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The effect of different schedules of action observation training and motor imagery training on the changes in mental representation structure and skill performance

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Action observation (AO) training and motor imagery (MI) training have long been used independently as effective training methods to facilitate skill acquisition and learning. Recently, neurophysiological and behavioral studies on AO+MI training have shown that combinations of AO+MI training may be more effective than AO or MI training alone. However, the optimal scheduling of AO+MI training remains to be fully explored. Therefore, the purpose of this study was to examine the effect of different AO+MI training schedules of Taekwondo Poomsae on the changes in the structure formation of mental representations in long-term memory and motor variables over the course of learning. Forty participants with no previous experience in Taekwondo were randomly assigned to one of four groups: simultaneous training group (AO+MI, AO+MI, …), alternate training group (AO, MI, AO, MI, …), blocked training group (AO, AO, …, MI, MI, …), and no-training group. Participants practiced the Taekwondo Poomsae thirty trials a day for three days of training. Mental representation structure and skill performance were measured before and after three days of training as well as after a retention interval of one day. The results of this study showed that the three different AO+MI training improved mental representation structure and skill performance. In particular, the effect of alternate AO+MI training was relatively stronger. Taken together, the findings of this study suggest that simultaneous, alternate, and blocked AO+MI can be used as effective training schedules for enhancing the learning of a sequential motor skill, among which alternate AO+MI training schedule may be more effective.

KEY WORDS: Motor learning, Mental representation, Motor memory, Skill acquisition, SDA-M.

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Introduction

Action observation (AO) training and motor imagery (MI) training are cognitive training methods that have been widely used independently as effective ways to promote motor learning, performance, and rehabilitation (Buccino, 2014; Decety, 1996; Ste-Marie et al., 2012). AO is a dynamic state during which a learner can understand the actions by observing actions performed by another person (Sale, Ceravolo, & Franceschini, 2014). MI is defined as a dynamic state during which a learner can rehearse motor actions mentally without overt physical execution (Jeannerod, 1995; Jeannerod & Decety, 1995). In this regard, AO and MI are motor simulations that are performed in the absence of movement execution (Jeannerod, 2001).

Despite their similarity in that both are motor simulations, there is a difference in the cognitive process between AO and MI (Cuenca-Martínez, Suso-Martí, León-Hernández, & Touche, 2020; Ram, Riggs, Skaling, Landers, & McCullagh, 2007; Vogt, Rienzo, Collet, Collins, & Guillot, 2013). AO goes through an external stimulus-driven process, which is guided externally in working memory by observation of actions in an environment such as a live demonstration, recorded video, or virtual reality (Wright, McCormick, Birks, Loporto, & Holmes, 2014). In contrast, MI undergoes an internal stimulus-driven process that generates action representations based on the information stored in long-term memory (Holmes & Calmels, 2008; Murphy, 1994).

Given the difference in cognitive processing between the two motor simulations, AO may help novice learners form an action representation by externally providing visual image information related to a skill to be learned, while MI of the observed actions is more likely to result in the formation of more robust action representations by helping them actively engage in the simulation process (i.e., active AO as opposed to passive AO). In this regard, a combination of AO and MI is more likely to be effective than AO or MI alone at the initial learning stage (Romano Smith, Wood, Coyles, Roberts, & Wakefield, 2019).

In recent years there has been a growing interest in the effectiveness of such AO+MI training schedules. Among the various AO+MI schedules, simultaneous AO+MI seems to be an effective schedule, but it remains unclear whether it is more or less effective. To explain, simultaneous AO+MI undergoes a dual simulation process (Eaves, Riach, Holmes, & Wright, 2016). It processes the external visual stimuli obtained through AO and mentally imagines the observed actions simultaneously. However, the smaller the similarity between the external stimulus of AO and the internal stimulus of MI, the less effect of simultaneous AO+MI may be due to increased cognitive load (Eaves, Haythornthwaite, & Vogt, 2014). Specifically, if the information obtained through AO conflicts with the image to be imagined, exceeds the capacity of working memory, or requires complex mental rotation, the efficiency of simultaneous AO+MI may be influenced by the increased cognitive processing load during synchronized imagery. The fact that the capacity of work memory is limited (Baddeley, 1992; Furley & Memmert, 2010) and that such capacity limitation can affect motor learning (Buszard et al., 2017) supports this claim. Therefore, more research is needed that looks at how to best schedule AO+MI training.

Alternate forms of AO+MI training, in which MI is performed after AO, may help reduce the limitation of simultaneous AO+MI, especially in sequential motor skill learning. Specifically, learners first obtain the action information necessary for forming the visual representation through AO. Subsequently, learners undergo the preparatory process such as transforming the perspective, rotating the orientation of the image, or recalling action sequence, etc., to adapt to the preferred MI based on the information obtained through the AO. Then, during MI, learners are more likely to be able to develop the formation of mental representations more efficiently by concentrating their attention within the capacity of working memory (Buszard et al., 2017; Engle, 2010; Williams & Ericsson, 2005).

Regarding the role of mental representations in long-term memory, perceptual-cognitive perspective proposed that the planning and execution of motor actions are guided by mental representations in long-term memory that are formed based on perceptual information of movements (Hommel, Müsseler, Aschersleben, & Prinzb, 2001; Jeannerod, 2001; Schack, 2004). Previous studies have shown that mental representations in long-term memory can be developed through cognitive training such as AO training or MI training (Frank, Kim, & Schack, 2018; Frank, Land, Popp, & Schack, 2014; Kim, Frank, & Schack, 2017). Considering this point, mental representation in long-term memory can be regarded as an important factor to examine the degree of motor learning. However, no studies have been conducted to examine the effects of different training schedules of AO+MI on mental representations in long-term memory and skill performance.

In this study, we extended the study of Kim et al. (2017), which compared the effects of AO training and MI training on the development of mental representation structure and skill performance, and the study of Kim, Frank, & Schack (2020), which examined the effect of alternate AO+MI training on cognitive and skill performance suggesting that alternate AO+MI training may be more effective compared to independent AO or MI training. The present study focused on the effects of different training schedules of AO+MI on mental representations and performance of sequential skill, aiming at providing an optimal training schedule for facilitating sequential skill learning. We hypothesized that alternate and blocked AO+MI training would be more effective in performing sequential skills and in developing mental representation structures than simultaneous AO+MI training on the basis of the possibility of more efficient cognitive processing. In addition, we predicted that the correlation between changes in long-term memory and changes in skill performance would be significant in all AO+MI training if the development of mental representations adequately reflects the process of motor learning.

