Effect of neuromuscular electrical stimulation on word memory

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Abstract

The effect of neuromuscular electrical stimulation to word memory

Aim: The purpose of the present study is to investigate whether neuromuscular electrical stimulation (NMES) enhances memory function. Methods: Thirteen healthy university students performed 10min of NMES and voluntary isometric contraction for knee extensor muscles at 20% of maximal voluntary contraction on separated days. After each experiment, 10 Hungarian word memorizes was conducted immediately for 10 minutes. After 24 hours, word remember test and memory retention rate were measured. These procedures were also performed following 10min of rest as control trial. Result: The test score was significantly higher compared with the test score after Rest for NMES ($p<0.05$), but not for VOL ($p > 0.05$). Conclusion: From these results, we suggested that NMES activate cognitive function and enhanced word memory.

神経筋電気刺激が単語記憶に及ぼす影響

目的：本研究の目的は神経筋電気刺激（NMES）によって単語記憶力が向上するかどうか調査することであった。方法：13人の健康な大学生が、最大随意収縮(MVC)の２０％でNMES、もしくは随意運動を各10分間実施した。各実験後すみやかに10分間で10問のハンガリー語記憶を行い、24時間後を目安に単語記憶テストによって記憶力の定着度を測定しました。これらの記憶テストの手順は10分間の安静後でも同様に行われました。結果：NMES後の単語テストスコアは安静時のスコアよりも有意に高かった（$p<0.05$）。結論：これらの結果からNMESは認知機能を活性化させ、単語記憶力を向上させることを示唆している。

El effecto de Estimulactión eléctrica neuromusclar a la memoria de palabras

Objectivo: El objectivo del presente estudio fue investigar si mejora la memoria palabras por estimulactión eléctrica neuromusclar (NMES). Métodos: Trece estudiante saludables hicienron NMES al 20% de MVC y extensión de rodilla isométrica (VOL) por 10 minutos cada uno en el dia diferente. Después de cada experimento, participantes recordaron 10 palabras Hungría inmediatamente por 10 minutos. 24 holas después, participantes hicieron la prueba de palabras y medimos la tasa de retención de memoria desde resultado dela prueba. Estos procedimientos también se realizaron después de 10min de descanso como control. Resultado: Los puntos de prueba después NMES fue alto significativamente comparado con los puntos de prueba despues descanso ($p<0.05$). Conclusión: Estos resultados sugieren que NMES actitivó la función cognitiva y mejoró la memoria de palabras.

Abbreviations:

NMES: neuromuscular electrical stimulation, VOL: voluntary exercise, QF: quadriceps femoris, STM: short term memory, LTM: long term memory, BDNF: brain derived neurotrophic factor, MVC: maximum voluntary contractions

Introduction

In recent years, the need for foreign language is increased with Globalization (Ministry of Education, Culture, Sports, Science and Technology (MEXT). 2018, British Council. 2018). Globalization is trendy word, and it seems that the development of information technology is one of the big factors progressing globalization. According to World Trade Organization (WTO) report in 2020, world merchandise trade in 2019 was slightly decreased compare with 2018. However, in the information businesses such as telecommunications, computer and information service grew 11% in 2019 from 2018 (WTO. 2020). Internet users and the volume of internet access have been increasing every year (International Telecommunication Union (ITU). 2020). International Organization for Migration (IOM) reported that human immigrations have been increasing and there are huge changes in immigrations between 2000 and 2020 (IOM. 2020). According to ministry of economy, trade, and industry in Japan (METI) show the changes in the number of foreign people coming in Japan (e-stat. 2006-2019). Also, many Japanese enterprises have been moving their company to foreign countries and Japanese people living in foreign countries have been increasing (METI. 1999, 2019).

Japanese Government defined three factor as global person and language ability is the one of those factors (MEXT. 2012). Government and enterprises are positive to recruit, cultivate such a global person (Ministry of internal affairs and communications. (MIC). 2017). Their policy with Globalization and the influx of diverse cultures into Japan may affect the number of Japanese international students, it has been increased every year (MEXT. 2021). Also, other research says language business sales in 2019 make a more profit compared with 2015 (Yano Research Institute Ltd. 2016, 2020). Therefore, those human resources who can adapt to globalization has been required.

