ACTION OBSERVATION AND MOTOR IMAGERY AS A COGNITIVE INTERVENTION

CHANGES IN PERCEPTUAL-COGNITIVE AND SKILL PERFORMANCE FOLLOWING TRAINING

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EHRENWÖRTLICHE ERKLÄRUNG ZUR DISSERTATION

Sehr geehrte Damen und Herren,

hiermit erkläre ich an Eides statt, dass ich die Dissertation mit dem Titel "Action observation and motor imagery as a cognitive intervention: Changes in perceptual-cognitive and skill performance following Training" selbstständig und ohne fremde Hilfe verfasst habe. Andere als die von mir angegebenen Quellen und Hilfsmittel habe ich nicht benutzt. Die den herangezogenen Werken wörtlich oder sinngemäß entnommenen Stellen habe ich als solche gekennzeichnet. Ich versichere außerdem, dass ich die vorliegende Dissertation nur in diesem und keinem anderen Promotionsverfahren eingereicht habe und dass diesem Promotionsverfahren keine endgültig gescheiterten Promotionsverfahren vorausgegangen sind.

Bielefeld, den 04. May 2021

Taeho Kim

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CHAPTER 2

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SUMMARY

Acquisition and learning of motor skills are generally accomplished through systematic and repetitive physical practice. However, considering that most of the motor skills include not only physical factors but also cognitive factors, it implies that cognitive training, as well as physical training, can also be effective in enhancing motor learning. Actually, as a representative cognitive training, action observation (AO) training and motor imagery (MI) training are effective training methods widely used for facilitating motor learning. Nevertheless, there is still a lack of research on a systematic comparison of AO and MI as well as on a combination of AO+MI. The present research has sought to provide a deeper understanding of cognitive training by providing changes in perceptual-cognitive expertise and skill performance following AO training, MI training, and different AO+MI training schedules. In addition, we aimed to provide insight into the motor learning process by identifying a link between changes in mental representations in long-term memory and cognitive or skill performance.

Chapter 1 provides an overview of seminal theoretical perspectives that illustrate the learning process of motor skills. In addition, neuropsychological and behavioral evidence supporting the effects of action observation and motor imagery, which have been used as an effective cognitive intervention to enhance motor performance and learning, will be described. Subsequently, by comparing and analyzing the mechanisms of action observation and motor imagery, the potential effects on the combination of the two cognitive interventions will be described. Finally, the purpose of the present study and research questions will be described.

Chapter 2 deals with our first study that examined the effects of action observation training and motor imagery training on mental representation structure and skill performance of a complex skill. Action observation training and motor imagery training have independently been studied and considered effective training methods for facilitating skill learning. However, there are relatively few comparative studies of the two training methods. The first study provides in-depth insight into the two training methods by comparing and analyzing the effects of action

observation and motor imagery on mental representation level and motor outcome level, as well as the relationship between mental representation structure in long-term memory and skill performance.

Chapter 3 deals with our second study that examined a functional link between mental representations in long-term memory and cognitive performance in working memory. There have been various attempts to understand the perceptual-cognitive mechanisms underlying the superior performance of skilled players compared to novices in sports. However, no studies are examining the relationship between mental representations and cognitive performance according to the skill level of players. The second study gives an in-depth insight into a functional link between mental representations in long-term memory and cognitive information processing ability in working memory by analyzing mental representation structure and cognitive performance according to skill level. In addition, the results of the second study, derived from the cross-sectional design, contribute to the understanding of the learning process at the perceptual-cognitive level concerning the effects of action observation (AO), motor imagery (MI).

Chapter 4 deals with our third study that examined the effect of alternate training of action observation and motor imagery on cognitive performance and skill performance. There is considerable research on the effects of action observation training and motor imagery training for enhancing skill learning. However, little is known about the effect of alternate training of action observation and motor imagery on cognitive and skill performance. The third study provides insights into the potential applicability of the combination of action observation and motor imagery by comparing and analyzing the changes in cognitive performance in working memory and skill performance following action observation training, motor imagery training, and alternate training of action observation and motor imagery.

Chapter 5 deals with our fourth study that examined the effect of different schedules of action observation training and motor imagery training on the changes in mental representation structure and skill performance. 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, we compared the effect of different AO+MI training schedules on the development of mental representation structure and skill performance. We found 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 most effective.

Chapter 6 will summarize the key findings derived from the four studies, the implications of those findings, and the limitations of the present research and the direction of further research.

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1. GENERAL INTRODUCTION

1.1. Motor skills and motor learning

In our lives, we are involved in the performance of a myriad of human activities called motor skills such as walking, running, catching, dancing, typing, throwing a baseball, and so on. Motor skills can be defined as activities that require voluntary control of the movements of body segments and joints to achieve a goal (Magill & Anderson, 2014). All the motor skills that we perform naturally are the result of systematic, repetitive, and continuous practice. The need for physical practice to accomplish such motor skills is theoretically well established. For example, achieving complex motor skills such as playing a piano or tennis requires a considerable amount of practice. Along with continuous practice, skill performance improves as the efficiency of the movements of the skills increases. Finally, at some point in time, learners learn specific motor skills as they have relatively persistent performance capabilities. First, we will look at representative theories that explain the processes by which motor skills are learned. Then, we will look at the changes in various perceptual-cognitive and performance variables that reflect the process of learning that emerges through practice.

1.1.1. Theoretical approaches on motor learning: Fitts and Posner three-stage model

Fitts and Posner (1967) introduced a 3-stage model of skill learning. Since then, this model has been referred by many researchers so far. Fitts and Posner suggested that learning a skill is accomplished in three stages. The first stage is the cognitive stage of learning. During the first stage, beginners focus their consciousness primarily on the cognitive aspects of what to do and how to do it. At this stage, beginners show many performance errors, lack of performance consistency, and lack of knowledge of what to do to correct their errors. The second stage is the associate stage of learning. The entry of the second stage occurs after a certain amount of practice and performance improvement. During the associative stage, learners attempt to associate their body movements with clues related to performance in the environment to achieve skill goals. At this stage, learners show fewer performance errors and variability compared to the cognitive stage and have the ability to detect their performance errors. However, there are still a lot of parts that need to be refined for skill learning. The third stage is the autonomous stage. The entry of the third stage occurs after a considerable amount of practice and experience. The learners who enter the autonomous stage perform skills almost automatically or habitually because they perform skills excellently without conscious attention. Therefore, the learners at this stage show very little performance error and variability compared to the cognitive and associative stages and can detect and correct their performance errors. However, Fitts and Posner emphasized that not everyone who learns skills can reach the autonomous stage. The quality of practice and instruction as well as the amount of practice is an important factor for reaching the third stage (Ericsson, 1998). Fitts and Posner's theory is based on the general cognitive theory. On the other hand, Gentile's theory (1967), which be discussed next, follows an information processing model considerably.

1.1.2. Theoretical approaches on motor learning: Gentile's two-stage model

In addition to the three-stage model of Fitts and Posner (1967), another model explaining skill learning referred to widely by researchers was proposed by Gentile (1972, 2000). Gentile proposed that the learning of motor skill progresses through two stages: the initial stage of learning and later stage of learning and that the two stages are differentiated in terms of goals that learners achieve. First, in the initial stage of learning, beginners have two important goals to accomplish. The first goal is to acquire a pattern of movements to perform skills to some extent. This means developing the movement characteristics taking into account the environmental regulatory conditions (e.g., cup size, cup position, and contents in the cup in the case of a cup grasping task) that may affect the performance of the skills. The second goal is to acquire the capacity to distinguish between environmental regulatory conditions that affect skill performance and environmental non-regulatory conditions (e.g., cup color) that do not affect skill performance. In this regard, at the initial stage of learning learners should participate in a significant amount of cognitive problem-solving activities to achieve these two goals. In addition, efficiency and consistency in the patterns of movements are still low at this stage, similar to the characteristics of learners in the cognitive or associative stages of Fitts and Posner. In the later stage of learning, learners have three important goals to achieve. The first goal is to develop competencies that enable learners to adapt their movement patterns to the needs of the changing performance environment. The second goal is to improve the consistency of their performance. The third goal is to enhance the efficiency of energy and effort required to perform skills. As learners learn these three goals in the later stages of learning, the result is that learners automatically recognize the clues associated with their performance in the environment, adapt their movements accordingly, and have their abilities to perform consistently. Gentile's theory follows an information processing model based on action goals to be achieved in the initial stage of learning and later stage of learning. On the other hand, Bernstein's theory (1967), which will be discussed next, follows an information processing model based on the control of degrees of freedom of body joints and muscles.

1.1.3. Theoretical approaches on motor learning: Bernstein's description of the learning process

To perform complex motor skills, the motor control system should be able to solve the problem of the degree of freedom of body muscles and joints related to performing skills (Whiting, 1984). For novice learners, solving the problem of the degree of freedom is considered an important part of the skill learning process (Bernstein, 1967). Bernstein (1967) described the process of learning complex motor skills in three stages, centering on the degree of freedom. First, in the first stage, novice learners freeze the degrees of freedom of the body that is used to perform a new skill. Freezing the degree of freedom means reducing the number of degrees of freedom. Thus, in the process of developing movements to achieve a skill goal, learners can minimize the body elements that they need to control. However, at this stage, there is a limitation that the adaptability of motor skills is so low that it cannot cope with various environmental changes appropriately. The second stage is the stage of releasing the degree of freedom. At this stage, learners increase the number of degrees of freedom available by releasing the degrees of freedom that were frozen. This is to form functional units necessary to perform skills by combining the increased degree of freedom according to each function of the skill. These functional units are called coordination structures in the dynamic system theory (Haken, Kelso, & Bunz, 1985). At this stage, diversity or adaptability to cope with environmental changes is improved. The third stage is the utilization step of the reaction. There is a reaction phenomenon such as inertia or friction between the performer and the environment. To utilize the internal and external forces of the body to perform skills more efficiently, it is necessary to utilize more extra degrees of freedom than the stage of releasing degrees of freedom. At this stage, the interaction of reaction forces occurs in the body segments related to movements, and the functional actions thus formed increases the efficiency of the performance and energy of learners. In addition, learners perform more sophisticated skills by constantly modifying the dynamic cyclic relationship between perception and movements in a changing environment. So far, Fitts and Posner's theory based on a general cognitive theory, Gentile's theory and Bernstein's theory based on an information processing model. Subsequent sections will discuss the perceptual-cognitive perspective that describe motor learning as a result of the development of mental representations at a higher level and the cognitive action architecture approach that support them.