Methods

Participants

Forty volunteers (19 males, 21 females; M_{age} = 25.55, *SD* = 5.06) participated in the experiment. All participants self-reported that they had normal or corrected to normal vision. They were all beginners who had never experienced Taekwondo training before. They were assigned to one of four groups in a random manner with ten participants in each group: simultaneous AO+MI training group (*n* = 10, M_{age} = 25.90, *SD* = 5.69), alternate AO+MI training group (*n* = 10, M_{age} = 27.40, *SD* = 6.60), blocked AO+MI training group (*n* = 10, M_{age} = 23.20, *SD* = 4.08), and non-training group (*n* = 10, M_{age} = 25.70, *SD* = 2.91). The study was in compliance with the ethical guidelines of the Helsinki Declaration and was conformed to the guidelines of the ethics committee of Bielefeld University. All participants signed informed consent for participating in the study and received 30 euros in cash at the end of the experiment. From the present results, the sample size of ten participants per group had an actual power of more than 95%, which was adequate to detect differences between groups or between measurement times at a significant level of 5% (i.e., Critical F value = 2.508).

Measurement

Imagery Ability. The individual imagery ability of the participants was evaluated to exclude participants with extremely low imagery ability that might affect the effectiveness of cognitive training. The revised version of the Movement Imagery Questionnaire (MIQ-R; Hall & Martin, 1997) was completed to evaluate the participants' motor imagery ability to form visual and kinesthetic mental images. The MIQ-R was a self-report questionnaire consisting of eight items, four items for visual imagery ability, and four items for kinesthetic imagery ability. Every item was rated on a seven-point Likert scale ranging from 1 ("very hard to see or feel") to 7 ("very easy to see or feel"). The MIQ-R has been reported to have adequate reliability and validity for both subscales (Monsma, Short, Hall, Gregg, & Sullivan, 2009).

Mental Representation Structure. The structural dimensional analysis of the mental representation (SDA-M) method was used to measure the mental representational structure of Taegeuk il-Jang in Taekwondo Poomsae. The SDA-M method provides psychometric information about the mental representation structure of the planned actions in long-term memory (see Schack, 2012 for more detail on the SDA-M method). This method has been used to identify the mental representation structure of complex actions in the sports arena, such as golf, judo, tennis, and dance and has proven its reliability and validity (Bläsing, Tenenbaum, & Schack, 2009; Kim et al., 2017; Schack & Mechsner, 2006; Weigelt, Ahlmeyer, Lex, & Schack, 2011). Specifically, the method provides information about the functional relationship between the basic action concepts (BACs) that consist of a particular motor action. Each BAC is a basic unit of mental representation that is functionally connected to the movement of action. In this study, 17 procedural basic actions constituting Taekwondo Taegeuk il-Jang were regarded as BACs (see Table I), and the mental representational structure was measured. A splitting task was performed to collect data for the analysis of mental representation structures. Each of the 17 basic actions as an anchor was compared with each of the 16 basic

TABLE I
Basic Actions of the Taekwondo Taegeuk il-Jang

Sequence number	Basic actions (BAs)
1	Start in the ready or "Joon Bi" stance
2	Turn left 90 degrees into a walking stance with left foot forward, left low block
3	Step forward into a walking stance with right foot forward, right middle punch
4	Turn right 180 degrees into a walking stance with right foot forward, right low block
5	Step forward into a walking stance with left foot forward, left middle punch
6	Turn left 90 degrees into a front stance with left foot forward, left low block, right middle punch
7	Turn right 90 degrees into a walking stance with right foot forward, left inside block
8	Step forward into a walking stance with left foot forward, right middle punch
9	Turn left 180 degrees into a walking stance with left foot forward, right inside block
10	Step forward into a walking stance with right foot forward, left middle punch
11	Turn right 90 degrees into a front stance with right foot forward, right low block, left middle punch
12	Turn left 90 degrees into a walking stance with left foot forward, left high block
13	Right front kick, foot placed down into a walking stance with right foot forward, right middle punch
14	Turn right 180 degrees into a walking stance with right foot forward, right high block
15	Left front kick, foot placed down into a walking stance with left foot forward, left middle punch
16	Turn right 90 degrees into a front stance with left foot forward, left low block
17	Step forward into a front stance with right foot forward, right middle punch with Kihap

Note: Each basic action was considered as a basic action concept in the SDA-M method.

actions remaining, respectively. Participants were asked to judge whether the two presented basic actions are close in terms of execution time (i.e., yes or no). In the same way, participants made a total of 272 (i.e., 17 anchors × 16 basic actions remaining) judgments. Subsequently, the algebraic sum of the number of the responses of yes or no for each anchor was calculated. It was converted to Z values for standardization of the data. Then, the transformed Z values of each participant were merged into a Z-matrix to form the base point for subsequent analysis. The Z-matrices were transformed into a Euclidean distance for hierarchical clustering analysis using the average-linkage method. Through this procedure, the 17 basic actions were displayed in the form of cluster solutions in the dendrogram. It was determined whether the formed clusters were statistically significant at the 5% significance level on the y-axis of the dendrogram based on a critical Euclidean distance (d_{crit}). Specifically, the clusters under the horizontal line indicating the critical Euclidean distance in the dendrogram were interpreted as statistically significant.

Skill Performance. Participants were asked to perform Taekwondo Taegeuk il-Jang twice in the pre-, post-, and retention test, respectively. They were required to perform the actions as accurately as possible in order and were instructed to stop performing when the sequence of Poomsae actions was no longer remembered. Their performances were video-recorded and two Taekwondo experts with a fifth-degree black belt evaluated the accuracy of movements and action sequences based on the recorded video clips. The evaluators were unaware of the purpose of the experiment and the video clips were provided in an anonymous random order regardless of measurement time. For the accuracy score of movements, it was distributed between 1 point ("very poor") and 5 points ("very good"). For the accuracy score of action sequences, it was ranged from 1 (i.e., remembering only one action) point to 17 points (i.e., remembering all the action sequences correctly) in consideration of the 17 basic actions consisting of Taekwondo Taegeuk il-Jang.

Post-Training Questionnaire. During the three-day training period, participants in the training groups (i.e., simultaneous, alternate, and blocked AO+MI training) were required to answer the questionnaire in the form of self-reports shortly after each daily training session to determine how motivated participants were each day and how easy it was to perform given tasks as directed. The items of the post-training questionnaire consisted of a seven-point Likert scale ranging from one point ("very demotivated or very difficult") to seven points ("very motivated or very easy").

Procedure

This study was conducted in the order of a pre-test, a 3-day experiment, a post-test, and a retention test (see Table II).

Pre-Test. During the experiment period, all participants visited the laboratory and participated in the experiment individually. Before the experiment, participants were instructed to complete the MIQ-R (Hall & Martin, 1997) to assess whether they had adequate visual and kinesthetic imagery abilities and to exclude the data of participants with low imagery ability scores from the analysis. In the pre-test, the SDA-M and skill tests were performed to determine the initial level of mental representation structure and skill performance of all participants.