Rodrigo (2017), in his paper, investigated vocabulary knowledge in the production written in case of English as a Foreign Language (EFL) learner and he concluded vocabulary is essential process for learning language (Rodrigo. 2017). However, there is not much time for students or workers to study foreign language such as English because they have other fundamental curriculum or their work. But if they learn and memorize vocabulary more efficiently, they can save the time and use it for other things.

There are some ways to enhance human memory. Slow-wave-sleep enhance memory consolidation and transform memory for long-term memory afterwards, rapid-eye-movement sleep stabilize transformed memory (Rasch B et al. 2013). Hence, memory is kept for long time. Among them, many results of memory improvement caused by physical exercise have been reported. For instance, long-term aerobic exercises increased the size of hippocampus and induced memory improvement (Kirk et al. 2011). Marin (2021), reported moderate intensity exercise significantly enhance cognitive function compared with rest state and high intensity exercise (Marin. 2021). These studies reporting the enhancement of cognitive function following physical exercise would have another advantage such as countermeasures to sedentary lifestyle. According to Regina Guthold

(2018), in his report, current global estimates show one of four adults and 81% of adolescents don't do enough physical activity, especially the volume of not enough exercise people in high-income country is two times more than low-income country (Regina Guthold. 2018). Furthermore, COVID-19 pandemic in Japan would have further spurred a lack of exercise for Japanese people (Japan Sports Agency. 2021). On the other hand, exercises are recommended worldwide because it brings various benefits such as prevention of type 2 diabetes (Kirwan et al. 2017), depression (Brosse et al. 2002), and coronary heart disease (Cattadori et al. 2018).

Memory is divided into declarative memory and non-declarative memory, and declarative memory also divided into semantic-memory and episodic-memory (Tulving. 1972). Then, word memory classified to semantic memory which is the memory that meaning of things as in general knowledge. But human memory system is not still perfectly elucidated. In this study, we approved multi store model of memory, it is the theory that memory has two storage bank, short-term memory (STM) and long-term memory (LTM) (Atkinson and Shiffrin. 1968). On the first phase, memory is created in hippocampus as STM, but not all memories are retained as STM. The Hippocampus distinguish that those STM is needed to retain for LTM or no. Over the next few days, chosen STM gradually shifts to LTM in the cerebrum through nerve cells.

There are some factors to enhance word memory. In this experiment, we took attention to brain-derived neurotrophic factor (BDNF). Hofer (1990), in his report, BDNF promotes development, growth, maintenance, regeneration of nerve cells and it is most scattered in hippocampus, followed by the cerebrum (Hofer. 1990). Also, previous reports revealed that BDNF has a great relationship with learning and memory function (Linnarsson. 1997, Mu JS. 1999). Recent study says voluntary exercise and neuromuscular electrical stimulation (NMES) enhance the BDNF volume, then BDNF are significantly enhanced in NMES than voluntary exercise (Kimura et al. 2019). In this study, we used NMES because it activates typeIIb fiber predominantly and promote glucose metabolism in the muscle (Clamann et al. 1974). In the case of voluntary exercise, it is difficult to use glucose metabolism because it is needed to exert high-intensity exercise. In addition, it occurs fatigue on the brain and decrease of brain function (Komiyama et al. 2017). On the other hand, NMES can induce glucose metabolism as low-intensity exercises (Malone. 2012). Therefore, NMES enhance BDNF easily than voluntary exercise. Using NMES is more effective and efficient on the way of learning language.

The purpose of the present study is to investigate whether neuromuscular electrical stimulation enhances memory function compared to voluntary exercise. We hypothesized that NMES enhances the word memory consolidation. NMES activate the volume of BDNF more than voluntary exercise. Therefore, increased BDNF positively enhance memory function (Kimura et al. 2019).

Materials and Methods

Participants

Thirteen healthy Japanese young male/female students in Chukyo University volunteered for the present study as participants (20-22ys). The participants gave written informed consent after receiving detailed explanation of this study's purpose, experimental benefit, and risk.