1.1.4. Theoretical approaches on motor learning: Perceptual-cognitive perspective on motor learning

Perceptual-cognitive perspective has received much attention as a remarkable explanation for the question in the field of motor learning and control. According to the perceptual-cognitive perspective, the planning and execution of movement actions are guided by mental representations in long-term memory that are formed based on perceptual information of movement actions. Approaches that support the perceptual-cognitive view include the theory of event coding (Hommel, Müsseler, Aschersleben, & Prinzb, 2001), the ideomotor approach (Knuf, Aschersleben, & Prinz, 2001), the action simulation theory (Jeannerod, 2001), and the cognitive architecture approach (Schack, 2004). These models emphasize the importance of mental representation for motor control. The perceptual-cognitive perspective assumes that mental representations and motor movements are functionally connected. Thus, practice increases the efficiency of motor control by contributing to the formation of more elaborated mental representations. Regarding the development of mental representations, physical practices generally contribute to the development of mental representations (Frank, Land, & Schack, 2013), but cognitive training such as action observation training or motor imagery training can also contribute to the development of mental representations (Frank, Kim, & Schack, 2018; Frank, Land, Popp, & Schack, 2014).

1.1.5. Theoretical approaches on motor learning: Cognitive action architecture approach on motor learning

According to the cognitive action architecture (CAA) approach (Schack, 2004; Schack & Hackfort, 2012) among the approaches that support perceptual-cognitive perspective, mental representations play an important role in the planning and execution of motor actions and consist of basic action concepts defined as representational units of motor actions. The CAA approach assumes that well-organized mental representations contribute not only to performance enhancement at the perceptual-cognitive level but also to performance improvement at the motor output level. More specifically, the CAA approach suggested that motor actions are controlled by a hierarchically organized mental system and sensorimotor system. According to this approach, the mental system consists of mental control and mental representation levels. The sensorimotor system consists of sensorimotor representation level and sensorimotor control level. Motor action is hierarchically controlled from a high level (i.e., mental control level) to a low level (i.e., sensorimotor control level). First, at the mental control level (IV), the goals and strategies of motor actions are established. Subsequently, at the mental representation level (III), the mental representation based on basic action concepts serves as a cognitive reference for implementing the set action goals and strategies. At the sensorimotor representation level (II), sensorimotor representation serves as a sensory reference for body movements so that motor actions established and prepared in the mental system can be output smoothly according to a cognitive reference. Finally, at the sensorimotor control level (I), the motor actions are performed according to cognitive and sensory references. These four levels are functionally connected, and the functional relationship between the four levels changes continuously through practice. Most importantly, the CAA approach emphasizes the importance of mental representation as a cognitive reference in the learning process of motor skills as well as in the execution of motor actions. So far, we have looked at some theories that explain motor learning and its process. We will then look at changes in various aspects that reflect skill learning through systematic and continuous practice.

1.1.6. Changes in perceptual-cognitive expertise and skill performance following practice

There are many implicit and explicit changes in the learning process of motor skills, but the changes in performance are manifested explicitly. Performance improvement is a typical change reflecting skill learning. Snoddy (1926) mathematically formulated changes in performance following a practice. This is referred to as the power law of practice According to the law, the rate of performance improvement is high at the initial learning stage, while the rate of improvement decreases as learning progresses (Chen, Liu, Mayer-Kress, & Newell, 2005; Crossman, 1959). Practice also increases the efficiency of coordination, which means the harmonious movement of body segments (Anderson & Sidaway, 1994; Southard & Higgins, 1987). The efficiency of coordination is closely related to how to effectively control the number of degrees of freedom of the muscles or joints involved in performing motor skills (Bernstein, 1967; Whiting, 1984). The more effective learners control the problem of degrees of freedom, the more optimal is the pattern of coordination of body segments and muscles to perform their skills. Once motor skills are learned, the efficiency of coordination, as well as the efficiency of the muscles and energy used to perform the motor skills, increases (Almasbakk, Whiting, & Helgerud, 2001; Lay, Sparrow, Hughes, & O'Dwyer, 2002). The number of unnecessary muscles is reduced and only the necessary muscles are activated so that the amount of energy required to perform the skills is minimized (Sakurai & Ohtsuki, 2000; Sparrow, Hughes, Russell, & Rossignol, 1999). In addition, during skill learning, the ability to identify and correct movement errors are improved (Robertson, Collins, Elliott, & Starkes, 1994). Also, the brain regions activated when performing skills are different from those at the initial learning stage (Doyon, Penhune, & Ungerleider, 2003). With regards to changes in conscious attention, the amount of conscious attention is reduced as learners practice skills and become more skilled. Also, by giving conscious attention efficiently to information sources related to performance in the environment, skilled learners make faster and more accurate decisions and adapt to new environments than novice learners (Gray, 2004; Shinar, Meir, & Ben-Shoham, 1998). Regarding the change of mental representation following practice, perceptual-cognitive perspective emphasized the role of mental representation for skill learning. In order for such a view to be supported, changes in mental representation should be accompanied by changes in skill performance following practice. Indeed, Frank, Land, and Schack (2013) examined the effects of physical practice on the development of mental representational structure and the performance of complex motor skills. The result showed that the control group without any practice showed no change, whereas the physical training group showed that the mental representation structure was more elaborated and organized as well as improving the performance of the motor skills. This result suggests that skill learning is related to the functional adaptation of mental representations in long-term memory. So far, we have looked at changes in various aspects as learners learn motor skills through practice. When referring to practice for skill learning, it refers to various forms of physical practice. Systematic and repetitive physical practice is a proven method that has been used to achieve skill goals. However, not only physical training but also cognitive training such as action observation training or motor imagery training was reported to facilitate the learning of motor skills, either alone, or combined with physical practice (Hodges and Williams, 2012; Murphy, 1994; Ste-Marie et al., 2012). Indeed, action observation and motor imagery are representative cognitive interventions that have been widely used to enhance motor learning and performance. Not only examining the mechanisms and learning effects of these two interventions, but also identifying their pros and cons is an interesting and worthwhile attempt to find more effective AO and MI conditions for facilitating motor learning. Therefore, the following chapters will discuss a combined training of AO and MI, which can minimize their shortcomings by first examining AO and MI in more detail.

1.2. Action observation training and motor learning

Action observation can be defined as a dynamic state that cognitively simulates observed actions by observing the actions performed by others (Keysers & Gazzola, 2010; Sale, Ceravolo, & Franceschini, 2014)[1]. Action observation has been considered an important intervention for modifying or learning various social skills and behaviors (Bandura, 1986). According to the social cognitive theory of Bandura (1986), observer symbolically encodes information related to skills or behaviors through observation and then uses the coded information as a guide for future action. The application of action observation has extended to sports and rehabilitation areas. So far, many studies have suggested that action observation can be used as an effective cognitive intervention to promote motor learning, performance, and rehabilitation (Frank, Kim, & Schack, 2018; Hebert & Landin, 1994; McCullagh, Stiehl, & Weiss, 1990; Small, Buccino, & Solodkin, 2012; see Ste-Marie et al., 2012 for review). In this chapter, neurophysiological and behavioral evidence supporting the effects of action observation will be discussed in more detail.

1.2.1. Neurophysiological evidence of effects of action observation

In the 1990s, it was found that neurons in the F5 region of the premotor cortex were activated when a monkey observed that another monkey stretched his arm to grab something (Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). These neurons are referred to as mirror neurons and play an important role in the observation-execution system (Buccino & Riggio, 2006). Evidence that neurons similar to mirror neurons exist in the human brain have also been reported by neurophysiological and brain imaging studies (Buccino et al., 2001; Calmels et al., 2006; Cochin, Bathelemy, Roux, & Martineau, 1999; Grèzes, Armony, Rowe, & Passingham, 2003). This mirror neuron system in humans might provide a mechanism for how people perceive motor actions and form action representations through action observation (Grèzes, Costes, & Decety, 1998). In addition, researchers have reported that action observation of motor skills activates

[1] Action observation is also used in the term “modeling”. Here, we will use the term “action observation”

motor-related brain regions that are activated during the execution of the observed actions (Buccino et al., 2001; Fadiga, Craighero, & Olivier, 2005; Järveläinen, Schürmann, & Hari, 2004; Lepage & Théoret, 2006; Muthukumaraswamy & Johnson, 2004; Stefan et al., 2005). These neurophysiological findings of action observation imply that action observation can be used as an effective cognitive intervention to promote skill learning and performance.

1.2.2. Behavioral evidence of effects of action observation

Previous studies on action observation suggested that action observation is an effective cognitive intervention that can enhance motor outcome variables as well as motor production variables such as movement coordination patterns (Breslin, Hodges, Williams, Curran, & Kremer, 2005; Breslin, Hodges, Williams, Kremer, & Curran, 2006; Frank et al., 2018; Hayes, Ashford, & Bennett, 2008; Heyes & Foster, 2002; Horn, Williams, Hayes, Hodges, & Scott, 2007). The learning effect of action observation can be influenced by various factors such as learner's skill level, learning goal, model's proficiency, viewing perspective, amount of practice, video playback speed, and observation frequency, etc (see Ste-Marie et al., 2012 for review). Although the effect of action observation may vary with the various factors, action observation works as an effective cognitive intervention (see meta-analysis by Ashford, Bennett, & Davids, 2006). In addition, action observation can be applied to skill learning independently, but its effectiveness can be maximized when combined with physical practice (Shea, Wright, Wulf, & Whitacre, 2000). These findings show that action observation can be an effective cognitive intervention to promote skill learning and performance.

1.3. Motor imagery training and motor learning

Motor imagery can be defined as a dynamic state that simulates specific actions mentally in the absence of movement execution (Decety, 1996; Jeannerod & Decety, 1995). As with action observation, motor imagery has been widely used as an effective cognitive intervention to promote skill learning and performance, strategy development, and rehabilitation (see Jackson, Lafleur, Malouin, Richards, & Doyon, 2001; Jones & Stuth, 1997; Mizuguchi, Nakata, Uchida, & Kanosue, 2012; Murphy, 1994 for review). One of the representative theories explaining the learning effect of motor imagery is the symbolic learning theory (Sackett, 1934). According to this theory, learners encode the mental blueprint of movement patterns into the central nervous system with the symbolic code during motor imagery, and the coded cognitive representation or image serves as a guide to improve the performance of the skill. In this chapter, neurophysiological and behavioral evidence supporting the effects of motor imagery will be discussed in more detail.

1.3.1. Neurophysiological evidence of effects of motor imagery

Neurophysiological evidences are supporting the benefits of motor imagery for enhancing the learning and performance of motor skills (Bakker, Boschker, & Chung, 1996; Dickstein, Gazit-Grunwald, Plax, Dunsky, & Marcovitz, 2005; Ehrsson, 2003; Hanakawa, Dimyan, & Hallett, 2008; Jacobsen, 1931; Lafleur et al., 2002; Page, Szaflarski, Eliassen, Pan, & Cramer, 2009). In 1931, Jacobsen asked participants to imagine bending their right arm and lifting a weight. The result showed EMG activity in the biceps brachii of the imagined arm. Later, many other follow-up studies have demonstrated that motor imagery can activate the muscles involved in the actual execution of imaged actions (Bakker et al., 1996; Dickstein et al., 2005). In addition, the results of brain imaging studies have shown that motor imagery activates motor-related brain regions that are activated during the execution of imaged actions (see Decety, 1996 for review). Specifically, motor imagery seems to engage a neural motor network involving the premotor cortex, the supplementary motor area, the motor cortex, the basal ganglia, and the cerebellum, which are involved in the planning and execution of movements (Jeannerod, 2001; Munzert, Lorey, & Zentgraf, 2009). In this respect, motor imagery and the execution of the imaged action have similar neurophysiological responses, so it is referred to as the functional equivalence (Jeannerod, 1994; Lotze et al., 1999). Such functional equivalence is likely to contribute to the improvement of motor learning and performance not only by enhancing the formation of action representations but also by activating the perception-action neural motor pathway.