TABLE II
Experimental Procedure by Group and Measurement Time

	Pre-test	**Training**	**Post-test**	**Retention test**
Group	Day 1	Day 2 Day 3 Day 4	Day 4	Day 5
Simultaneous AO+MI (n = 10)	MIQ SDA-M Skill test	Simultaneous AO+MI training 15 times per day (15 AO and 15 MI trials)	SDA-M Skill test	SDA-M Skill test
Alternate AO+MI (n = 10)	MIQ SDA-M Skill test	Alternate AO+MI training 30 times per day (15 AO and 15 MI trials)	SDA-M Skill test	SDA-M Skill test
Blocked AO+MI (n = 10)	MIQ SDA-M Skill test	Blocked AO+MI training 30 times per day (15 AO and 15 MI trials)	SDA-M Skill test	SDA-M Skill test
Control (n = 10)	MIQ SDA-M Skill test	No training	SDA-M Skill test	SDA-M Skill test

Note: SDA-M (Structural Dimensional Analysis of Mental representation): the psychometric method for measuring mental representations in long-term memory. MIQ (Movement Imagery Questionnaire): the imagery questionnaire to assess visual, kinesthetic, and overall imagery abilities.

Experimental Treatment. From the day following the pre-test, participants assigned to one of three training groups in a random order (i.e., simultaneous AO+MI, alternate AO+MI, and blocked AO+MI), performed thirty trials a day for three days. In contrast, participants in the control group visited the laboratory but did not receive any training. All participants were provided only information on their tasks, and no information was allowed to be shared during the experiment. To begin training, participants assigned to simultaneous, alternate, and blocked AO+MI training groups sat on a chair that was 2 meters ahead of the screen projected by an LCD projector and listened to their task from the experimenter.

Simultaneous AO+MI training group. Participants assigned to the simultaneous AO+MI training group were asked to imagine the observed actions as vivid and realistic as possible whilst observing the video of Taekwondo Taegeuk il-Jang. The video consisted of scenes where skillful male and female models of similar age to participants performed Taekwondo Taegeuk il-Jang together. The video was projected life-size onto the wall. In the video, the actions of the models were presented in front and back views from the third-person perspective at normal speed. Additionally, participants could use their preferred imagery perspective (i.e., internal or external perspective) for imagery. Participants in the simultaneous group were trained fifteen times a day for three days to be comparable with the other experimental groups, which were exposed to 15 AO trials and 15 MI trials. After each day of training, they were asked to answer the post-training questionnaire about the motivation level of the day and the ease of the task.

Alternate AO+MI training group. Participants in the alternate AO+MI training group were asked to attentively observe the same video used in other training groups and then imagine the observed actions as vivid and realistic as possible with their preferred imagery perspective. In this way (i.e., AO, MI, AO, MI, …), fifteen times of observation and fifteen times of imagery were performed per day for 3 days. After the daily training, participants completed the post-training questionnaire.

Blocked AO+MI training group. Participants in the blocked AO+MI training group were asked to observe the same video attentively fifteen times in a row, and then imagine the observed actions fifteen times consecutively as vivid and realistic as possible with their preferred imagery perspective (i.e., AO, AO, …, MI, MI, …). Thus, the number of training trials per day for 3 consecutive days was the same for the other training groups. After the daily training, participants completed the post-training questionnaire.

Non-training group. Participants in the non-training group performed thirty minutes of daily reading tasks unrelated to Taekwondo in the lab for three days.

Post-Test and Retention Test. The post-test was conducted immediately after 3 days of the experiment, and the retention test was carried out the next day. The items (i.e., SDA-M test and skill performance test) measured were the same as those in the pre-test.

Data Analysis

Imagery Ability. One-way analysis of variance (ANOVA) was performed to examine differences in visual, kinesthetic, and overall imagery abilities among the four groups. For post-hoc pairwise comparisons between groups, Bonferroni's corrected multiple comparison test was performed at a significant level of 5%.

Mental Representation Structure. Cluster analysis was first performed using data collected through the split task of the SDA-M method (Schack, 2012). The cluster analysis provided information on how the 17 basic actions constituting Taekwondo Taegeuk il-Jang were clustered together. To determine the statistically significant clusters, the significance level was set at 5%, which corresponded to the horizontal line of the dendrogram and the critical value of the horizon was the Euclidean distance value of 3.51 (i.e., $d_{crit} = 3.51$). In this study, the Euclidean distance represented the cognitive distance between basic actions, and the smaller the Euclidean distance, the closer the distance between basic actions was. More specifically, it was indicated that the order of the basic actions was more accurate as the average Euclidean distance of the Taegeuk il-Jang was closer to zero. In addition, two-way ANONVAs (four groups × three measurement times) were performed using the Euclidean distance data collected from the splitting task. As a post-hoc test for a significant interaction, a one-way ANOVA was conducted with a Bonferroni correction for multiple comparisons. The significance level was set at 5%.

Skill Performance. To analyze the accuracy of movements and action sequences, a two-way ANOVA (four groups × three measurement times) with repeated measures of the second variable was performed. As a post-hoc test for a significant interaction, a one-way ANOVA was conducted to examine differences between measurement times by group and vice versa. The level of significance was set at 5%. In addition, Kappa analysis was conducted to identify the interrater reliability among measurement times based on the scores of the two raters.

Post-Training Questionnaire. Two-way ANOVA (three training groups × three training days) with the repeated measures of the second variable was performed to examine how motivated participants were and how easy they performed the given training during the three-day training period. The significance level for data analysis was set at 5%.

Correlation. Two-tailed Pearson's correlation analysis was performed to examine the correlations between mental representation and skill performance (i.e., the accuracy of movements and action sequences) for the whole measurement period according to the group. Euclidean distance value and skill performance score were used for correlation analysis. The significance level of the data analysis was set at 5%.

Results

Imagery Ability

Analysis of visual imagery ability, ($F_{(3,36)} = 1.043$, $p = 0.385$, $\eta_p^2 = 0.080$), kinesthetic imagery ability, ($F_{(3,36)} = 0.493$, $p = 0.690$, $\eta_p^2 = 0.039$), and overall imagery ability, ($F_{(3,36)} = 0.719$, $p = 0.547$, $\eta_p^2 = 0.057$), showed that the main effects of the group were not significant. The mean scores of the imagery abilities were 6.28, 6.22, and 6.25, respectively. These results indicate that the four groups had adequate visual imagery ability, kinesthetic imagery ability, and overall imagery ability with an average of more than six points ("easy to see or feel") for participating in the cognitive training (Frank et al., 2014; Kim et al., 2017; Smith & Collins, 2004; Smith, Wright, & Cantwell, 2008) All participants took part in the experiment without dropping due to the lack of the imagery ability of four points ("not easy or not hard") or less on average.

