 trials at a frequency of 5 s. The participants were asked to answer orally the number of times each target number appeared after each block. The participants practiced the motor task until a certain level of performance was achieved before the first recording session, and they were briefed about the method to execute the dual task.

The frequency of finger tapping in the motor task was quantified by considering the coefficient of variation (CV=standard

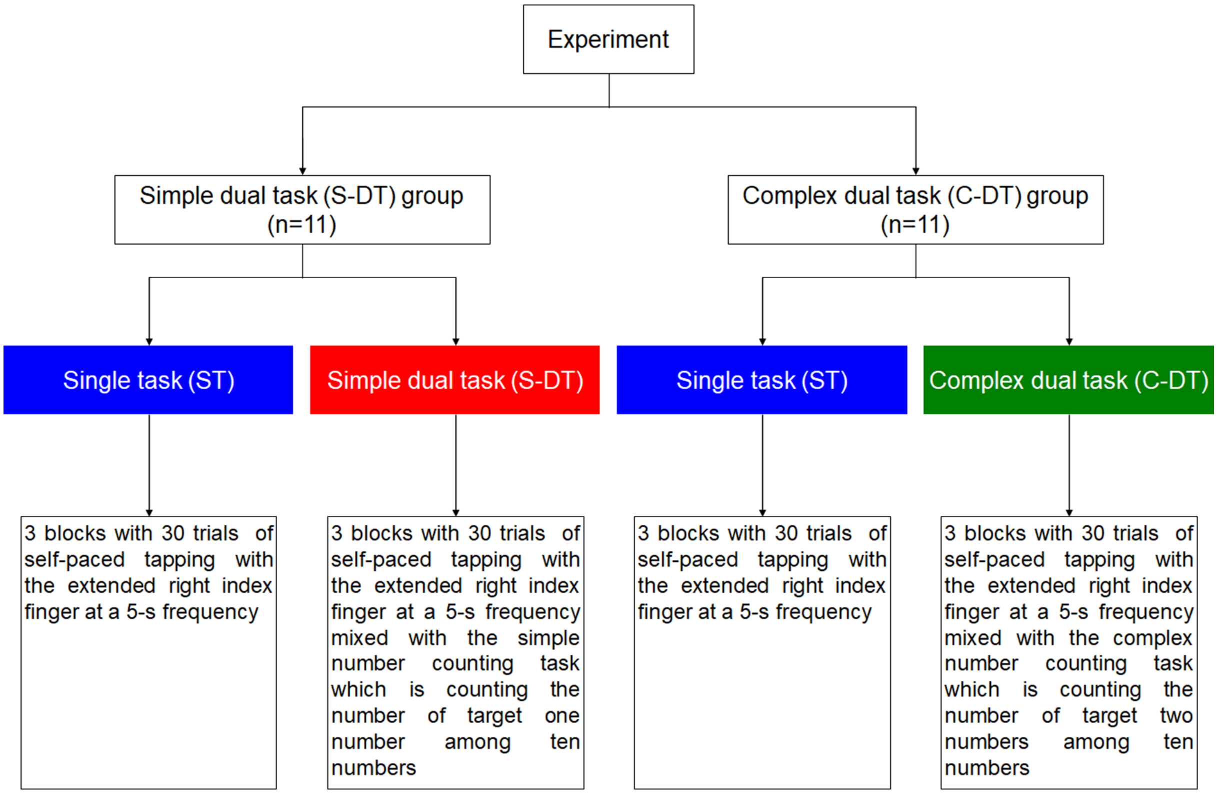

Fig. 1. A diagram of the different stages of the experiment. The paradigm used here is similar to that employed in previous studies[9–11].

deviation / average) between movement onset for each experimental task condition. In the visual number counting task, the accuracy of the number of target numbers under the DT (S-DT and C-DT) conditions was used. The signal was digitized at 1,000 Hz, with an amplifier band-pass from 0.05 to 10 Hz[9] and a 50-Hz notch filter[20]. To reduce high frequency noise further, the time-averaged MRCPs were filtered at 15 Hz. The baseline was calculated from 2,800 to 2,600 ms before movement onset. Data were segmented into epochs from 2,700 ms prior to movement onset to 1,000 ms after it. An electromyography artifact was defined as an electromyography signal at less than a 3-s interval or more than a 7-s interval and excluded from the analysis. Trials with electrooculography artifacts were excluded by using a threshold of 120 μV[9]. An amplitude of peak negativity and time of peak negativity were considered as the initial features. An integral value from −2,000 ms to the time of peak negativity was also defined as the overall trend. The integral value was used in this study since one component of MRCP is a slowly rising negativity that occurs at approximately 2,000 ms prior to movement onset[7].