1.3.2. Behavioral evidence of effects of motor imagery

There are a number of behavioral evidence that motor imagery promotes skill learning and performance (see Jones & Stuth, 1997; Lotze & Halsband, 2006; Martin, Moritz, & Hall, 1999; Mizuguchi et al., 2012; Murphy, 1994 for review). The effects of motor imagery can vary depending on various factors such as characteristics of skill, learner's skill expertise, duration of practice, and imagery perspective, etc (see meta-analysis by Driskell, Copper, & Moran, 1994). However, there is no doubt about the positive effects of motor imagery on skill learning and performance enhancement (see Mizuguchi et al., 2012; Murphy, 1994 for review). In addition, although motor imagery can be used independently as a cognitive intervention, the combination of motor imagery and physical practice can be expected to have greater learning effects than physical practice alone (Liu, Song, & Zhang, 2014). Thus, these findings show that motor imagery can be an effective cognitive method that can facilitate motor learning and performance independently or in combination with physical practice.

1.4. Similarities and differences between action observation and motor imagery

As we have seen, action observation and motor imagery can be regarded as motor simulations performed in the absence of movement execution (Jeannerod, 2001). Both action observation and motor imagery have been widely used for effective cognitive interventions to promote motor learning and rehabilitation, and they can be used as a complement to physical exercises or used alone if physical movements are limited due to neurological impairment (see Mizuguchi et al., 2012; Mulder, 2007; Ste-Marie et al., 2012 for review, see Ashford, Bennett, & Davids, 2006; Driskell, Copper, & Moran, 1994 for meta-analysis). Nonetheless, studies of action observation and motor imagery have been conducted independently or mainly on the study of the functional equivalence between the two interventions (Filimon, Nelson, Hagler, & Sereno, 2007; Grezes & Decety, 2001; Williams, Cumming, & Edwards, 2011), or on the differences in learning effects between the two interventions (Kim, Cruz, & Ha, 2011; Ram, Riggs, Skaling, Landers, & McCullagh, 2007; Soohoo, Takemoto, & Mccullagh, 2001). In this chapter, therefore, we will look at the similarities and differences between action observation and motor imagery, and the advantages and limitations of each. By doing so, we intend to bring about a combination of motor imagery and action observation, which is an effective way to complement the limitations of action observation and motor imagery and to make better use of the advantages of both.

1.4.1. Similarities between action observation and motor imagery

First, with regards to the similarity of action observation and motor imagery, motor-related brain regions that are active at the time of execution of imaged or observed actions are also activated not only during action observation but also during motor imagery (Buccino & Riggio, 2006; Filimon, Nelson, Hagler, & Sereno, 2007; Lotze et al., 1999). It is used in terms of the "functional equivalence" or "shared motor representations" between motor imagery, action observation, and action execution. The functional equivalence was supported by many neuroimaging studies (see meta-analysis by Grezes & Decety, 2001). Second, regarding the development of mental representations with action observation training or motor imagery training, the previous two studies (Frank et al., 2014; Frank et al., 2018) reported that action observation training and motor imagery training seem to promote the development of mental representation structure of a complex motor skill (i.e., golf putt), respectively. Specifically, Frank et al (2018) reported that action observation training alone contributed significantly to the development of mental representations of golf putt. In addition, Frank et al. (2014) reported that motor imagery training also enhanced the cognitive adaptation process, inducing more elaborate mental representations during motor skill learning. These findings suggest that action observation and motor imagery are to some extent similar in terms of operating mechanisms and behavioral effects. Despite these similarities, however, there is a difference between action observation and motor imagery.

1.4.2. Differences between action observation and motor imagery

The key difference between action observation and motor imagery is the location of the initial stimulus information needed to form action representations (Ram, Riggs, Skaling, Landers, & McCullagh, 2007; Soohoo, Takemoto, & Mccullagh, 2001; Vogt, Rienzo, Collet, Collins, & Guillot, 2013). Action observation involves an external stimulus-dependent process that forms action representations using external stimulus information stored temporarily in working memory through the observation of a live demonstration or recorded video (Holmes & Calmels, 2008). On the other hand, motor imagery undergoes an internal stimulus-dependent process that forms action representations using internal stimulus information already stored in long-term memory (Holmes & Calmels, 2008). Specifically, action observation and motor imagery are essentially similar in that they form action representations necessary to perform a skill. However, action observation requires an external stimulus, which is a visual image, whereas motor imagery does not require an external visual image.

1.4.3. Limitations of action observation and motor imagery

Many researchers have pointed out that a large number of motor imagery studies involve additional interventions such as self-talk, relaxation techniques, action observation, and physical practice, making it difficult to extract the effects of pure motor imagery (see Martin, Moritz, & Hall, 1999 for review). It is difficult for novice learners to form performance-related action representations through motor imagery without previous experience with the task and without observing the performance of a model in advance (Ram et al., 2007). However, if learners have some experience related to the performance of the task, the learning effect of motor imagery may be expected (Corbin, 1967). Therefore, it is difficult to expect the effect of motor imagery because novice learners with no previous task experience have no information to form action representations (Frank, Land, Popp & Schack, 2014, Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004), which can act as a limitation of motor imagery. On the other hand, action observation can be effective for novice learners with no previous task experience in that it provides information externally for the formation of action representations (Frank et al., 2018b). However, if learners do not have conscious awareness or intention to imitate during action observation, the learning effect of action observation may be reduced (Wright, McCormick, Williams, & Holmes, 2016), which acts as a limitation of action observation. Is there any way to complement the limitations of action observation and motor imagery and take advantage of the benefits of both? In the next chapter, we will look at the method.

1.5. Combined training of action observation and motor imagery

A combination of action observation and motor imagery, which utilize both external stimuli and internal stimuli, can be an effective way to complement each limitation and take its advantage (see Eaves, Riach, Holmes, & Wright, 2016; Vogt et al., 2013 for review). Specifically, novice learners who have no task experience obtain the information required for the formation of action representations through action observation providing the visual image information related to the performance externally. At the same time or at a later time, more elaborate action representations may be formed by performing mental rehearsal visually and/or kinesthetically through motor imagery. Research on the combination of action observation and motor imagery has received much attention recently from researchers (see Eaves et al., 2016 for review). However, researches on a combined training of action observation and motor imagery have not yet been studied systematically and in-depth. Some neurophysiological and behavioral studies on the combination have shown that combined method of action observation and motor imagery may be more effective than action observation or motor imagery alone (Eaves, Behmer, & Vogt, 2016; Eaves, Haythornthwaite, & Vogt, 2014; Mouthon, Ruffieux, Wälchli, Keller, & Taube, 2015; Romano-Smith, Wright, Wood, & Wakefield, 2018; Scott, Taylor, Chesterton, Vogt, & Eaves, 2018; Taube et al., 2015; Taube, Lorch, Zeiter, & Keller, 2014; Wright et al., 2018). Nevertheless, there are still many research issues such as a systematic study on the comparison in pure effects of action observation and motor imagery, and a study on different combined training schedules of action observation and motor imagery. In the following section, we will look more closely at the neurophysiological and behavioral studies of the combination already studied.

1.5.1. Neurophysiological evidence of effects of the combination of action observation and motor imagery

There is some neurophysiological evidence supporting the effect of simultaneous AO+MI, which is one of the various AO+MI training schedules, in relation to either action observation or motor imagery alone. Simultaneous AO+MI is to perform motor imagery during action observation. Typically, simultaneous AO+MI requires participants to observe a model or their performance in a video while imagining simultaneously kinesthetic feelings and vivid movements associated with the actual performance of the observed action. Previous studies have shown that simultaneous AO+MI increases the activity of motor-related brain regions and corticospinal excitability compared to action observation or motor imagery alone using various kinds of experimental equipment such as TMS, EEG, or fMRI (Berends, Wolkorte, Ijzerman, & van Putten, 2013; Eaves et al., 2016 for review; Mouthon et al., 2015; Nedelko, Hassa, Hamzei, Schoenfeld, Dettmers, 2012; Ohno et al., 2011; Sakamoto, Muraoka, Mizuguchi, & Taube, 2015; Taube et al., 2015; Villiger et al., 2013; Vogt et al., 2013 for review; Wright et al., 2018; Wright et al., 2016; Wright, Williams, & Holmes, 2014). For example, Taube et al. (2015) examined how simultaneous AO+MI activates the brain regions involved in the execution of balance tasks. It was revealed that simultaneous AO+MI for the dynamic balance task activated the brain's motor centers including supplementary motor area (SMA), premotor cortex (MI), premotor cortices, basal ganglia, and cerebellum, which play an important role in balance control. In particular, simultaneous AO+MI showed greater activation in the supplementary motor area (SMA), basal ganglia, and cerebellum compared to independent action observation, and it showed greater activation in the bilateral cerebellum and precuneus compared to independent motor imagery. In addition, recently, Wright et al. (2018) compared the effect of independent action observation, independent motor imagery, and simultaneous AO+MI on corticospinal excitability for basketball free throws. Results showed that corticospinal excitability was significantly facilitated in simultaneous AO+MI condition compared to independent action observation condition and control condition, whereas independent action observation condition and motor imagery conditions did not differ from the control condition in corticospinal excitability. These findings imply that simultaneous AO+MI may be a more effective cognitive method for enhancing motor learning and performance than either action observation or motor imagery alone.

1.5.2. Behavioral evidence of effects of the combination of action observation and motor imagery

There are some behavioral evidence as well as neurophysiological evidence supporting the applicability of AO+MI (Battaglia et al., 2014; Bek, Poliakoff, Marshall, Trueman, & Gowen, 2016; Eaves et al., 2016, 2014; Eaves, Turgeon, & Vogt, 2012; Ram et al., 2007; Romano-Smith et al., 2018; Scott et al., 2018; Smith & Holmes, 2004; Smith, Wright, & Cantwell, 2008; Sun et al., 2014; Sun, Wei, Luo, Gan, & Hu, 2016; Taube et al., 2014; Wright & Smith, 2009). First, according to behavioral studies conducted in the sports field, simultaneous AO+MI training significantly improved the performance of golf putting and a bicep strength after training for six weeks, twice a week (Smith & Holmes, 2004; Wright & Smith, 2009). In addition, Sun, Wei, Luo, Gan, & Hu (2016) examined the effect of simultaneous AO+MI in stroke patients with hand motor dysfunction in the rehabilitation field. The result showed that simultaneous AO+MI improved the pinch grip strength and dexterity of the affected limb more effectively than alternate AO+MI. Recently, Romano-Smith et al. (2018) examined the effect of simultaneous AO+MI training and alternate AO+MI training on the performance of dart throwing. After six weeks of intervention, it was found that both of the two types of AO+MI training significantly improved performance. The authors suggested that a combination of action observation and motor imagery could be an effective method to promote skill learning, regardless of how action observation and motor imagery are combined. These findings support the applicability of AO+MI to enhance skill learning and performance.