Mental Representation Structure

Cluster analysis for the simultaneous AO+MI training group showed that significant clusters increased over time (see Figure 1). Specifically, no clusters in the pre-test, (BAC 1, 2), (BAC 15, 17) in the post-test, and (BAC 1, 2), (BAC 14, 15), (BAC 16, 17) in the retention test, respectively. Cluster analysis for the alternate AO+MI (A-AO+MI) training group showed that significant clusters increased over time (see Figure 2). Precisely, no clusters in the pre-test, (BAC 2, 4), (BAC 6, 7), (BAC 8, 9), (BAC 15, 17) in the post-test, and (BAC 1, 2, 4), (BAC 6, 7, 8, 9), (BAC 14, 15), (BAC 16, 17) in the retention test, separately. Cluster analysis for the blocked AO+MI (I-AO+MI) training group also showed that significant clusters increased over time (see Figure 3). Specifically, (BAC 6, 10) in the pre-test, (BAC 1, 2), (BAC 14, 15), (BAC 16, 17) in the post-test, and (BAC 1, 2, 3), (BAC 14, 15, 16, 17) in the

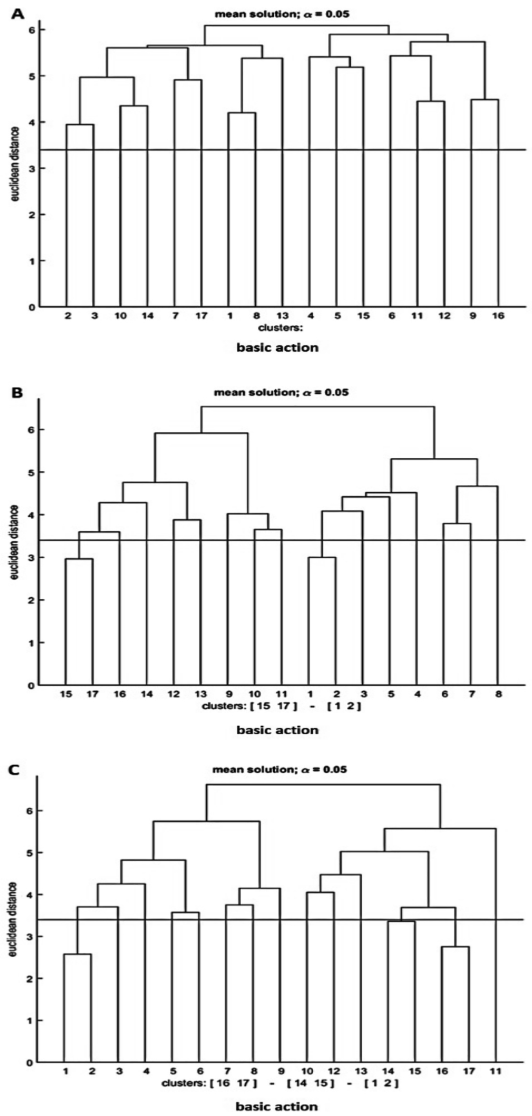

Fig. 1. - Mean dendrograms indicating mental representation structure of simultaneous AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test. The horizontal line indicates the critical Euclidean distance. The critical value of the Euclidean distance (d_{crit}) was 3.40 for an α level of 5%. Clusters below this line indicate statistically significant, while clusters above this line indicate statistically insignificant.

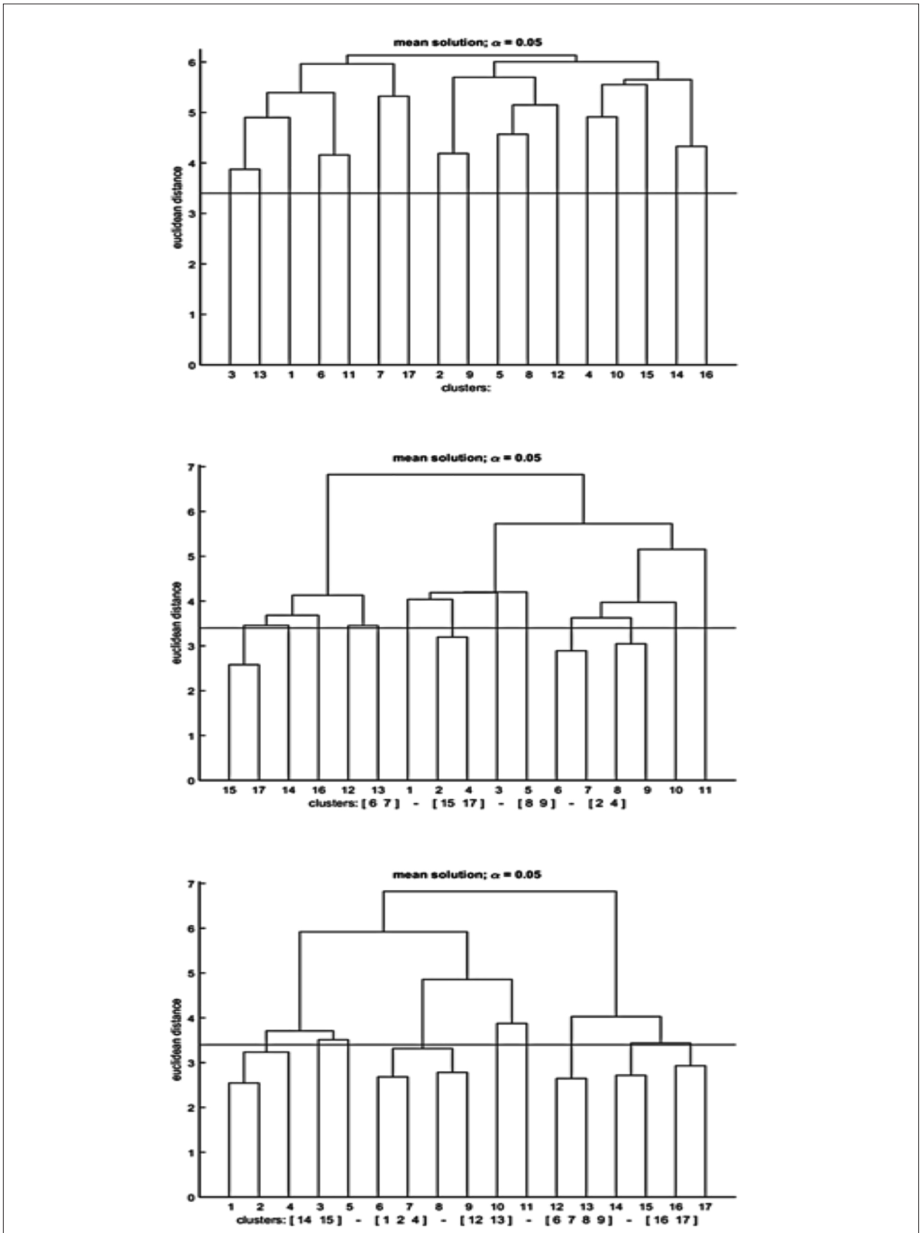

Fig. 2. - Mean dendrograms indicating mental representation structure of alternate AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test ($\alpha = 0.05$; $d_{crit} = 3.40$).