For the motor frequency variables with CV, two-way repeated measures analysis of variance (two-way ANOVA) with the S-DT and C-DT groups (group) and with the ST and DT (S-DT or C-DT) (divided attention load) conditions was used. In the visual number counting tasks, the accuracy of the number of target numbers under the DT (S-DT and C-DT) conditions was compared using the Mann-Whitney U test since normality was not confirmed according to the Shapiro-Wilk test. To determine the effect of the divided attention tasks on MRCP, two-way ANOVA (group and divided attention load) was used for the amplitude of peak negativity, time of the negative peak, and integral value from −2,000 ms to the time of peak negativity, as well as the motor frequency variables. Bonferroni's post hoc test was used in multiple pairwise comparisons. All statistical analyses were performed with SPSS23 software (IBM Corporation, Armonk, NY, USA) with the significance level set at $p<0.05$.

RESULTS

Table 1 shows the CV of movement frequency as a function of task condition: ST and S-DT in the S-DT group, and ST and C-DT in the C-DT group. There was not a significant interaction (group*single-dual task) in the result of the ANOVA for the CV($F(1,20)=1.41$, $p=0.25$, partial $\eta^2=0.07$). A comparison of the ST between both groups indicated that the CV was not different between the S-DT and C-DT groups ($F(1,10)=0.27$, $p=0.62$, partial $\eta^2=0.03$). The CV was more variable only for the ST versus the C-DT in the C-DT group ($F(1,10)=6.00$, $p=0.03$, partial $\eta^2=0.38$). The CV of the C-DT in the C-DT group was not a significant variable than the CV of the S-DT in the S-DT group ($F(1,10)=2.79$, $p=0.11$, partial $\eta^2=0.12$).

The accuracy of the visual number counting tasks was affected in both DT (S-DT and C-DT) conditions (Mann-Whitney

Table 1. Values of coefficient of variation of movement frequency and motor-related cortical potential features

Features of the participants			ST	S-DT or C-DT
Coefficient of variation (a.u.)		S−DT group	0.09 ± 0.02	0.10 ± 0.03
		C−DT group	0.10 ± 0.04	0.12 ± 0.04
Amplitude of peak negativity (μV)	C3	S−DT group	−4.65 ± 3.26	−6.49 ± 3.14
		C−DT group	−8.68 ± 6.63	−8.54 ± 4.43
	C4	S−DT group	−4.48 ± 3.89	−5.46 ± 3.30
		C−DT group	−6.29 ± 5.76	−6.50 ± 3.19
Time of peak negativity (ms)	C3	S−DT group	176 ± 124	186 ± 121
		C−DT group	193 ± 94	209 ± 107
	C4	S−DT group	165 ± 156	235 ± 127
		C−DT group	148 ± 120	188 ± 159
Integral value (−2,000 to 0 ms) (μV*ms)	C3	S−DT group	−2,931 ± 5,632	−9,614 ± 10,670
		C−DT group	−8,075 ± 5,408	−7,372 ± 5,435
	C4	S−DT group	−3,716 ± 5,512	−7,198 ± 9,658
		C−DT group	−7,452 ± 6,042	−6,603 ± 4,145

Mean ± standard deviation.
ST: single task; S-DT: simple dual task; C-DT: complex dual task; a.u.: arbitrary units.