1.6. Purpose of the present work – aims, research questions, and predictions

In summary, action observation and motor imagery have been used independently as an effective cognitive intervention to facilitate motor learning and performance. Previous studies have proposed functional equivalence or shared action representations between the two in that both action observation and motor imagery activate the regions of the brain involved in the execution of the observed or imaged actions (see meta-analysis by Grezes & Decety, 2001). However, there is a difference between the two motor simulations in that the locus of the initial stimulus information needed to form action representations is different (Ram et al., 2007; Soohoo et al., 2001; Vogt et al., 2013). Action observation involves an external stimulus-dependent process, in which an initial stimulus for the formation of action representations is provided externally (Holmes & Calmels, 2008). On the other hand, motor imagery goes through an internal stimulus-dependent process of forming action representations based on motor information already stored in long-term memory (Holmes & Calmels, 2008). Thus, if learners do not have the intention to imitate during action observation, or if learners have difficulty in forming action representations during motor imagery due to the lack of action information, the effects of action observation and motor imagery may be reduced (Mulder et al., 2004). The combination of action observation and motor imagery may be an effective way to complement such limitations. Specifically, novice learners who have no experience of task obtain the information necessary for the formation of action representations by first observing the performance of a model. And more elaborate action representations will be formed by mentally rehearsing the observed actions through motor imagery that are performed simultaneously or subsequently. As a result, it may effectively contribute to facilitating motor learning through the formation and development of action representations. Research on the combination of action observation and motor imagery has attracted much attention recently from researchers. Indeed, neuroscientific and behavioral studies on AO+MI support the potential effects of AO+MI (see Eaves et al., 2016; Vogt et al., 2013 for review). Nonetheless, there is still a need to continue researching regarding the comparison and combination of action observation and motor imagery. Based on the theoretical background, we conducted four studies related to action observation and motor imagery.

In the following, we will look at the purpose of the study set in each study and the hypothesis of the study in more detail. First, in the first study, we compared the effects of action observation (AO) training and motor imagery (MI) training on the development of mental representation and motor performance of complex action in novice learners who had no experience in a skill to be learned. Many previous studies have reported that AO training and MI training facilitate motor learning and performance (see meta-analysis by Ashford et al., 2006; Driskell et al., 1994; Feltz & Landers, 1983; see Mizuguchi et al., 2012; Ste-Marie et al., 2012 for review). However, the study of the pure effects of AO and MI has not been performed at the level of mental representation and motor output at the same time within our knowledge range. Therefore, in the first study, we tried to compare AO training and MI training systematically and in-depth by analyzing the effect of two types of cognitive training on mental representations and motor performance.

In the first study, it was expected that AO training group would induce a more elaborate mental representation structure and better performance improvement than MI training group since learners of MI group would have difficulty in forming action representations. Furthermore, if training changes not only performance but also mental representations, there is a possibility of a correlation between the change of mental representations and the change of performance, and the degree of the correlation is expected to depend on the training method.

In the second study, we examined the functional link between mental representations in long-term memory and cognitive information processing ability in working memory by analyzing mental representation structure and cognitive performance according to skill levels. Although there have been various attempts to identify the perceptual-cognitive mechanisms underlying the superior performance of skilled players over novices in sports, few studies have examined the relationship between mental representations and cognitive performance according to the skill levels of players. We hypothesized that if action representations play an important role as a cognitive reference in the planning and execution of intended motor actions, then skilled players would execute a better cognitive performance, with a more elaborate, well-organized mental representation structure compared to novices. Furthermore, it was expected that there would be a link between mental representations and cognitive performance.

In the third study, we investigated the effect of alternate training of action observation (AO) and motor imagery (MI) on cognitive performance and skill performance of complex motor action. As noted earlier, we have mentioned the combination of AO and MI as an effective way to complement the limitations of AO and MI. However, no study has examined the effect of alternate AO+MI training on the efficiency of information processing in working memory. Therefore, in the third study, we tried to provide a deeper understanding of the effect of alternate AO+MI training by examining the effect of alternate AO+MI training on cognitive performance and skill performance. The hypothesis was that if alternate AO+MI training serves as an effective way to complement the limitation of AO and MI, alternate AO+MI training would induce cognitive performance as well as skill performance better than AO or MI training alone. In addition, it was expected that if the motor learning process includes changes in cognitive performance and skill performance, a correlation between the change in cognitive performance and the change in skill performance would appear, and the degree of the correlation would vary according to the training method.

In the fourth study, we examined the effects of different training schedules of AO+MI on the changes in mental representation structure and skill performance of the complex procedural skill. Although the combination of AO+MI itself may be an effective method, the effects of AO+MI can vary depending on the training schedule. However, no studies have been conducted to examine changes in mental representations and skill performance according to different AO+MI training schedules. Therefore, in the fourth study, we examined an optimal AO+MI training schedule to promote motor learning by analyzing the effect of different training schedules of AO+MI on the development of mental representation structure and skill performance of the procedural motor skill. Compared to the control group that did not receive any training, it was expected that simultaneous, alternate, and blocked AO+MI training schedules would lead to the improvement of mental representation structure and skill performance. In particular, we hypothesized that alternate AO+MI training schedule performing MI after AO would be most effective in learning procedural skills. In addition, if there are changes in mental representation structure in long-term memory and skill performance in the process of motor learning, it was expected that it would show a correlation between change in mental representations and change in skill performance, and the degree of the correlation would vary according to different AO+MI training schedules.

Taken together, the four studies provide a deeper insight into action observation and motor imagery as cognitive interventions by not only comparing action observation and motor imagery at higher levels of motor control (i.e., mental control level and mental representation level), but also examining their combined effects. In addition, the studies also provide insight into how motor learning progresses by examining the connections between mental representations in long-term memory, cognitive performance in working memory, and behavioral outcomes. The findings of these studies could be used as educational, practical, and academic basic data for students, coaches, and researchers by providing more up-to-date information on action observation training and motor imagery training to facilitate motor learning and performance.

2. A SYSTEMATIC INVESTIGATION OF THE EFFECT OF ACTION OBSERVATION TRAINING AND MOTOR IMAGERY TRAINING ON THE DEVELOPMENT OF MENTAL REPRESENTATION AND SKILL PERFORMANCE

This chapter is based on

Kim, T., Frank, C., & Schack, T. (2017). A systematic investigation of the effect of action observation training and motor imagery training on the development of mental representation structure and skill performance. *Frontiers in Human Neuroscience*, *11*(499), 1-13. doi:10.3389/fnhum.2017.00499

Abstract

Action observation training and motor imagery training have independently been studied and considered as an effective training strategy for improving motor skill learning. However, comparative studies of the two training strategies are relatively few. The purpose of this study was to investigate the effects of action observation training and motor imagery training on the development of mental representation structure and golf putting performance as well as the relation between the changes in mental representation structure and skill performance during the early learning stage. Forty novices were randomly assigned to one of four groups: action observation training, motor imagery training, physical practice, and no practice. The mental representation structure and putting performance were measured before and after 3 days of training, then after a 2-day retention period. The results showed that mental representation structure and the accuracy of the putting performance were improved over time through the two types of cognitive training (i.e., action observation training and motor imagery training). In addition, we found a significant positive correlation between changes in mental representation structure and skill performance for the action observation training group only. Taken together, these results suggest that both cognitive adaptations and skill improvement occur through the training of the two simulation states of action and that perceptual-cognitive changes are associated with the change of skill performance for action observation training.

2.1. Introduction

Motor learning means a relatively permanent change in the competence of skill performance, resulting from systematic and repeated practice (e.g., Magill, 2000). The learning of a motor skill is commonly attained via physical repetition of a skill before moving to a different motor skill (e.g., Coker, 2004). However, research has shown that cognitive training, such as motor imagery and action observation training, can also be applied effectively to facilitate skill learning, either alone, or combined with physical practice (e.g., Hodges & Williams, 2012).

Motor imagery refers to a dynamic state during which learners simulate specific motor actions mentally, without actual movement (e.g., Decety, 1996; Jeannerod, 1995). Furthermore, motor imagery training has been used as an effective means to facilitate motor learning and performance (e.g., Driskell, Copper, & Moran, 1994; Murphy, 1994; Schack, Essig, Frank, & Koester, 2014). Meta-analyses on this topic have reported that motor imagery training has a positive effect on motor performance, even though the degree of its effectiveness varies with the moderators, such as type of task, the experience level of participants, duration of practice, and other factors (e.g., Driskell et al., 1994). In addition, motor imagery training was shown to be more effective compared to no practice but was less effective than the physical practice. Moreover, the combination has been proven to be as effective, or even more effective, than either motor imagery or physical practice alone (e.g., Bajaj, Butler, Drake, & Dhamala, 2015; Hall, Buckolz, & Fishburne, 1992; Liu, Song, & Zhang, 2014). Thus, these findings show that motor imagery training can be an effective type of cognitive training as a complement to physical practice to enhance motor outcomes.

Action observation is an effective means of observational practice that has been considered extensively for enhancing motor learning and performance (e.g., Ste-Marie et al., 2012), as well as for modifying social behavior (e.g., Bandura, 1986). Research on action observation showed that action observation training benefits not only performance production variables like movement coordination pattern (e.g., Horn, Williams, Hayes, Hodges, & Scott, 2007), but also performance outcome variables related to motor learning (e.g., Hayes, Ashford, & Bennett, 2008). To assess the motor learning effect of action observation training, previous studies compared the effect of action observation training with the effect of physical practice or no practice. From this, action observation training was found to be superior to no practice (e.g., Hayes et al., 2008; Kohl & Shea, 1992). In addition, it was suggested that the combination of action observation training and physical practice provides more unique opportunities than either action observation or physical practice alone (e.g., Shea, Wright, Wulf, & Whitacre, 2000; Weeks & Anderson, 2000). These findings show that action observation training can be an effective type of cognitive training as a complement to physical practice to facilitate behavior outcomes.