Experimental design

Participants visited laboratory three times and took three types of experiments per day. 10-minutes of word memorizes was done after 10-minutes-rest, voluntary exercise and NMES. Order of three conditions was randomized. We prepared three type of word test (Fig.1, 2, 3), each test has 10 words in Hungarian and Japanese. Hungarian is a suited language to this study because its language has 26 alphabets, accent sigh so that it was character that participants were familiar with, and all participants didn't have knowledge with Hungarian. After 24 hours from test memorizes, we sent the digital answer sheet by email in each experiment (Fig.4, 5, 6). In the answer sheet, the word meaning was list upped only in Japanese and participants answered the spells in Hungarian. The order of 5/10 words was changed. Asked words are same with memorized 10-words the day before. Participants answered memorized words as passible as they can remember and sent back to us. Answered sheets are scored as follows rule. [+1 point if 1 alphabet matches.], [+1 point if the position of accent sign matches.], [0 point if alphabet don't match although the position of accent sign matches and vice versa. This is preventing the score from being attached an accent sign to all alphabets.], [0 point if it is recognized that the answered word was clearly mistaken for other word.].

On present study, right side quadriceps femoris (QF) muscle was observed as the measurement site for voluntary exercise and NMES experiment. The participants were tested for maximum voluntary contractions (MVC) before starting voluntary exercise and NMES in order to determine 20% of MVC as target force. The participants were seated comfortably with the right leg fixed in a custom-made dynamometer (Takei Scientific Instruments CO., Ltd., Niigata Japan) with a force transducer (LU-100KSE; Kyowa electronic Instrument, Tokyo Japan) and both hip and knee joint angles flexed at 90° (180°corresponds to full extension) using previously reported procedure (Watanabe et al., 2016). The participants were asked to gradually increase their knee extension force from the baseline to maximum in 2-3 s and then sustain it maximally for 2 s.

Voluntary exercise

As mentioned above, MVC was measured. After sufficient rest period, participants were continuously seated and performed knee extension force at 20% of MVC on and off alternately for 10 minutes. On and off rate was 3 s/3 s except leg rise and fall down time. Lab chart 8 software observed the force of QF muscle during knee extension.

Neuromuscular electrical stimulation (NMES)

As mentioned above, MVC was measured. After sufficient rest period, participants were continuously seated and we put the NMES pads (20Hz) (Homer ION CO., Ltd., Tokyo Japan) on upper QF muscle and lower QF muscle. Before starting NMES experiment, we adjusted electric current (mA) of NMES at 20% of MVC intensity for each participant because required NEMS intensity differs depend on the muscle mass of participants. After sufficient rest, QF muscle is stimulated on and off alternately with NMES for 10 minutes according to previous research (Kimura T et al. 2019). On and off rate was 3 s/3 s except leg rise and fall down time.

Word memorizes

After voluntary exercise or NMES over, participants immediately seated in a normal chair and began a 10-minutes word memorizes. Memorizing environment was that participants could hear a slight amount of life sounds. Nothing was allowed other than memorizing in the brain. After memorizing section over, Word memorizing sheet was promptly recovered.

Data analysis and statistics

All data are provided as mean and SD. Before the analysis, the normal distribution of the data was confirmed using Shapiro-Wilk test. The parametric analysis was used for normally distributed data and the non-parametric analysis was used for non-normally distributed data. Present study was normally distributed data, but there were few participants (13 participants) therefore, this experimental data was treated as a non-parametric data. Friedman test was performed for three type of test score to investigate the difference between each type of test score. Post-hoc test was used After Friedman's test. The level of statistical significance was set at $p < 0.05$. statistical analyses were performed using SPSS software (version 25; SPSS, Tokyo, Japan).

1	マンション	lakás
2	取る	vesz
3	柔らかい	puha
4	凍った	fagyott
5	鉛筆	ceruza
6	見る	látni
7	食べる	eszik
8	覚える	tanul
9	調べる	kitalál
10	お菓子	édesség

Fig.1 Word test (Rest).

1	紙	papír
2	持つ	van
3	音楽	zene
4	意地悪な	átlagos
5	湿った	nedves
6	行く	megy
7	投げる	dobás
8	蹴る	rúgás
9	掃除する	tiszta
10	筆箱	ecsetdoboz

Fig.2 Word test (Voluntary exercise).

1	落ちる	ledob
2	鉄	vas
3	走る	fuss
4	退屈な	unalmas
5	疲れた	fáradt
6	歩く	séta
7	洗う	mosas
8	遊ぶ	játék
9	木材	faipari
10	クリスマス	karácsony

Fig.3 Word test (NMES).