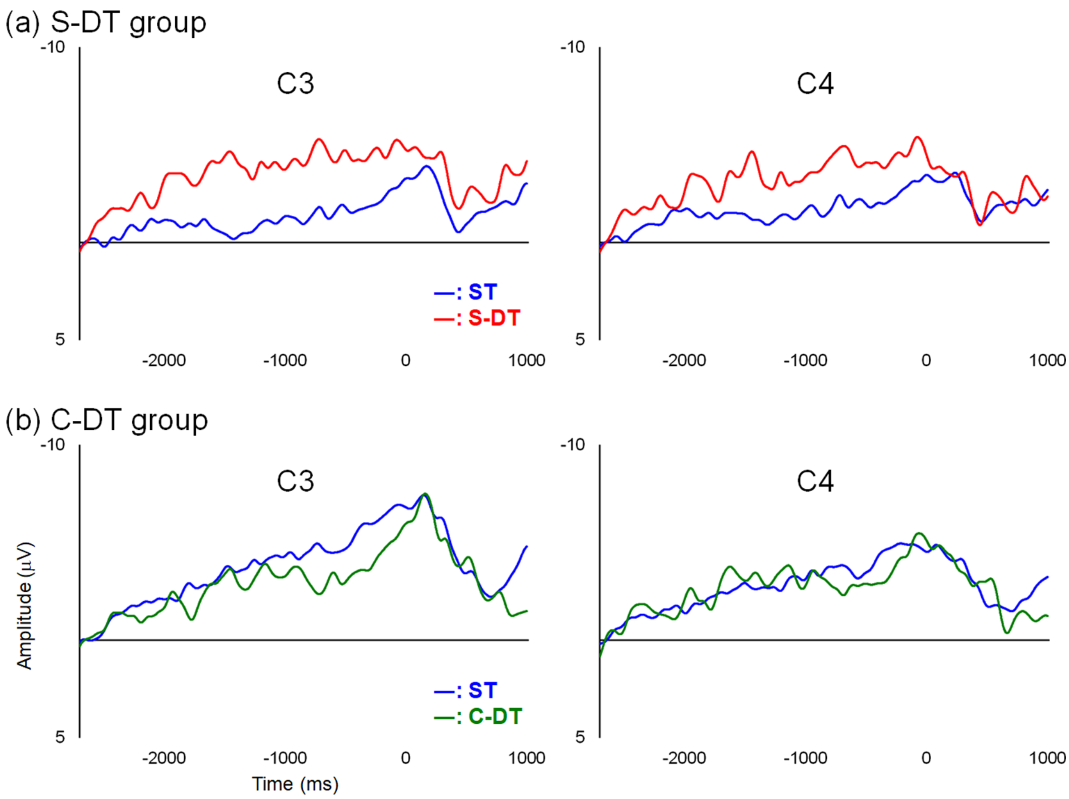

Fig. 2. Grand average of motor-related cortical potential from all participants obtained from C3 and C4 in the (a) simple dual task (S-DT) group and (b) complex dual task (C-DT) group.

U=18.00, p=0.00, r=0.60, S-DT: 96.45 ± 4.20%, C-DT: 90.73 ± 2.90%). The correlation coefficient between the CV of movement frequency and accuracy of the visual number counting task in the DT (S-DT and C-DT) conditions was −0.45 (p=0.03).

Figure 2 illustrates the average MRCP from C3 and C4 in the task conditions: ST and S-DT in the S-DT group, and ST and C-DT in the C-DT group. The amplitude of peak negativity, time of the negative peak, and integral value on both C3 and C4 of the ST in the S-DT group were not significantly different from that in the C-DT group. The amplitude of peak negativity and integral value on C3 were higher in the S-DT condition than in the ST condition in the S-DT group ($F(1,10)=6.50$, $p=0.03$, partial $\eta^2=0.39$ and $F(1,10)=8.39$, $p=0.02$, partial $\eta^2=0.46$, respectively). No significant variations were found in the time of peak negativity on C3 in the S-DT and C-DT groups. No MRCP parameters on C4 were significant in both task conditions.