Jeannerod (2001) has proposed that simulation states (S states) such as action observation and motor imagery are functionally equivalent to action execution, assuming that both are based on action representations encoded in the brain. This proposal has been supported by many brain-image studies, which showed that both action observation and motor imagery lead to the activation of motor-related brain areas (e.g., Filimon et al., 2007; Lorey et al., 2013; Lotze et al., 1999). These studies suggested that, to some extent, they make use of the same neural substrates as those involved during the execution of observed or imagined actions. Furthermore, many studies have reported that the neural representations for action observation and motor imagery are somewhat similar to those for motor execution (e.g., Clark, Tremblay, & Ste-Marie, 2004; Filimon et al., 2007; Zabicki et al., 2016). For action observation, motor-related information, which is available through the visual system, is encoded into a type of mental representation in long-term memory for the organization of a future intended action (e.g., Holmes & Calmels, 2008; Ste-Marie et al., 2012). Motor imagery is required to consciously retrieve a stored mental representation in long-term memory (e.g., Bandura, 1997; Jeannerod & Decety, 1995; Soohoo, Takemoto, & Mccullagh, 2001; Wright, McCormick, Birks, Loporto, & Holmes, 2014). These indicate that mental representations, which play a key role in the control and organization of intended actions (e.g., Land, Volchenkov, Bläsing, & Schack, 2013), are involved during action observation and motor imagery.

Although motor imagery and action observation rely on a similar action representation, there is a difference between them in aspects of the mechanism of the cognitive process. Motor imagery is a knowledge-driven cognitive process that is internally simulated based on information in long-term memory, without an external stimulus (e.g., Helm, Marinovic, Krüger, Munzert, & Riek, 2015; Holmes & Calmels, 2008; Murphy, 1994; Soohoo et al., 2001). Instead, action observation is a percept-driven cognitive process that is externally guided by an external stimulus, such as a live demonstration or recorded video (e.g., Holmes & Calmels, 2008; Ram, Riggs, Skaling, Landers, & McCullagh, 2007; Vogt, Rienzo, Collet, Collins, & Guillot, 2013). Therefore, motor imagery completely relies on mental representations stored in long-term memory to generate a motor image (e.g., Farah, 1984; Frank, Land, Popp, & Schack, 2014; Mulder, Zijlstra, Zijlstra, & Hochstenbach, 2004; Schack, Essig, Frank, & Koester, 2014). On the contrary, action observation is not dependent on the mental representation in long-term memory, since it completes a percept-driven process (e.g., Guillot & Collet, 2010; Wright, McCormick, Birks, Loporto, & Holmes, 2015); that is, visual information provided externally is held in working memory, and does not necessarily rely on representations stored in long-term memory. This implies that, despite the functional equivalence between action observation and motor imagery, the two simulation states (S-states) of action may not necessarily lead to the same effect in the improvement of the mental representation and performance.

The perceptual-cognitive perspective specifies that cognitive representations, which guide motor actions, are formed based on perceptual information (Zentgraf et al., 2009). In this sense, the perceptual-cognitive perspective on motor control addresses the idea that intended and executed motor actions are based on the mental representation of motor actions stored in long-term memory (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001; Schack & Mechsner, 2006). From the cognitive action architecture approach (CAA-A; Schack, 2004; for reviews, see e.g., Land, Volchenkov, Bläsing, & Schack, 2013), the organization of motor action for the execution is functionally guided by mental representations encoded in long-term memory. In other words, mental representations function as a cognitive reference for movement control. The framework of mental representation is composed of basic action concepts (BACs), which are identified as major representation units for complex actions (e.g., Schack & Mechsner, 2006; Schack, 2004). Based on the cognitive action architecture approach (CAA-A), functional changes in the relation of basic action concepts appear over the motor learning process within a conceptual framework in long-term memory (e.g., Bläsing, Tenenbaum, & Schack, 2009; Frank, Land, & Schack, 2013; Schack & Ritter, 2009).

To investigate the role of mental representations in long-term memory, Schack and Mechsner (2006) compared the difference in mental representation structure according to different skill levels, employing the structural dimensional analysis of mental representation (SDA-M; for more details, see Schack, 2012). According to the results, mental representation structures of high-level experts were not only well organized but also corresponded to the functional demands of the task. In contrast, mental representation structures of low-level players and novices were relatively less organized and less linked to the functional demands of the task. Similar results were also reported in some studies that examined the difference in mental representation structure with skill expertise using the SDA-M for diverse motor tasks (e.g., Bläsing et al., 2009; Schack & Hackfort, 2007; Velentzas, Heinen, Tenenbaum, & Schack, 2010). In addition, according to Frank et al. (2013), the mental representation structure of golf novices became functionally more organized with physical practice over time, whereas no practice did not cause any changes in mental representation structure. These findings suggest that mental representations serve as a basis for action control, adapting functionally over the course of motor learning.

Given that most motor skills include both physical and cognitive elements, not only a physical practice but also cognitive training may lead to the development of mental representation. Recently, Frank et al. (2014) examined the effect of motor imagery training on mental representation structure and performance of novice golf players. The study showed that mental representation structure was functionally well organized particularly following motor imagery training. Moreover, in a recent study by Frank, Kim & Schack (2017), it was shown that action observation training for golf beginners led to more functional mental representation structures along with performance improvement. These findings suggest that both motor imagery training and action observation training can enhance the functional adaption of task-specific mental representation in the early learning stage.

Taken together, motor imagery training and action observation training in themselves have a positive effect on the improvement of skill performance of novice learners in the early skill acquisition stage. Some studies have compared the differences in neurophysiologic and behavioral effects between motor imagery training and action observation training. Nevertheless, to date, no studies have compared how motor imagery and action observation training affect the formation process of mental representation in novices. Thus, in this study, we aimed at investigating the differences in the effects of the two types of cognitive training on the development of mental representation structure and the performance of the golf putting task. It was expected that motor imagery training and action observation training as well as a physical practice would lead to functional changes of mental representation structure, along with performance improvement, compared to no practice (i.e., control group). Furthermore, it was expected that action observation training would be relatively more effective than motor imagery training in the development of mental representation since it was predicted that novices have available limited representation structure of the golf putt in their long-term memory. Therefore, we expected that the allocation of new and well-structured motor information through action observation would lead to more elaborate representation and better performance than the simulation through motor imagery. In addition, based on the CAA-A, it was expected that the structured change of mental representation would be somewhat linked to performance improvement.

2.2. Methods

2.2.1. Participants

Forty participants from a local university (18 males, 22 females; M_{age} = 25.20, *SD* = 4.12) took part in this study. All participants were beginners with no prior experience in golf and had a normal or corrected-to-normal vision. They were randomly assigned into four groups, maintaining an equal group size: action observation training group (*n* = 10, M_{age} = 23.30, *SD* = 3.40, 4 males), motor imagery training group (*n* = 10, M_{age} = 26.50, *SD* = 3.87, 4 males), physical practice group (*n* = 10, M_{age} = 26.30, *SD* = 4.79, 4 males), and control group with no practice (*n* = 10, M_{age} = 24.70, *SD* = 4.06, 6 males). This study was carried out in accordance with the recommendations of the ethics committee of the University of Bielefeld (EUB) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the ethics committee of the University of Bielefeld (EUB).

2.2.2. Structural dimensional analysis of mental representation

The SDA-M was used to evaluate the mental representation structure (e.g., Schack, 2012) of the golf putt. This method provides psychometric information on the structure of movement representation in long-term memory. More specifically, it is possible to investigate the status of the clustering and relations regarding BACs of a motor action through SDA-M. Thus, SDA-M has been employed as a reliable method to measure the mental representation structure of motor action (e.g., Bläsing et al., 2009; Frank et al., 2013; Schack & Mechsner, 2006). The following 16 BACs for golf putting that were developed by Frank et al. (2013) were applied in this study (see Table 1.1.). From a functional and biomechanical perspective, each of the 16 BACs can be allocated to one of four movement phases: BAC 1–4 (preparation phase), BAC 5–7 (backswing phase), BAC 8–11 (forward swing phase), and BAC 12–16 (attenuation phase).

Table 1.1. Basic action concepts of the golf put

Movement phase	**Number**	**Basic action concept (BAC)**
Preparation	1	Shoulders parallel to target line
	2	Align club face square to target line
	3	Grip check
	4	Look to the hole
Backswing	5	Rotate shoulders away from the ball
	6	Keep arms-shoulder triangle
	7	Smooth transition
Forward swing	8	Rotate shoulders towards the ball
	9	Accelerate club
	10	Impact with the ball
	11	Club face square to target line at impact
Attenuation	12	Follow-through
	13	Rotate shoulders through the ball
	14	Decelerate club
	15	Direct clubhead to planned position
	16	Look to the outcome

Note: Each movement phase contains basic action concepts that are functionally related to one another

To measure the mental representation structure, a splitting task was conducted (step 1 of the SDA-M). It aimed to acquire the data on the representational distance among the 16 cognitive units (16 BACs) for golf putting. Participants were instructed to judge whether an anchor concept and a concept were functionally related to each other during the execution of the movement. Each of 16 BACs was presented as an anchor concept, whereas the remaining 15 BACs were provided, one by one in a random order, to be compared with the anchor concept. The anchor concept was not changed to a different concept until it was compared to each of the remaining 15 BACs. Once one process for an anchor concept was finished, another BAC was changed to the role of an anchor. This procedure was performed for each of the 16 BACs (for more details, see Schack, 2012).

2.2.3. Skill performance

All participants were asked to perform a golf putt toward a golf hole (10.8 cm in diameter) projected by a beam at a distance of 3 m from the starting point on a synthetic putting green (length = 9 m, width = 4 m). Specifically, participants were required to putt a golf ball as close as possible to the target. To assess the accuracy of the performance, the two-dimensional position coordinate, of where the ball stopped after each golf putt trial, was recorded with six T10 CCD cameras (Vicon Motion Systems Ltd., Oxford, UK). Based on the collected data, the mean radial error (MRE) was calculated, which reflected the accuracy of the performance (e.g., Hancock, Butler, & Fischman, 1995).

2.2.4. Imagery ability

The revised version of the Movement Imagery Questionnaire (MIQ-R; Hall and Martin, 1997) was used for the measurement of visual and kinesthetic imagery ability. The MIQ-R was composed of eight items: four items for visual imagery and four items for kinesthetic imagery. Participants were asked to execute a movement that was specified in each item. Then, participants were instructed to imagine the same movement that they had executed either visually or kinesthetically, without performing any actual movement. Next, they were required to rate how easy or difficult it was to imagine the movement on a seven-point Likert scale, ranging from 1 (very difficult to see or feel) to 7 (very easy to see or feel). The MIQ-R was found to have adequate internal reliability coefficients (0.84 for visual imagery subscales and 0.88 for kinesthetic imagery subscales) and sufficient test-retest reliability coefficients (0.80 for visual imagery subscales and 0.88 for kinesthetic imagery subscales; Monsma, Short, Hall, & Gregg, 2009).