卒業論文テスト解答用紙　安静時

・覚えているところまで可能な限り思い出して記述してください

・わからないアルファベット箇所は◯または
空白にしておいて、続きのアルファベットを覚えていれば書いてください
→　例: co◯er　または co er

・アクセント記号の付け方が分からなければ、単語の後に " ←この記号を付けて
おいてください
→　例: bebé ＝ bebe"

氏名

柔らかい　_____
お菓子　_____
凍った　_____
取る　_____
鉛筆　_____
見る　_____
マンション　_____
食べる　_____
覚える　_____
調べる　_____

Fig.4 Answer sheet (Rest)

卒業論文テスト解答用紙　随意運動

・覚えているところまで可能な限り思い出して記述してください

・わからないアルファベット箇所は◯または
空白にしておいて、続きのアルファベットを覚えていれば書いてください
→　例: co◯er または co er

・アクセント記号の付け方が分からなければ、単語の後に " ←この記号を付けて
おいてください
→　例: bebé ＝ bebe"

氏名

音楽　____
筆箱　____
意地悪な　____
持つ　____
湿った　____
行く　____
紙　____
投げる　____
蹴る　____
掃除する　____

Fig.5 Answer sheet (Voluntary exercise)

卒業論文テスト解答用紙　NMES

・覚えているところまで可能な限り思い出して記述してください

・わからないアルファベット箇所は◯または
空白にしておいて、続きのアルファベットを覚えていれば書いてください
→　例: co◯er　または co er

・アクセント記号の付け方が分からなければ、単語の後に　"　←この記号を付けて
おいてください
→　例: bebé ＝ bebe"

氏名

走る　_____
クリスマス _____
退屈な　_____
鉄　_____
疲れた　_____
歩く　_____
落ちる　_____
洗う　_____
遊ぶ　_____
木材　_____

Fig.6 Answer sheet (NMES)

Results

Fig. 7 illustrated mean and SD of word test score after Rest, Voluntary exercise, NMES experiment, it was 35.0±13.6, 38.1±12.6, 43.1±9.0 respectably. There was significant difference in Friedman's test ($p<0.05$), and Significant difference was confirmed between Rest and NMES ($p<0.05$) but was not confirmed between Rest and Voluntary and between Voluntary and NMES in Post-hoc test ($p>0.05$). Thus, there was significant difference in word test score between Rest-NMES ($p<0.05$) (Fig.7). But no significant difference was observed in word test score between Rest and Voluntary ($p>0.05$) (Fig.7).

The mean of test scores was increased from Rest toward NMES, and SD areas narrowed. Fig. 8 and Fig. 9 explain the word test score graph of each participant. Table.1 is the detailed figure of word test score, it said that the rate of highest score test in each participant was NMES (69.23%), next one was Voluntary exercise (23.07%), and lowest was Rest (15.38%). Highest rate of test score in 2nd was Voluntary (46.15%), highest rate of test score in 3rd was Rest (61.53%). The percentage total was not 100% because Subject 7 got same score in Rest and Voluntary exercise.