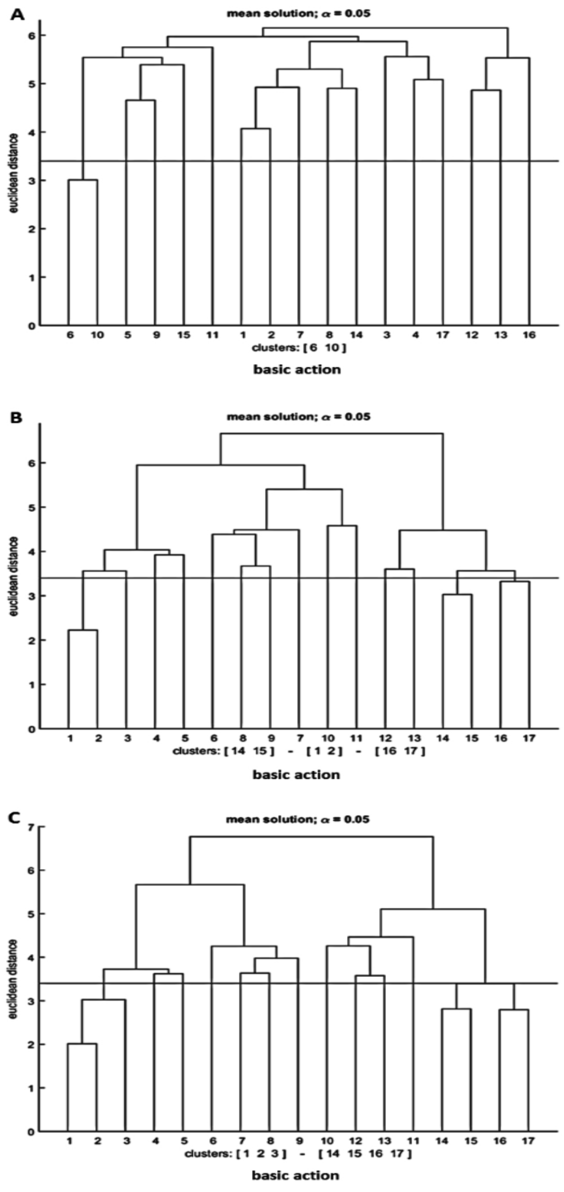

Fig. 3. - Mean dendrograms indicating mental representation structure of blocked AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test ($\alpha = 0.05$; $d_{crit} = 3.40$).

retention test, correspondingly. In contrast, cluster analysis for the control group did not show any significant clusters in the pre-, post-, and retention tests (see Figure 4). In addition, analysis of Euclidean distance by group (i.e., simultaneous, alternate, blocked AO+MI, and control group) and measurement time (i.e., pre-, post-, and retention test) showed that the main effect of the group, ($F_{(3,36)} = 426.915$, $p = 0.000$, $\eta^2_p = 0.973$), and the main effect of the measurement time, ($F_{(2,72)} = 957.937$, $p = 0.000$, $\eta^2_p = 0.964$), were significant. The post-hoc test on the main effect of group showed the Euclidean distances of the training groups were significantly shorter than those of the control group, ($p = 0.000$), and the simultaneous and alternate AO+MI training groups were significantly shorter in the Euclidean distance than blocked AO+MI training group, ($p = 0.000$). In addition, the post-hoc test on the main effect of measurement time showed that the Euclidean distance was significantly shorter in the post-test than in the pre-test, ($p = 0.000$), and in the retention test than in the post-test, ($p = 0.000$). However, the interaction between group and measurement time was also significant, ($F_{(6,72)} = 125.638$, $p = 0.000$, $\eta^2_p = 0.913$, see Figure 5), indicating that the differences in the Euclidean distance between the groups may vary depending on the measurement times, or vice versa. Results of the post-hoc test on the differences between the groups by measurement time showed that there was no difference between the groups in the pre-test, ($p = 0.292$), whereas in the post- and retention tests, the Euclidean distances of the training groups were significantly shorter than that of the control group, ($p = 0.00$). Particularly, in the post-test, the Euclidean distances of the simultaneous and alternate AO+MI were shorter than that of the blocked AO+MI, ($p = 0.000$), and there was no difference between the simultaneous AO+MI and the alternate AO+MI, ($p = 1.000$). However, the Euclidean distance was significantly shorter in the order of alternate, simultaneous, and blocked AO+MI in the retention test ($p = 0.000$). In addition, results of the post-hoc test on the differences between the measurement times by group showed that the Euclidean distances of the training groups were continuously shortened over time, ($p = 0.000$), while the control group did not show any difference between the measurement times, ($p = 0.447$).

Skill Performance

For the accuracy of movements, the two-way analysis of variance showed a significant interaction, $F_{(6,72)} = 3.061$, $p = 0.010$, $\eta^2_p = 0.203$), indicating that the differences between the groups may have varied depending on the mea-