DISCUSSION

To our knowledge, this is the first investigation of the effects of dual task complexity on movement frequency, which relies on an internal pacemaker and feedback, and the accuracy of a visual number counting task on MRCP in electroencephalogram electrodes C3 and C4. MRCP magnitude, such as the amplitude of the negative peak and integral value, from C3 was significantly higher in the medium-load divided attention condition (i.e., under the S-DT) than in the low-load attentional diversion condition (i.e., under the ST) in the contralateral region, whereas it was similar between the high-load divided attention condition (i.e., under the C-DT) and the low-load attentional diversion condition.

In this study, the participants were subdivided into two groups (S-DT and C-DT groups). Since the CV of movement frequency and MRCP parameters of the ST in the S-DT group was not significantly different from that in the C-DT group, the features of the S-DT and C-DT groups were considered to be the same. The CV between movement onset was significantly more variable in the C-DT than in the ST, whereas it was similar in the S-DT group. The accuracy of the visual number counting task was also significantly lower in the C-DT than in the S-DT. Further, the significant correlation between the CV of movement frequency and the accuracy of the visual number counting task in the DT (S-DT and C-DT) conditions was confirmed. These behavioral data can be explained by dual-task interference, which is a reduction in the performance of one or both individual tasks that are performed concurrently[3)].

The amplitude and integral value of MRCP were significantly higher in the S-DT than in the ST, whereas they were similar between the C-DT and ST. The magnitude and time course of MRCP are influenced by various factors[4–7)]. Our results were similar to those of previous MRCP studies using a dual task[9–11)]. Baker et al. showed that pre-movement neural activity in the MRCP is attenuated when cognitive resources are not readily available for movement preparation, and early stage pre-movement activity reflects the engagement of specific cognitive processes that overlap with cognitive control and working memory[10)]. Therefore, we suggest that MRCP magnitude was higher in the S-DT than in the ST since the engagement of specific cognitive processes was strongly required in the S-DT. However, The C-DT was similar to the ST since the cognitive resources of the participants may not be readily available for movement preparation in the C-DT. Our results also suggest that the amplitude of the negative peak and integral value of MRCP can be used during motor preparation to detect changes in the divided attention of participants, specifically at different levels of task complexity.

In the case of hand movements, the bilateral supplementary motor area (SMA) and lateral precentral gyrus are considered to be the main sources of MRCP[7)]. Previous studies using functional magnetic resonance imaging (fMRI) suggest a role for the SMA in the preparation of voluntary actions[21–24)]. The SMA is more active when attending to a movement that is being performed intentionally than when it is performed automatically[25, 26)] or when attention is occupied by a distractor task[27)]. The SMA is also involved in orienting attention to points in time[28, 29)] and in selecting the right moment to initiate an action[30, 31)]. Therefore, we suggest that the motor task used in the present study reflects the function of the SMA.

Anatomical connections between the prefrontal cortex and SMA are known to exist[32, 33)]. The dorsolateral prefrontal cortex (DLPFC) is also known to be involved in our tasks, which included working memory[34–38)]. Wiese et al. suggested that prefrontal lesions lead to reduced neuronal input into the SMA, and this deficit in the preparatory motor network may cause the reduced MRCPs observed in patients with traumatic frontal brain injury[39)]. Therefore, we hypothesize that the functions of the prefrontal cortex, including the DLPFC, and the SMA, and the state of these networks influenced the magnitude of MRCP in the present study.

The participants performed the dual task for the first time in this study. When participants have to perform two tasks concurrently, cognitive processing is enhanced, but this effect is more enhanced for cognitive skills related to a novel and complex task[40)]. This may be related to the effect of not only attention but also executive function or working memory, which refers to the cognitive processes in divided attention or when performing a new task[3, 16, 41)].

In the present study, we used a visual number counting task with two levels of difficulty to alter the participants' attention. Attention is affected by not only visual stimuli but also auditory or tactile stimuli in daily life. Four studies, in which a significant effect of treatment on divided attention was reviewed by Loetscher et al.[8)], assessed divided attention using the Paced Auditory Serial Addition Test[42–44)] or the divided attention subtest from the Tests of Attentional Performance[45)]. The Paced Auditory Serial Addition Test was performed with an auditory task, while the subtest from the Tests of Attentional Performance was assessed by auditory and visual tasks in parallel. In the future, we would like to examine if the same results can be obtained even if the type of sensory stimulus is changed.