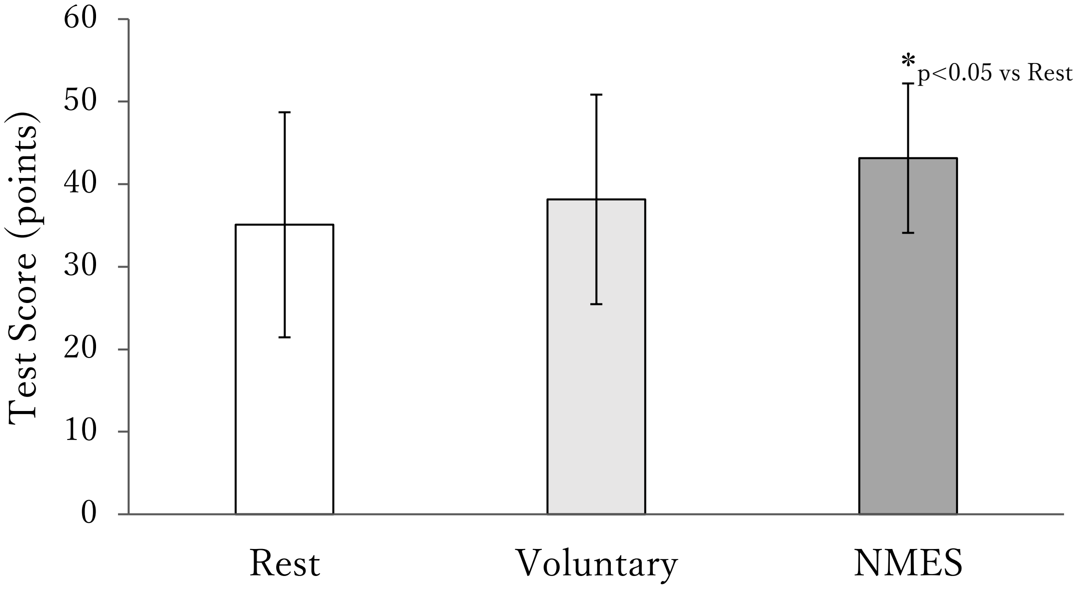

Fig. 7 Mean (±SD) of test score after Rest, Voluntary exercise, and NMES. * $p<0.05$ vs. Rest