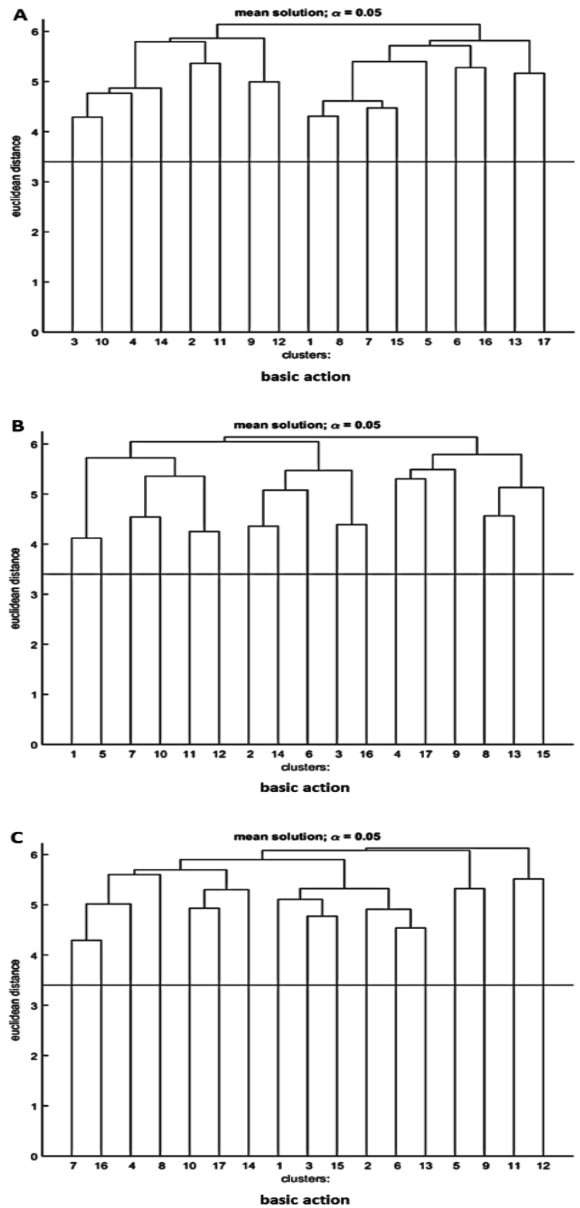

Fig. 4. - *Figure 4.* Mean dendrograms indicating mental representation structure of control group at (A) pre-test, (B) post-test, and (C) retention test ($\alpha = 0.05$; $d_{crit} = 3.40$).

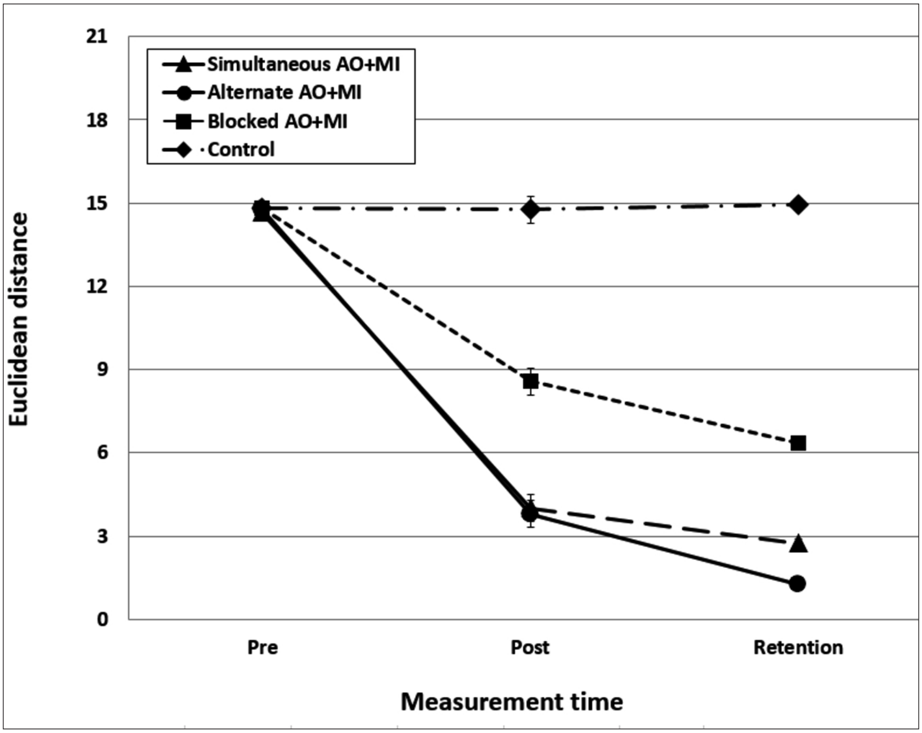

Fig. 5. - Changes in Euclidean distance across group and measurement time. Error bars indicate standard errors.

surement times, or vice versa (see Figure 6). First, the result of the post-hoc test on the differences between the groups by measurement time showed that there were no differences between the groups in the pre- (p = 0.981) and post-test (p = 0.035). However, the accuracy of alternate AO+MI group was significantly higher than that of the control group in the retention test (p = 0.018). Second, the result of the post-hoc test on the differences between the measurement times by group showed that the accuracy of simultaneous AO+MI group was higher in the retention test than in the pre-test (p = 0.032), that the accuracy of alternate AO+MI group was higher in the post-test (p = 0.002) and retention test (p = 0.000) than in the pre-test, and that the accuracy of blocked AO+MI group was higher in the post-test than in the pre-test (p = 0.045). However, the control group did not show any difference in accuracy between the measurement times (p = 0.092).

For the accuracy of action sequences, the two-way analysis of variance also showed a significant interaction, $F_{(6,72)} = 17.305$, $p = 0.000$, $\eta^2_p = 0.591$), meaning that the differences between the groups can be changed according to the measurement time, or vice versa (see Figure 7). First, the result of the post-hoc test on the differences between the groups by measurement time showed that there were no differences between the groups in the pre-test ($p = 0.983$). However, the accuracy of the three AO+MI training groups was significantly higher than that of the control group in the post- ($p = 0.000$) and retention test ($p = 0.000$). In particular, the accuracy of alternate AO+MI group ($p = 0.000$) and blocked AO+MI group ($p = 0.019$) was higher than that of simultaneous AO+MI group in the post-test, and alternate AO+MI was more accurate than simultaneous AO+MI in the retention test ($p = 0.000$). There was no difference between alternate and blocked AO+MI groups according to the measurement time. Second, the result of the post-hoc test on

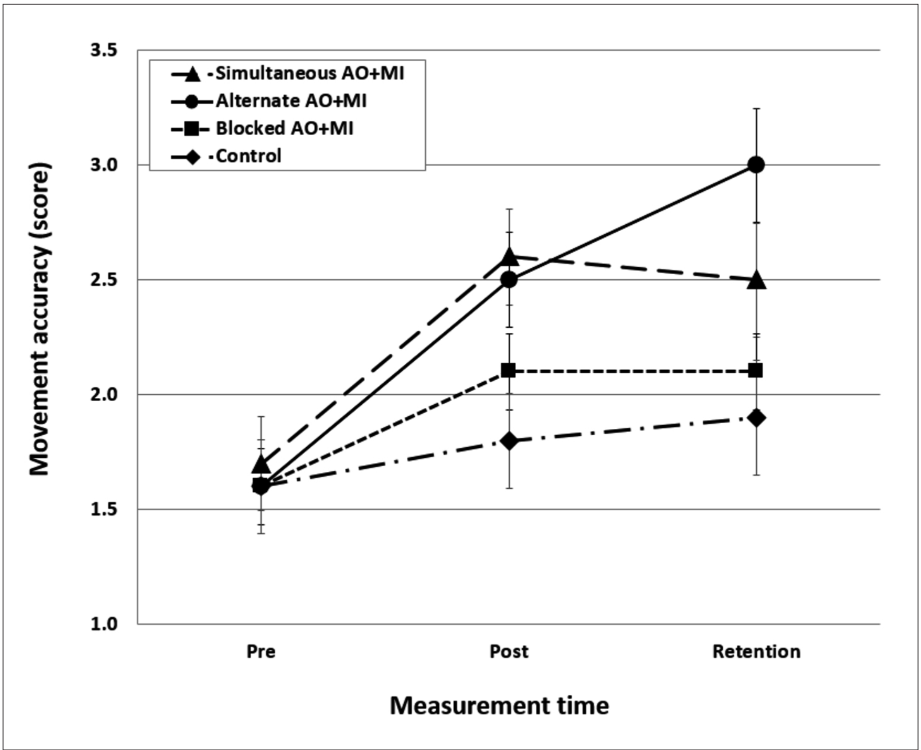

Fig. 6. - The movement accuracy of skill performance across group and measurement time. Error bars indicate standard errors.