The participants in this study were young adults. Age has been shown to affect brain activity during dual-task performance in investigations using near-infrared spectroscopy[46–48)] and fMRI[49)]. This was also similar to pre-movement neural activity, i.e., MRCP[50–52)]. Different patterns of increased or decreased activation of task-specific or non-specific neuronal areas have been reported[3)]. We strongly recommend that further studies (e.g., a comparison of participants' age, disease, and neuroimaging) should be performed to understand better the neural bases of motor preparation.

In the present study, we explored the effects of dual task complexity with movement frequency, which relies on an internal pacemaker and feedback, and the accuracy of a visual number counting task on MRCP in electroencephalogram electrodes C3 and C4. The amplitude and integral value of MRCP from C3 were significantly higher in the S-DT than in the ST, whereas they were similar between the C-DT and ST. Medium-load divided attention (i.e., S-DT) led to a significantly greater change in MRCP magnitude than in low-load divided attention (i.e., ST). However, the MRCP of high-load divided attention (i.e., C-DT) was similar to that of low-load divided attention. These results suggest that MRCP reflects the function of or network between the SMA and DLPFC and may serve as a marker for screening the capacity of individuals when performing dual tasks.

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Conflict of interest

None.

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REFERENCES

1) Nasar JL, Troyer D: Pedestrian injuries due to mobile phone use in public places. Accid Anal Prev, 2013, 57: 91–95. [Medline] [CrossRef]
2) Redelmeier DA, Tibshirani RJ: Association between cellular-telephone calls and motor vehicle collisions. N Engl J Med, 1997, 336: 453–458. [Medline] [CrossRef]
3) Leone C, Feys P, Moumdjian L, et al.: Cognitive-motor dual-task interference: a systematic review of neural correlates. Neurosci Biobehav Rev, 2017, 75: 348–360. [Medline] [CrossRef]
4) Di Russo F, Berchicci M, Bozzacchi C, et al.: Beyond the “Bereitschaftspotential”: action preparation behind cognitive functions. Neurosci Biobehav Rev, 2017, 78: 57–81. [Medline] [CrossRef]
5) Hallett M: Movement-related cortical potentials. Electromyogr Clin Neurophysiol, 1994, 34: 5–13. [Medline]
6) Lang W: Surface recordings of the Bereitschaftspotential in normal. In: The Bereitschaftspotential. Movement-related cortical potentials. New York: Klüver Academic/Plenum Publishers, 2003, pp 19–34.
7) Shibasaki H, Hallett M: What is the Bereitschaftspotential? Clin Neurophysiol, 2006, 117: 2341–2356. [Medline] [CrossRef]
8) Loetscher T, Lincoln NB, Wong D, et al.: Cognitive rehabilitation for attention deficits following stroke. Cochrane Database Syst Rev, 2013, 2019: CD002842. [Medline]