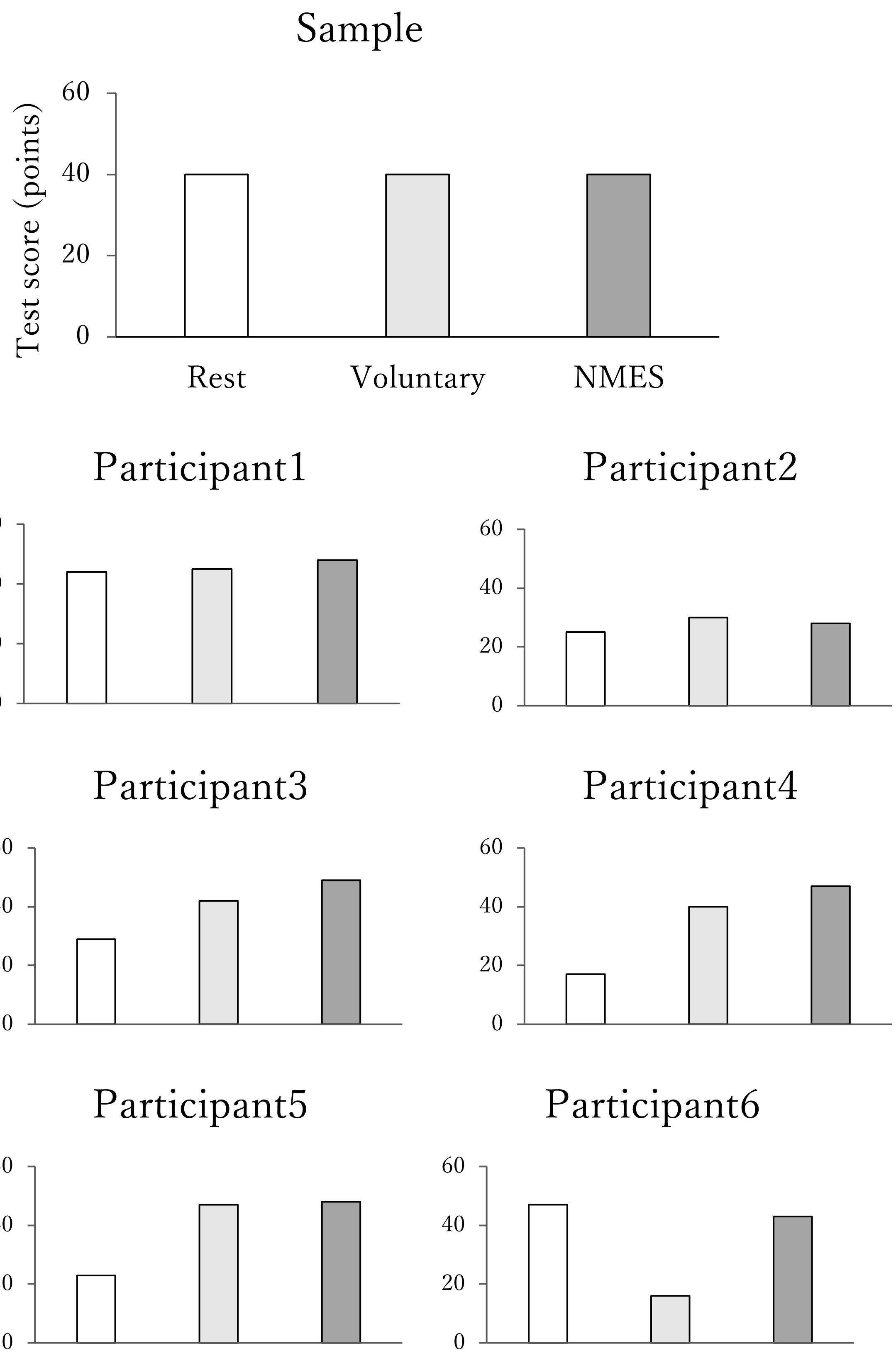

Fig. 8 Word test score graph in participants (participants 1〜6) referred to table 1.

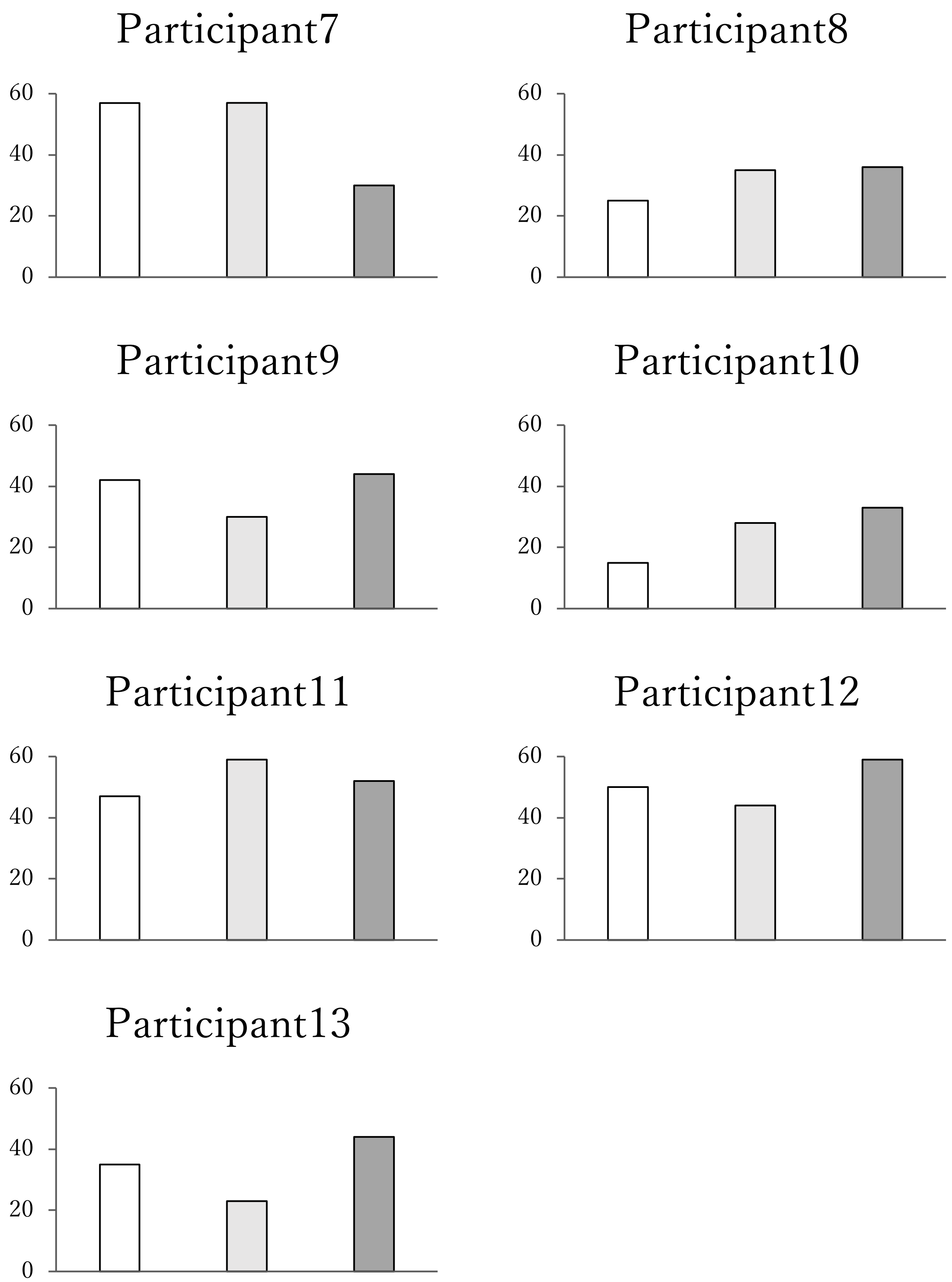

Fig. 9 Word test score graph in participants (participants 7～13) referred to table 1.