the differences between the measurement times by group showed that the accuracy of the three training groups (i.e., simultaneous, alternate, and blocked AO+MI) was significantly improved in the post-test compared to the pre-test ($p = 0.008$, $p = 0.000$, $p = 0.000$). Such improvement was maintained in the retention test. In contrast, the control group did not show any difference in accuracy between the measurement times ($p = 0.847$).

In addition, as a result of performing Kappa analysis to identify the reliability between the two raters, for the accuracy of movements, it showed a moderate agreement among measurement times (i.e., Kappa value 0.563, 0.581, and 0.503 between rater1_{block1}, and rater2_{block1}, rater1_{block2}, and rater-2_{block2}, and rater1_{block3}, and rater2_{block3}, respectively). The accuracy of action sequences also showed a moderate agreement among measurement times (i.e., Kappa value 0.534, 0.518, and 0.516 between rater1_{block1}, and rater2_{block1}, rater1_{block2}, and rater2_{block2}, and rater1_{block3}, and rater2_{block3}, respectively).

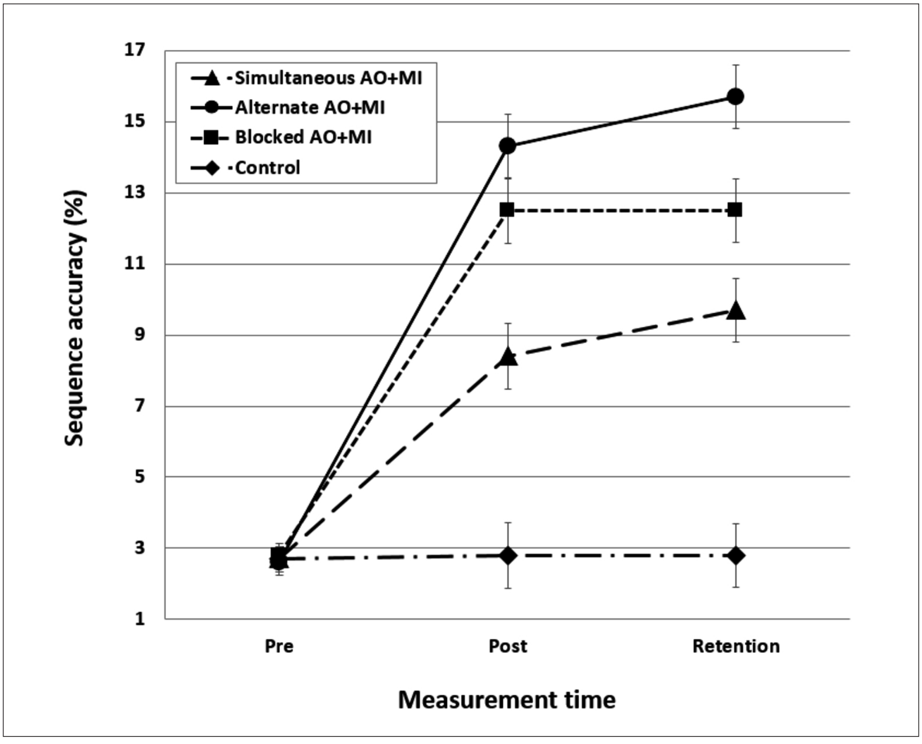

Fig. 7. - The sequence accuracy of skill performance across group and measurement time. Error bars indicate standard errors.

Post-Training Questionnaire

The analysis of the motivation level of the training groups showed that the main effect of group, ($F_{(2,27)} = 1.300$, $p = 0.289$, $\eta^2_p = 0.088$), the main effect of training day, ($F_{(2,54)} = 2.341$, $p = 0.106$, $\eta^2_p = 0.080$), and the interaction of the two variables, ($F_{(4,54)} = 0.473$, $p = 0.756$, $\eta^2_p = 0.034$), were not significant. The mean motivation scores of the training groups were 5.93 ("motivated"), 6.07 ("motivated"), and 6.43 ("motivated") for the simultaneous, alternate, and blocked AO+MI training group, respectively. In addition, the analysis of the ease of training of the training groups showed that the main effect of training day, ($F_{(2,54)} = 13.141$, $p = 0.000$, $\eta^2_p = 0.327$), was significant. However, it was revealed that the main effect of group, ($F_{(2,27)} = 0.623$, $p = 0.544$, $\eta^2_p = 0.044$), and the interaction of the two variables, ($F_{(4,54)} = 1.745$, $p = 0.154$, $\eta^2_p = 0.114$), were not significant. The results of the post-hoc test on the main effect of training day showed that the third training day was significantly easier than the first ($p = 0.000$) and second training day ($p = 0.032$). The mean ease scores of the training groups were 5.13 ("rather easy"), 4.83 ("rather easy"), and 5.23 ("rather easy") for the simultaneous, alternate, and blocked AO+MI training group, correspondingly.

Correlation

For simultaneous AO+MI group, Pearson correlations between Euclidean distance and movement accuracy ($r = -0.429$, $n = 30$, $p = 0.018$) and between Euclidean distance and sequence accuracy ($r = -0.683$, $n = 30$, $p = 0.000$) were significant. Similarly, for alternate AO+MI group, Pearson correlations between Euclidean distance and movement accuracy ($r = -0.591$, $n = 30$, $p = 0.001$), between Euclidean distance and sequence accuracy ($r = -0.920$, $n = 30$, $p = 0.000$) were significant. For blocked AO+MI group, Pearson correlation between Euclidean distance and sequence accuracy ($r = -0.815$, $n = 30$, $p = 0.000$) was significant. However, the control group did not show any correlation among the variables.

Discussion

The purpose of this study was to examine an optimal AO+MI training schedule for facilitating sequential skill performance by comparing the effects of different AO+MI training schedules on mental representations in long-term memory and sequential skill performance. It was hypothesized that alternate and blocked AO+MI training would be more effective in developing mental representation structure and the performance of sequential skills than simultaneous AO+MI training. In addition, it was expected that the correlation between mental representation structure in long-term memory and skill performance would be significant in all AO+MI training. Our results partly support our hypothesis.