9) Aliakbaryhosseinabadi S, Kamavuako EN, Jiang N, et al.: Influence of dual-tasking with different levels of attention diversion on characteristics of the movement-related cortical potential. Brain Res, 2017, 1674: 10–19. [Medline] [CrossRef]
10) Baker KS, Mattingley JB, Chambers CD, et al.: Attention and the readiness for action. Neuropsychologia, 2011, 49: 3303–3313. [Medline] [CrossRef]
11) Aliakbaryhosseinabadi S, Kostic V, Pavlovic A, et al.: Influence of attention alternation on movement-related cortical potentials in healthy individuals and stroke patients. Clin Neurophysiol, 2017, 128: 165–175. [Medline] [CrossRef]
12) Plummer P, Eskes G, Wallace S, et al. American Congress of Rehabilitation Medicine Stroke Networking Group Cognition Task Force: Cognitive-motor interference during functional mobility after stroke: state of the science and implications for future research. Arch Phys Med Rehabil, 2013, 94: 2565–2574.e6. [Medline] [CrossRef]
13) Snowden AW, Buhusi CV: Neural correlates of interval timing deficits in schizophrenia. Front Hum Neurosci, 2019, 13: 9. [Medline] [CrossRef]
14) Conte A, Gilio F, Iezzi E, et al.: Attention influences the excitability of cortical motor areas in healthy humans. Exp Brain Res, 2007, 182: 109–117. [Medline] [CrossRef]
15) Stefan K, Wycislo M, Classen J: Modulation of associative human motor cortical plasticity by attention. J Neurophysiol, 2004, 92: 66–72. [Medline] [CrossRef]
16) Ziemann U, Paulus W, Nitsche MA, et al.: Consensus: motor cortex plasticity protocols. Brain Stimul, 2008, 1: 164–182. [Medline] [CrossRef]
17) Oldfield RC: The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia, 1971, 9: 97–113. [Medline] [CrossRef]
18) Faber LG, Maurits NM, Lorist MM: Mental fatigue affects visual selective attention. PLoS One, 2012, 7: e48073. [Medline] [CrossRef]
19) Van der Linden D: The urge to stop: the cognitive and biological nature of acute mental fatigue. In: Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington DC: American Psychological Association, 2011, pp 149–164.
20) Bozzacchi C, Giusti MA, Pitzalis S, et al.: Similar cerebral motor plans for real and virtual actions. PLoS One, 2012, 7: e47783. [Medline] [CrossRef]
21) Ball T, Schreiber A, Feige B, et al.: The role of higher-order motor areas in voluntary movement as revealed by high-resolution EEG and fMRI. Neuroimage, 1999, 10: 682–694. [Medline] [CrossRef]
22) Cunnington R, Windischberger C, Deecke L, et al.: The preparation and readiness for voluntary movement: a high-field event-related fMRI study of the Bereitschafts-BOLD response. Neuroimage, 2003, 20: 404–412. [Medline] [CrossRef]
23) Cunnington R, Windischberger C, Moser E: Premovement activity of the pre-supplementary motor area and the readiness for action: studies of time-resolved event-related functional MRI. Hum Mov Sci, 2005, 24: 644–656. [Medline] [CrossRef]
24) Wildgruber D, Erb M, Klose U, et al.: Sequential activation of supplementary motor area and primary motor cortex during self-paced finger movement in hu-