2.2.5. Post-experimental questionnaire

The participants of the action observation training and motor imagery training groups were asked to complete a post-experimental questionnaire immediately after the practice session of each day, which aimed to examine how easily they observed or imagined a movement. More specifically, the participants of the observation training group were required to indicate, on a seven-point Likert scale, anchored by 1 = ‘‘very difficult’’ to 7 = ‘‘very easy’’, how easy it was to observe in accordance with the instruction. The participants of the motor imagery training group were also asked to rate based on a seven-point Likert scale. The scale ranged from ‘‘very difficult’’ at 1 to ‘‘very easy’’ at 7, which indicated how easy or difficult it was to imagine the movement according to the instruction.

2.2.6. Procedure

This study was composed of a pre-test, 3 days of an experimental treatment, a post-test, and a retention test (see Table 1.2.).

Table 1.2. Experimental procedure by group and time period

Group	Pre-test	Treatment	Post-test	Retention test
	Day 1	**Day 1 Day 2 Day 3**	**Day 3**	**Day 5**
Action observation training group (n = 10)	SDA-M + Putting task	Observation training 60 times per day	SDA-M + Putting task	SDA-M + Putting task
Motor imagery training group (n = 10)	SDA-M + Putting task	Imagery training 60 times per day	SDA-M + Putting task	SDA-M + Putting task
Physical practice group (n = 10)	SDA-M + Putting task	Physical practice 60 times per day	SDA-M + Putting task	SDA-M + Putting task
Non-practice group (n = 10)	SDA-M + Putting task	No practice	SDA-M + Putting task	SDA-M + Putting task

Note: SDA-M (structural dimensional analysis of mental representation): the psychometric method for measuring the mental representation structure of golf putting; putting task: 15 putting trials after two warm-up trials

2.2.6.1. Pre-test

All participants participated individually in this experiment. A pre-test was carried out before beginning the experiment to evaluate the initial state of the mental representation structure and putting performance. Specifically, participants were asked to read and sign an informed consent form. Then, they were provided with an explanation regarding the splitting task and the meaning of each of the 16 BACs of the putt. The splitting task was conducted to measure the mental representation structure. After that, participants were required to perform two practice trials of golf putting followed by 15 test trials and try to putt the ball as close as possible to the target. After testing, participants were asked to complete the MIQ-R (Hall & Martin, 1997).

2.2.6.2. Experimental treatment

Participants in experimental groups took part in a training program for 3 days and performed 60 trials per day. In contrast, participants in the control group did not receive any training.

2.2.6.2.1. Action observation training group

Participants in the action observation training group performed 60 observational trials on each day of the practice phase. More specifically, they were requested to observe a video of a putting scene that showed putts completed by an expert golfer. The video was displayed with a first-person viewpoint of the expert model. A screen (1.5 × 1.5 m) was located in front of each participant. Participants were instructed to make a putting posture, and grasp the putter on the green as if they were performing the putting. Then, they were required to observe the putting scene as attentively as possible without actually performing it. There was a small break each time 20 observational trials were completed. The observational training was followed by the completion of a post-experimental questionnaire on how easily they observed the movement.

2.2.6.2.2. Motor imagery training group

Participants in the motor imagery training group conducted 60 mental trials on each day of the practice phase. Specifically, they were asked to imagine the full putting scene from the starting position on the green until the ball stopped on the target, without actually performing the putt, however. Their main task was to imagine the putting scene as clearly and vividly as possible, and for it to feel as real as possible, from their internal perspective. Participants were instructed to make a putting posture by grasping the putter on the green as if they were performing the putting. Then, they were required to imagine, with their eyes closed and at their own pace, that they raised one of their five fingers each time they completed the imagery of one putt. There was a small break after each time the imagery was performed 20 times. Following the mental training, participants completed a post-experimental questionnaire regarding how easily they imagined the movement.

2.2.6.2.3. Physical practice group

Participants in the physical practice group performed 60 physical trials for the putt on each day of the practice phase. Specifically, they were requested to putt the ball toward the positioned target that was 3 m away from the starting point, in such a way that the ball rolled and then stopped as close to the target as possible. The putting practice was conducted at their own pace, and there was a short break each time the putting was performed 20 times. No feedback was provided, except for the immediately visible outcome of each putt.

2.2.6.2.4. Control group

Participants assigned to the control group did not participate in any training for 3 days of the training period.

2.2.6.3. Post-test and retention-test

The post- and retention tests were administered the day after the end of the experiment, and 2 days after the post-test, respectively. The experimental protocol and the items measured were identical to those from the pre-test except for completing the MIQ-R in the pre-test.

2.2.6.4. Data analysis

2.2.6.4.1. Imagery ability

A one-way ANOVA was used independently for the kinesthetic imagery score, visual imagery score, and the combined score to examine whether there was a difference in imagery ability for basic body movements among the four groups.

2.2.6.4.2. Post-experimental questionnaire

ANOVA was used to compare the action observation training and the motor imagery training groups' results of the post-experimental questionnaire, which was performed during the 3 days of each treatment. Two-way ANOVAs (two cognitive training groups × three practice days) with repeated measures on the last factor were conducted to compare the difference between the ease of action observation and motor imagery. The significance level for data analysis was set at 5%.

2.2.6.4.3. Mental representation structure

Cluster analysis was conducted based on the data extracted from the splitting task, which aimed to assess not only how many significant clusters there were in the mean dendrogram by group and test session, but also how well-structured their relations were (e.g., Schack, 2012). The significance level for cluster analysis was set at 5%, which corresponded to a critical value of 3.41 (i.e., d_{crit} = 3.41). The critical value (d_{crit}) was displayed as the horizontal line on the dendrogram. The clusters below the line were considered statistically significant. Then, statistical analysis of invariance was performed to examine statistical differences in mental representation structure according to group and test session (e.g., Frank et al., 2013; Schack, 2012). For invariance analysis, a critical value was $\lambda = 0.68$. A value equal to or more than 0.68 (i.e., $\lambda \geq 0.68$) indicated that there was no difference (two cluster solutions were invariant), while a value less than 0.68 (i.e., $\lambda < 0.68$) indicated that there was change (two cluster solutions were variant). In addition, the Adjusted Rand Index (ARI; e.g., Santos & Embrechts, 2009) was calculated to evaluate the degree of similarity between a group dendrogram and a reference dendrogram, reflecting well the four phases of the golf putt (e.g., Frank et al., 2013). The value of ARI ranged from ''−1'' to ''1''. The value ''−1'' or ''1'' indicated ''completely different'' or ''completely same'' in terms of the degree of similarity, respectively.

2.2.6.4.4. Skill performance

MRE was calculated based on two-dimension coordinates of each putting trial, which reflected the accuracy of putting performance (e.g., Hancock et al., 1995). The calculated variable was analyzed by two-way ANOVAs (four groups × three test sessions) with repeated measures on the last factor. In addition, further analysis was conducted with a one-way ANOVA to investigate differences between test sessions by group, and vice versa. The significance level for all analyses was set at 5%.

2.2.6.4.5. Correlation

A two-tailed Pearson's correlation coefficient analysis was performed to investigate the relationship between the change of mental representation structure over time (i.e., from pre- to post- and retention test) and the change of skill performance over time. Adjusted rand index, which reflects the similarity between each individual's mental structure and the expert reference mental structure, and mean radial error, which reflects the accuracy of skill performance, were used for the analysis of the correlation. The significance level for all analyses was set at 5%.

2.3. Results

2.3.1. Imagery ability

The assessment result for general imagery ability showed that there was no main effect of group for the visual imagery score, $F(3,36) = 0.389$, $p = 0.762$, $\eta_p^2 = 0.031$, the kinesthetic imagery score, $F(3,36) = 0.366$, $p = 0.778$, $\eta_p^2 = 0.030$, and the combined score, $F(3,36) = 0.157$, $p = 0.925$, $\eta_p^2 = 0.013$. This meant that there was no difference among groups in imagery ability before the experiment began. Furthermore, the mean score for the three imagery variables was 5.80, 5.33, and 5.40, respectively. Specifically, each group scored an average of five points (i.e., somewhat easy to see or feel) or more, for visual, kinesthetic, and overall imagery scores. This indicated that each group had adequate imagery ability (e.g., Frank et al., 2014; Smith and Collins, 2004; Smith et al., 2008).

2.3.2. Post-experimental questionnaire

The analysis result for the ease of complying with the instruction showed that the main effect of group, $F(1,18) = 4.987$, $p = 0.038$, $\eta_p^2 = 0.217$ and practice day, $F(2,36) = 17.934$, $p = 0.000$, $\eta_p^2 = 0.499$, was significant, respectively. However, it was revealed that a significant interaction between group and practice day, $F(2,36) = 4.796$, $p = 0.014$, $\eta_p^2 = 0.210$, was also significant. For the post hoc test, the difference between groups by practice day (or vice versa) was analyzed. The result of the first post hoc test showed that on the first and second practice day, the score of the action observation training group was significantly higher than the score of the motor imagery training group for the ease of complying with the instruction ($p = 0.020$, $p = 0.017$). However, it was revealed that there was no significant difference between the two groups on the last practice day ($p = 0.458$). In addition, the result of the second post hoc test showed that for the action observation training group, the score of the second practice day had significantly increased compared to the score of the first practice day ($p = 0.045$), and such an increased score was maintained on the last practice day ($p = 0.157$). In contrast, for the motor imagery training group, it was shown that there was no significant difference between the first and second practice day ($p = 0.153$), whereas the score of the third practice day was higher than the score of the first ($p = 0.002$) and second practice day ($p = 0.032$).

2.3.3. Mental representation structure

2.3.3.1. Action observation training group

The cluster analysis showed that the number of statistically significant functional clusters had increased over the test sessions (see Figure 1.1.). More specifically, the clusters were (BAC 1, 2, 6), (BAC 8, 13), (BAC 9, 12), (BAC 10, 11) at the pre-test, (BAC 1, 2, 15), (BAC 3, 6), (BAC 10, 11) at the post-test, and (BAC 1, 2, 3, 6, 15), (BAC 8, 9), (BAC 10, 11), (BAC 12, 13) at the retention test. Furthermore, the invariance analysis was conducted to determine whether there was a statistically significant difference between the test sessions. The invariance analysis indicated that there was an evident significant difference between the pre- and post-tests ($\lambda = 0.37$), between the post- and retention tests ($\lambda = 0.42$), and between the pre- and retention tests ($\lambda = 0.48$). Lastly, to evaluate the degree of similarity between the mean dendrogram of the action observation training group and the reference dendrogram that was composed of four phases (i.e., preparation BACs 1–4, backswing BACs 5–7, forward swing BACs 8–11, and attenuation BACs 12–16), the ARI was calculated. The ARI analysis revealed that the similarity became higher over the test session, given that the ARI value ranges from −1 (i.e., completely different) to +1 (i.e., completely the same). Specifically, $\mathrm{ARI}_{\mathrm{pre}} = 0.05$, $\mathrm{ARI}_{\mathrm{post}} = 0.07$, and $\mathrm{ARI}_{\mathrm{retention}} = 0.10$ were shown at pre-, post-, and retention tests, respectively.