Subjects		Rest	Voluntary	NEMS		Rest	Voluntary	NEMS
1		44	45	48		○	◍	●
2		25	30	28		○	●	◍
3		29	42	49		○	◍	●
4		17	40	47		○	◍	●
5		23	47	48		○	◍	●
6		47	16	43		●	○	◍
7		57	57	30		●	●	○
8		25	35	36		○	◍	●
9		42	30	44		◍	○	●
10		15	28	33		○	◍	●
11		47	59	52		○	●	◍
12		50	44	59		◍	○	●
13		35	23	44		◍	○	●
					● 1st	15.38%	23.07%	69.23%
					◍ 2nd	23.07%	46.15%	23.07%
					○ 3rd	61.53%	30.76%	7.69%

Table. 1 Word test score and rank distribution of scores in each participant.

Discussion

In present study, there was significant difference in test score between Rest and NMES, suggesting that NMES could enhance memory function. This improvement of memory test following NMES could be explained by actions of BDNF (Linnarsson et al. 1997, Mu JS. 1999). Since a significant difference in memory function was observed between Rest and NMES, it seems that BDNF activity was increased and could enhance memory function in NMES experiment. NMES condition in the present study was different from previous study (Kimura et al. 2019), in terms of electric current (mA) and duration. Regarding of the intensity of electric current (mA), the present study was restricted adjusting 20% of MVC. Furthermore, NMES accumulates lactate on the muscle by promoting glucose metabolism. Lactate accumulation is an index of glycogen usage. As a result, exerted muscle force was decreased toward the end of experiment. Hence, we adjusted NMES output as much as possible aiming at 20% of MVC during NMES. However, stimulus intensity of previous study was progressively increased to the highest tolerated intensity during the experiment (31.3±7.6mA). It was difficult to compare electric current (mA) as index. But considering electric current (mA) on the present study was around 20～35mA, there was not big difference in electrical current from previous study (Kimura et al. 2019). Furthermore, the frequency of NMES devise and stimulated muscle site was same with the previous study (Kimura et al. 2019). The big difference was in stimulate duration. Present study's NMES duration (300s) was 4-fold times shorter than previous study (Kimura et al. 2019) although, there was significant difference in test score between Rest and NMES. Thus, this result showed the possibility that BDNF had been activated and affect memory function even with short stimulate duration.

But there were no significant differences in test score between Rest and Voluntary and between Voluntary and NMES. This means secretions of BDNF were similar among them. In previous study (Kimura et al. 2019), there was significant difference between Rest and Voluntary and Voluntary and NMES. Voluntary exercise in previous study (Kimura et al. 2019) was performed as same with the conditions of NMES experiment, Participants did knee extension alternately left and right and on-off ratio of 4.5s-4.5s (leg rise time 1.0s, fall time 0.5s) for 20 minutes. Knee extension intensity was calculated based on NMES intensity data. Voluntary exercise intensity in the present study was also same with NMES. As mentioned above there was 4-fold times difference. It seems that the reason why there was no significant difference between Voluntary and NMES, was lactate concentrations. Ferris. 2007, reported that there was significant correlation between the change in blood lactate and the change in serum BDNF (Ferris et al. 2007). Motor unit induces from low-threshold motor units in voluntary exercise, but NMES induces preferential recruitment of high-threshold motor units or random-order recruitment of low- and high-threshold motor units (Bickel. 2011) and glucose metabolism (Hamada. 2003). Therefore, since sufficient Voluntary exercise and NMES to increase BDNF, was not performed in this experiment, there was no significant difference between Voluntary and NMES and between Rest and Voluntary.