man evaluated by functional MRI. Neurosci Lett, 1997, 227: 161–164. [Medline] [CrossRef]
25) Jueptner M, Stephan KM, Frith CD, et al.: Anatomy of motor learning. I. Frontal cortex and attention to action. J Neurophysiol, 1997, 77: 1313–1324. [Medline] [CrossRef]
26) Rowe J, Friston K, Frackowiak R, et al.: Attention to action: specific modulation of corticocortical interactions in humans. Neuroimage, 2002, 17: 988–998. [Medline] [CrossRef]
27) Johansen-Berg H, Matthews PM: Attention to movement modulates activity in sensori-motor areas, including primary motor cortex. Exp Brain Res, 2002, 142: 13–24. [Medline] [CrossRef]
28) Coull JT, Frith CD, Büchel C, et al.: Orienting attention in time: behavioural and neuroanatomical distinction between exogenous and endogenous shifts. Neuropsychologia, 2000, 38: 808–819. [Medline] [CrossRef]
29) Coull JT, Nobre AC: Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. J Neurosci, 1998, 18: 7426–7435. [Medline] [CrossRef]
30) Deecke L, Kornhuber HH, Lang W, et al.: Timing function of the frontal cortex in sequential motor and learning tasks. Hum Neurobiol, 1985, 4: 143–154. [Medline]
31) Macar F, Anton JL, Bonnet M, et al.: Timing functions of the supplementary motor area: an event-related fMRI study. Brain Res Cogn Brain Res, 2004, 21: 206–215. [Medline] [CrossRef]
32) Bates JF, Goldman-Rakic PS: Prefrontal connections of medial motor areas in the rhesus monkey. J Comp Neurol, 1993, 336: 211–228. [Medline] [CrossRef]
33) Luppino G, Matelli M, Camarda R, et al.: Corticocortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. J Comp Neurol, 1993, 338: 114–140. [Medline] [CrossRef]
34) Brass M, Haggard P: The what, when, whether model of intentional action. Neuroscientist, 2008, 14: 319–325. [Medline] [CrossRef]
35) Jahanshahi M, Jenkins IH, Brown RG, et al.: Self-initiated versus externally triggered movements. I. An investigation using measurement of regional cerebral blood flow with PET and movement-related potentials in normal and Parkinson's disease subjects. Brain, 1995, 118: 913–933. [Medline] [CrossRef]
36) Jenkins IH, Jahanshahi M, Jueptner M, et al.: Self-initiated versus externally triggered movements. II. The effect of movement predictability on regional cerebral blood flow. Brain, 2000, 123: 1216–1228. [Medline] [CrossRef]
37) Lewis PA, Miall RC: Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. Curr Opin Neurobiol, 2003, 13: 250–255. [Medline] [CrossRef]
38) Rammsayer TH: Neuropharmacological evidence for different timing mechanisms in humans. Q J Exp Psychol B, 1999, 52: 273–286. [Medline]
39) Wiese H, Stude P, Nebel K, et al.: Impaired movement-related potentials in acute frontal traumatic brain injury. Clin Neurophysiol, 2004, 115: 289–298. [Medline] [CrossRef]
40) Montani V, De Filippo De Grazia M, Zorzi M: A new adaptive videogame for training attention and executive functions: design principles and initial validation. Front Psychol, 2014, 5: 409. [Medline] [CrossRef]
41) Springer S, Giladi N, Peretz C, et al.: Dual-tasking effects on gait variability: the role of aging, falls, and executive function. Mov Disord, 2006, 21: 950–957. [Medline] [CrossRef]
42) Barker-Collo SL, Feigin VL, Lawes CM, et al.: Reducing attention deficits after stroke using attention process training: a randomized controlled trial. Stroke, 2009, 40: 3293–3298. [Medline] [CrossRef]
43) Westerberg H, Jacobaeus H, Hirvikoski T, et al.: Computerized working memory training after stroke--a pilot study. Brain Inj, 2007, 21: 21–29. [Medline] [CrossRef]
44) Winkens I, Van Heugten CM, Wade DT, et al.: Efficacy of time pressure management in stroke patients with slowed information processing: a randomized controlled trial. Arch Phys Med Rehabil, 2009, 90: 1672–1679. [Medline] [CrossRef]
45) Röhring S, Kulke H, Reulbach U, et al.: Effectivity of a neuropsychological training in attention functions by a teletherapeutic setting. NeuroRehabilitation, 2004, 10: 239–246.
46) Beurskens R, Helmich I, Rein R, et al.: Age-related changes in prefrontal activity during walking in dual-task situations: a fNIRS study. Int J Psychophysiol, 2014, 92: 122–128. [Medline] [CrossRef]
47) Holtzer R, Mahoney JR, Izzetoglu M, et al.: fNIRS study of walking and walking while talking in young and old individuals. J Gerontol A Biol Sci Med Sci, 2011, 66: 879–887. [Medline] [CrossRef]
48) Ohsugi H, Ohgi S, Shigemori K, et al.: Differences in dual-task performance and prefrontal cortex activation between younger and older adults. BMC Neurosci, 2013, 14: 10. [Medline] [CrossRef]
49) Van Impe A, Coxon JP, Goble DJ, et al.: Age-related changes in brain activation underlying single- and dual-task performance: visuomanual drawing and mental arithmetic. Neuropsychologia, 2011, 49: 2400–2409. [Medline] [CrossRef]
50) Berchicci M, Lucci G, Pesce C, et al.: Prefrontal hyperactivity in older people during motor planning. Neuroimage, 2012, 62: 1750–1760. [Medline] [CrossRef]
51) Falkenstein M, Yordanova J, Kolev V: Effects of aging on slowing of motor-response generation. Int J Psychophysiol, 2006, 59: 22–29. [Medline] [CrossRef]
52) Yordanova J, Kolev V, Hohnsbein J, et al.: Sensorimotor slowing with ageing is mediated by a functional dysregulation of motor-generation processes: evidence from high-resolution event-related potentials. Brain, 2004, 127: 351–362. [Medline] [CrossRef]