First, with respect to cluster analysis of mental representational structure, the results of this study showed that clusters of three training groups (i.e., simultaneous, alternate, and blocked AO+MI) increased significantly over time, with the exception of the control group. These results indicate that the structure of mental representation has become more organized through the three training schedules. The results of the Euclidean distance, meaning the cognitive interval between the basic action concepts (Schack, 2012), decreased significantly in the three training groups over time, which supports the above interpretation. In addition, the Euclidean distance of the alternate AO+MI group was significantly shorter than the other three groups in the retention test. Therefore, the results of mental representation analysis suggest that the three AO+MI training schedules are effective in the formation of mental representation, and especially alternate AO+MI training may be relatively more effective.

Alternate AO+MI performing MI immediately after AO may be more likely to contribute to forming a more clear and realistic representation internally by providing formation externally in advance. AO goes through a percept-driven cognitive process that depends on the information provided externally for the formation of mental representations (Holmes & Calmels, 2008). On the other hand, MI undergoes a knowledge-driven cognitive process that depends on the information in long-term memory for the formation of mental representations (Holmes et al., 2010). Given such a difference in the cognitive process, alternate AO+MI may have contributed to more effectively to the cognitive processing of novice learners who have to process excessive information related to the accuracy of movements as well as the sequence of skills.

Concerning the outcome of the skill performance (i.e., the accuracy of movements and action sequence), the accuracy of movements significantly improved in all training groups (i.e., simultaneous, alternate, and blocked AO+MI) over time. In particular, alternate AO+MI training was found to be the most improved. Besides, the accuracy of the action sequence was also significantly improved over time by the three training schedules. Especially, the accuracy of alternate and blocked AO+MI training was found to be higher in performing action sequences than simultaneous AO+MI training.

These results suggest that the combined training of AO and MI is effective in accurately performing sequences of actions and carrying out actions in the learning process of sequential motor skill, and more importantly that alternate AO+MI training schedule seems to be most effective in improving the two learning factors.

This result is different from the recent finding of Romano-Smith et al. (2018), which examined the effect of simultaneous and alternate AO+MI training on the performance of dart throwing. They reported that both simultaneous and alternate AO+MI training schedules were effective in performance and learning of the aiming skill, but there was no difference in effectiveness between the two training schedules. One reason for the difference in findings between the studies may be due to differences in the tasks used in the studies. Taekwondo Taegeuk il-Jang used in this study was a task consisting of 17 different goal-oriented actions, while each of the tasks such as golf putting, balance test, and dart throwing used in previous studies (Romano-Smith et al., 2018; Smith & Holmes, 2004; Taube et al., 2014) was a single goal-oriented action. It may be quite difficult for beginners to cognitively process the accuracy and sequence of the 17 different goal-oriented actions during simultaneous AO+MI because cognitive demands in working memory are particularly high in the initial learning stage and the capacity of working memory is limited (Furley & Memmert, 2010; Lee, Lu, & Ko, 2007; Logie, 2011; Maxwell, Masters, & Eves, 2003). In this case, the alternate AO+MI training schedule, which can process cognitive information step by step and gradually, may be more effective in sequential motor learning. In addition, the blocked AO+MI training schedule, which conducts the MI section after the AO section, was not as effective as the alternate AO+MI training schedule but was somewhat effective. However, the blocked AO+MI training schedule has a limitation that the learners do not see the performance of the model again after the AO section for confirming correct movements. Therefore, the results of this study show that the alternate AO+MI training schedule may be more effective for learning sequential motor skills than simultaneous and blocked AO+MI training schedules.

Finally, regarding the relationship between changes in mental representation (i.e., Euclidean distance) and skill performance (i.e., the accuracy of movements and action sequences), the results of this study showed that the control group did not show a significant correlation between the two variables. However, for the three training groups (i.e., simultaneous, alternate, and blocked AO+MI), the correlation between the two variables was significantly correlated. In particular, there was a strong positive relationship between change in mental representation and change in the accuracy of the action sequence in the alternate AO+MI group. These results indicate that AO+MI training schedules to promote learning of sequential motor skill has formed a connection between mental representation in long-term memory and the outcome of skill performance. In particular, it suggests that such a relationship may be most effectively strengthened by alternate AO+MI training. Besides, this result indirectly supports the PC perspective (Bernstein, 1967), which emphasized the important role of mental representations in the learning of motor skills, assuming the connection between the upper-level mental representation and the lower-level sensorimotor control.

Regarding the potential limitations of the study derived in this study, first, the sample size in each group (i.e., n = 10) was small. The sample size calculation based on the results of the study indicated that the sample size had the actual power to detect statistical differences between groups or measurement times at a significance level of 5%. Larger sample size is needed, however, to increase the reliability of research findings and draw clearer conclusions. Second, in this study, two Taekwondo experts with a fifth-degree black belt evaluated based on the participants' video-recorded performances. Although there were specific evaluation criteria, it is difficult to completely exclude the subjective viewpoints of the evaluators. Therefore, to increase the reliability of the research results, it is necessary to additionally analyze quantitative data extracted through biomechanical equipment. Third, in this study, the measurement of skill performance was conducted in the form of blocks immediately after the post-test to minimize the effect of any physical attempt related to the skill on the cognitive aspect (i.e., mental representation structure). However, there is a limitation that the measurement of skill performance in such a block format may not adequately reflect changes in skill learning.

Despite some potential limitations of this study, considering the growing interest in AO+MI training as a cognitive training method for enhancing skill learning and performance in the field of motor learning, the present study will be able to provide some insight into the effective training schedules of AO+MI. In addition, the results of this study will be able to be used as educational information for leaders such as professors, teachers, supervisors, coaches to educate the learners on the importance of cognitive training as well as physical training to facilitate skill learning.

Conclusion

The findings of this study provide insight into an effective AO+MI training schedule to facilitate the learning of sequential motor skills by showing the effects of different AO+MI training schedules on mental representation in long-term memory and motor skill performance. The most important finding in this study was that although simultaneous, alternate, and blocked AO+MI training schedules were effective, the alternate AO+MI training schedule was particularly more effective than the other two training schedules in terms of the development of mental representations and outcome of sequential motor skill. In addition, the relationship between changes in long-term memory and motor outcomes was significantly correlated in all AO+MI training schedules but was most strongly enhanced by the alternate AO+MI training schedule. To our knowledge, this study is the first to compare the effects of different training schedules of AO+MI on mental representation and motor outcome levels in the learning process of sequential motor skills. However, it is difficult to generalize the results of this research on AO+MI training schedules because of the lack of accumulated research results. Therefore, it is necessary to examine the effectiveness of AO+MI training schedules under different task and contextual conditions through continuous research.

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