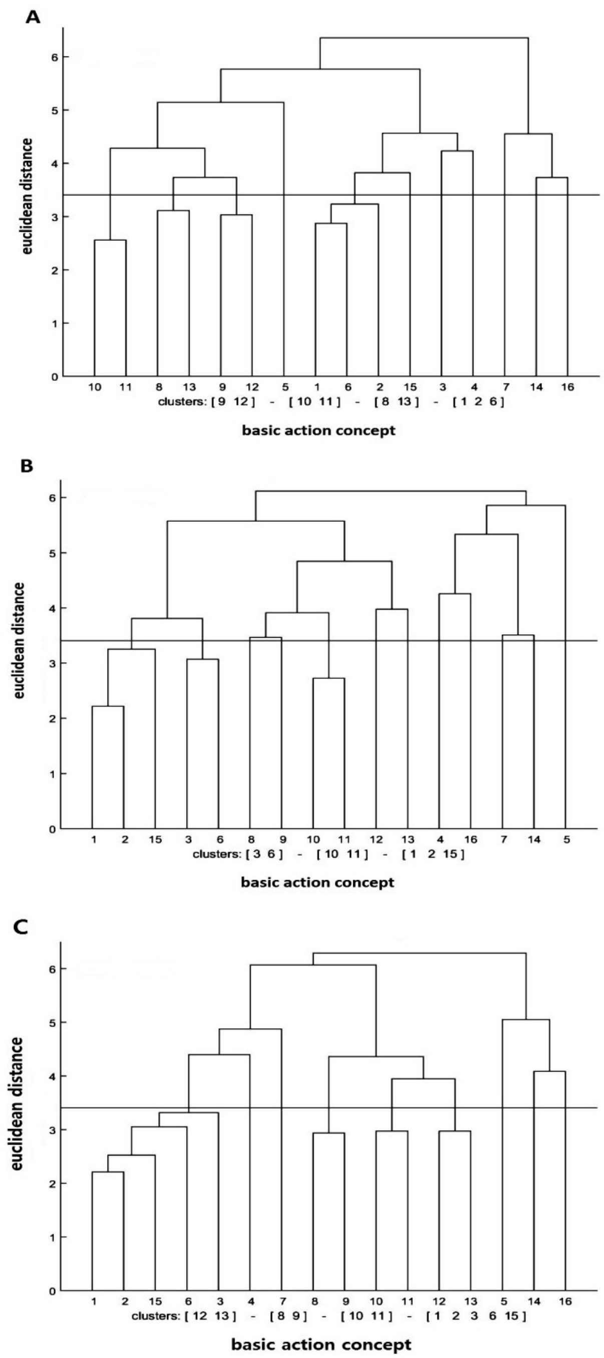


Figure 1.1. Mean dendrograms indicating mental representation structure of action observation training group at (A) pre-test, (B) post-test, and (C) retention test. The horizontal line indicates

the critical Euclidean distance. The critical value of the Euclidean distance ($d_{crit)}$) was 3.41 for an α level of 5%. The basic action concepts (BACs) above this line are considered not related. The underlined BACs below this line are considered functionally related to each other

2.3.3.2. Motor imagery training group

Similar to the result of the action observation training group, the cluster analysis of the motor imagery training group demonstrated that the number of statistically significant functional clusters had increased over the test sessions (see Figure 1.2.). More particularly, the clusters were (BAC 2, 6, 15), (BAC 4, 16), (BAC 7, 14), (BAC 8, 13) at the pre-test, (BAC 1, 2, 11), (BAC 4, 16), (BAC 8, 9) at the post-test, and (BAC 1, 6), (BAC 2, 3, 15), (BAC 7, 14), (BAC 8, 9), (BAC 10, 11) at the retention test. In addition, the invariance analysis showed that there was a significant difference between the pre- and post-tests ($\lambda = 0.33$), between the post- and retention tests ($\lambda = 0.33$), and between the pre- and retention tests ($\lambda = 0.30$). Lastly, the ARI analysis showed that the similarity between the mean dendrogram of the motor imagery training group and the reference dendrogram increased over the test sessions. Precisely, $\text{ARI}_{\text{pre}} = 0.01$, $\text{ARI}_{\text{post}} = 0.02$, and $\text{ARI}_{\text{retention}} = 0.04$ were displayed at the pre-, post-, and retention tests, respectively.

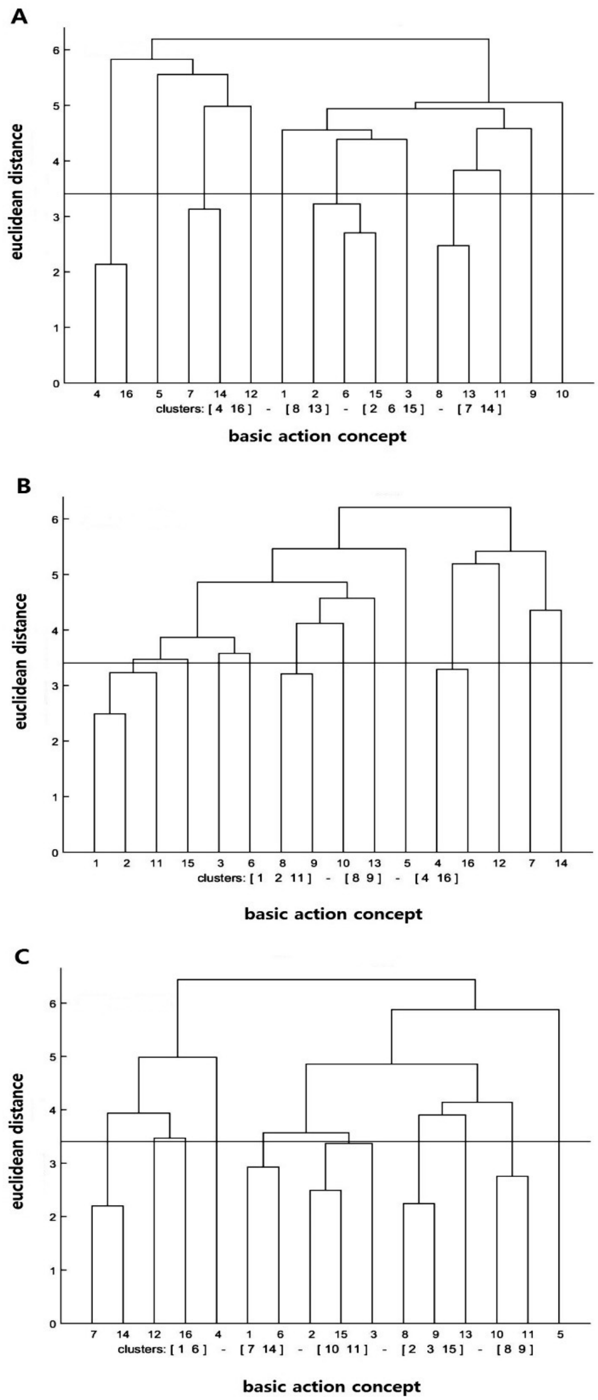


Figure 1.2. Mean dendrograms indicating mental representation structure of motor imagery training group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.41)

2.3.3.3. Physical practice group

The cluster analysis of the physical practice group revealed that the increase in the number of significant functional clusters was evident over the test session (see Figure 1.3.). In further detail, the clusters were (BAC 1, 2, 3, 4, 6, 15), (BAC 10, 13) at the pre-test, (BAC 1, 2, 3, 4, 6), (BAC 8, 9), (BAC 10, 11) at the post-test, and (BAC 1, 6), (BAC 2, 3, 4, 15), (BAC 8, 9), (BAC 10, 11, 13) at the retention test. Moreover, the invariance analysis demonstrated that there was a significant difference between the pre- and post-tests ($\lambda = 0.45$), between the post- and retention tests ($\lambda = 0.45$), and between the pre- and retention tests ($\lambda = 0.40$). Lastly, the ARI analysis showed that the mean dendrogram of the physical practice group and the reference dendrogram became more similar over the test sessions. Specifically, $\mathrm{ARI}_{\mathrm{pre}} = 0.08$, $\mathrm{ARI}_{\mathrm{post}} = 0.11$, and $\mathrm{ARI}_{\mathrm{retention}} = 0.13$ were shown at the pre-, post-, and retention tests, respectively.

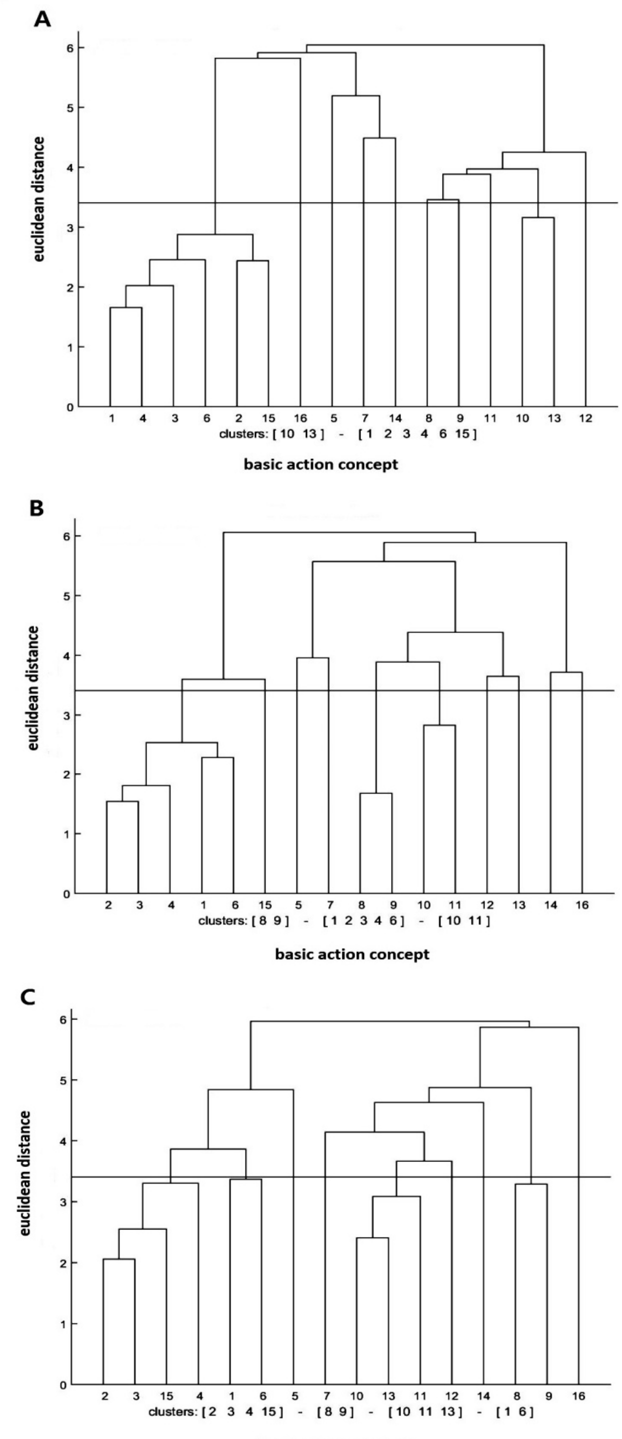


Figure 1.3. Mean dendrograms indicating mental representation structure of physical practice group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.41)