On the other hand, neurotransmitter would contribute to memory consolidation. Serotonin, dopamine, and noradrenaline are known for three major neurotransmitters, these are essential for communication between nerves. Noradrenaline is released from Locus coeruleus (LC), and it is a mainly noradrenaline supplier for brain, especially hippocampus and cerebrum, which are related to word memory (Tully and Bolshakov.2010). The frequency of firing in the locus coeruleus is increased with stimuli especially stress and pain (Borodovitsyna. 2018). So that NMES/Voluntary exercise gave stress to participants and noradrenaline would enhance memory consolidation. However, as the stimulus is repeated, the response is decreased as it gets used to the stimulus and nerve system excitement doesn't last long. It was considered that the noradrenaline concentration was increased during NMES/Voluntary exercise experiments, but noradrenaline wouldn't continue to affect until phase of word test. Therefore, neurotransmitters are unlikely to work significantly in 10min NMES/Voluntary experiments.

Regarding to difficulty of word test, Hungarian were adopted in present study because 26 alphabets are common in English and majority of European language, and accent sign is also common in European language. Recently, there are many people who speak or learn English and European languages. Furthermore, Hungarian is an unknown language for this study's participants, and knowledge-independent experimental results are expected. Therefore, Hungarian was selected as test language in this experiment. We picked up words with the almost same number of alphabets (55 alphabets), vowels (21-22 vowels), consonants (33-34 consonants), accents (5 accents), and letter composition to make word test in a well-balanced manner so that there would be not much difference in difficulty in each word test. But test score was greatly difference among participants. This is because simply participants' innate memory function and possibly due to memorizing environment. Basically, the memorizing environment was quiet, but could be some surrounding noise. According to previous study (Smith A. 2010), music could reinforce cognitive function and Jeon and Oh (2019), reported that noise listening study method was positively influencing learning and concentration improvement (Jeon and Oh. 2019). In present study as well, surrounding noise may have had some effect on concentration. Like environment effect, memory contains fragility that is susceptible to all external stimuli. Loftus and Palmer (1974), reported memories can be reconstructed by subsequent events, questions, etc. (Loftus and Palmer. 1974). In the case of present study as well, participants behavior after NMES were not restricted. Thus, it is possible that something emotional affected memorized word.

Calculation of glucose consumption

There was also the possibility that glycogen consumption in the QF muscle by glucose metabolism causes decrease in brain function. However, a rough calculation shows that consumed glucose in the body by NMES was at most about 17.71g, and it was concluded that there was almost no possibility of deterioration of brain function by glucose metabolism (the calculation was described below).

Glucose consumption of brain at rest is [5.4 mg/100 g (brain weight) /minute] in the case of awakening adult man (Kety. 1962). The average of human brain weight is about 1321.61g (age 20.52±2.44). thus, glucose consumption is about 0.76g (1400g brain during 10min) (Parvin et al. 2012). Human glycogen storage amount is 90g～150g in the liver and 100g～400g in the skeletal muscle, and the total glucose storage is 190g～550g (Wasserman. 2009). In present study, 20% of MVC was induced. The amount of energy use is determined based on METs method, but since oxygen uptake doesn't change much during NMES, so that the energy use estimation is made based on the ergometer bicycle (160-200W, 11 METs) that would introduce typeIIb fibers (National Institute of Health and Nutrition. 2012). If a person (70kg) exercise 11 METs for 5 minutes, he consumes 67.375kcal. this, glucose consumption is 16.9 g (1 g=4 kcal). NMES experiment was 5-minutes NMES and 5-minutes rest (total 10 minutes). Hence, glucose metabolism for 10 minutes was 16.9 g +0.76 g =17.66g. Glucose metabolism by NMES doesn't exceed glucose storage in the body (17.71g<190g～550g), and adult man (70 kg) have 5.25g of glucose flowing in their blood. It was concluded that there was almost no possibility of brain dysfunction due to glucose metabolism by NMES. On the other hand, glucose consumption by voluntary exercise was lower than NMES because it works predominantly in lipid metabolism.

In conclusion, we tested the effect of NMES on word memory. This research confirmed that the word test score was significantly improved after NMES compared to Rest, but significant difference was not confirmed between Voluntary and NMES and between Voluntary and Rest. This result suggested that NEMS enhanced brain memory system in language territory, and this result support that NMES enhance memory function compared with voluntary exercise. In the future, word learning during NMES may be possible.

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