2.3.3.4. Control group

The cluster analysis of the control group revealed that the number of functional clusters had increased significantly over the test sessions (see Figure 1.4.). More specifically, the clusters were (BAC 1, 2, 3, 6, 15) at the pre-test, (BAC 1, 2, 3, 6, 15), (BAC 7, 14), (BAC 9, 10) at the post-test, and (BAC 1, 2, 3, 6, 15), (BAC 8, 9), (BAC 10, 11), (BAC 12, 14, 16) at the retention test. Furthermore, the invariance analysis revealed that there was a significant difference between the pre- and post-tests ($\lambda = 0.38$), between the post- and retention tests ($\lambda = 0.45$), and between the pre- and retention tests ($\lambda = 0.42$). Lastly, the ARI analysis demonstrated that the mean dendrogram of the control group became more similar to the reference dendrogram over the test sessions. To be exact, $\mathrm{ARI}_{\mathrm{pre}} = 0.02$, $\mathrm{ARI}_{\mathrm{post}} = 0.03$, and $\mathrm{ARI}_{\mathrm{retention}} = 0.07$ were revealed for the pre-, post-, and retention tests, respectively.

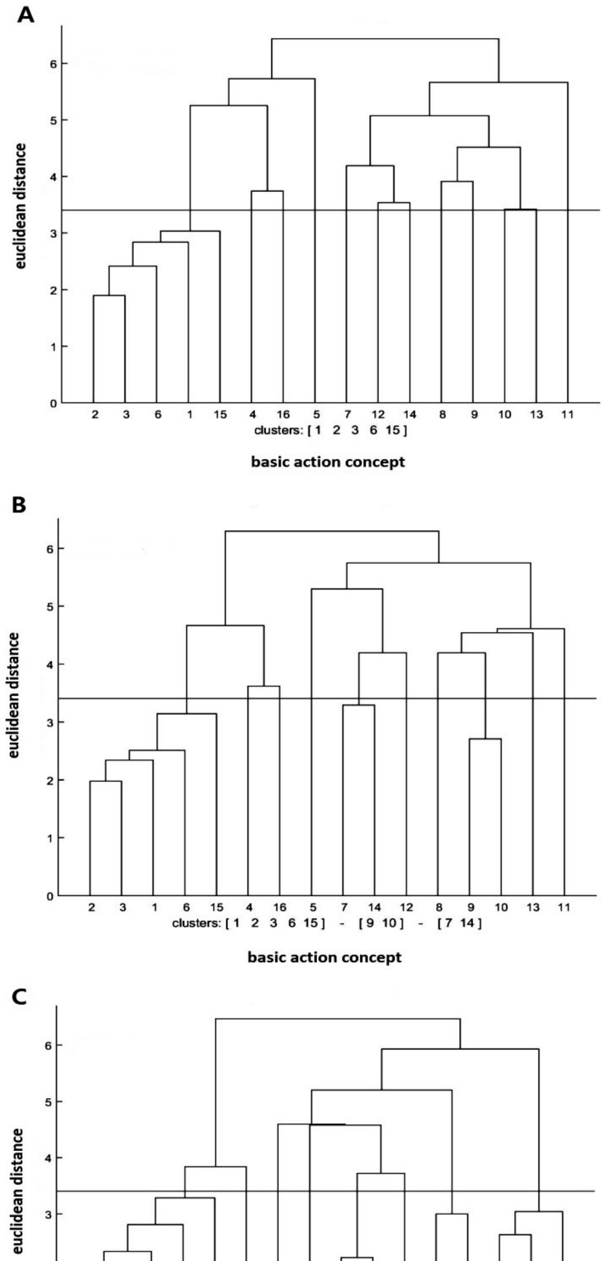


Figure 1.4. Mean dendrograms indicating mental representation structure of control group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.41)

2.3.4. Accuracy of performance

The analysis of the accuracy of putting performance revealed that the main effects of group, $F(3,36) = 4.583$, $p = 0.008$, $\eta_p^2 = 0.276$, and test session, $F(2,72) = 24.744$, $p = 0.000$, $\eta_p^2 = 0.407$, were significant, respectively (see Figure 1.5.). The result of the post hoc test on the main effect of the group showed that the physical practice group only performed significantly better than the control group, $p = 0.005$, $d = 1.25$, and that no significant differences were found among the AO training group, the MI training group, and the control group. In addition, the result of the post hoc test on the main effect of test session showed that the performance of the post-test, $p = 0.000$, $d = 1.03$ and the retention test, $p = 0.000$, $d = 1.06$, was significantly better than the performance of the pre-test, respectively, and that no significant difference was found between the post-test and the retention test. Moreover, the result of the post hoc test on the differences among test sessions by the group showed that the accuracy in the post-test of the AO training group, $p = 0.037$, $d = 0.96$, the MI training group, $p = 0.006$, $d = 1.50$, and the PP group, $p = 0.005$, $d = 1.55$, was significantly higher than the accuracy of the pre-test, respectively, and that such an improvement was maintained in the retention test. However, the control group did not show significant differences among the pre-test, the post-test, and the retention test, $p = 0.266$, $\eta_p^2 = 0.137$. In addition, the result of the post hoc test on the differences groups by test session showed that the accuracy of the AO training group, $p = 0.034$, $d = 0.97$, and the PP group, $p = 0.000$, $d = 1.56$, was significantly higher than the control group in the post-test and that the accuracy of the PP group, $p = 0.009$, $d = 1.26$, was significantly better than the control group in the retention test. For the pre-test, no significant differences in the accuracy were found among groups, $p = 0.587$, $\eta_p^2 = 0.052$.

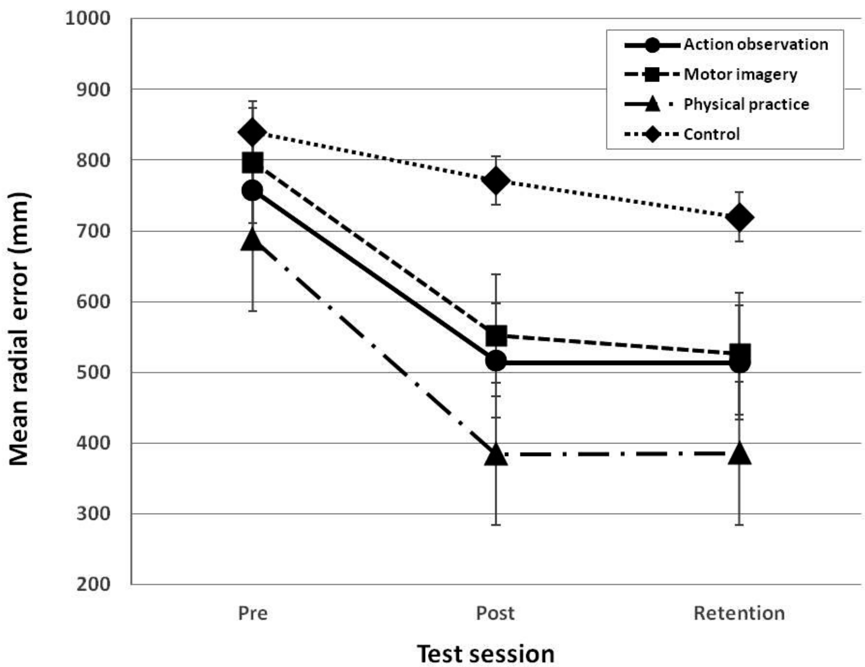


Figure 1.5. Mean radial error (MRE) across group and test session. MRE reflects the accuracy of the putting performance. Error bars indicate standard errors

2.3.5 Correlation

For the training groups (i.e., action observation training, motor imagery training, and physical practice), the Pearson correlation between ARI and MRE was significant, $r = -0.307$, n = 90, $p = 0.003$ (see Figure 1.6.). This indicates that the more elaborate the representation as shown by higher rand indices, the better the performance was as indicated by lower error scores. In addition, the correlation analysis for the action observation training group revealed that the Pearson correlation between ARI and MRE was significant, $r = -0.399$, $n = 30$, $p = 0.029$ (see Figure 1.7.). This also indicates that the relationship between mental representation structure and skill performance is positive for the action observation training group. However, for the motor imagery training group, $r = 0.010$, $n = 30$, $p = 0.956$, the physical practice group, $r = -0.241$, $n = 30$, $p = 0.200$, and the control group, $r = 0.135$, $n = 30$, $p = 0.477$, the Pearson correlation between the ARI and MRE was not significant.

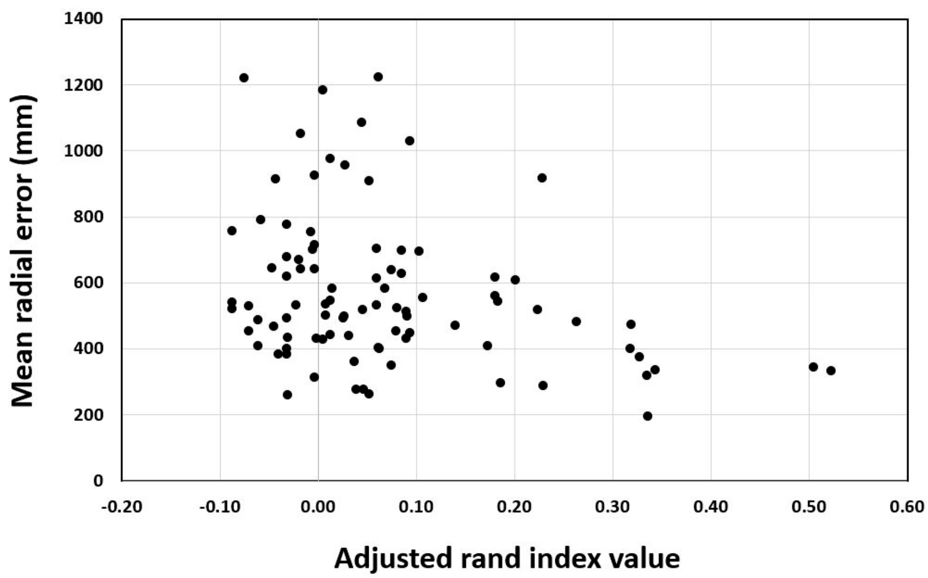


Figure 1.6. Pearson correlation between adjusted rand index and mean radial error over test sessions across all training groups

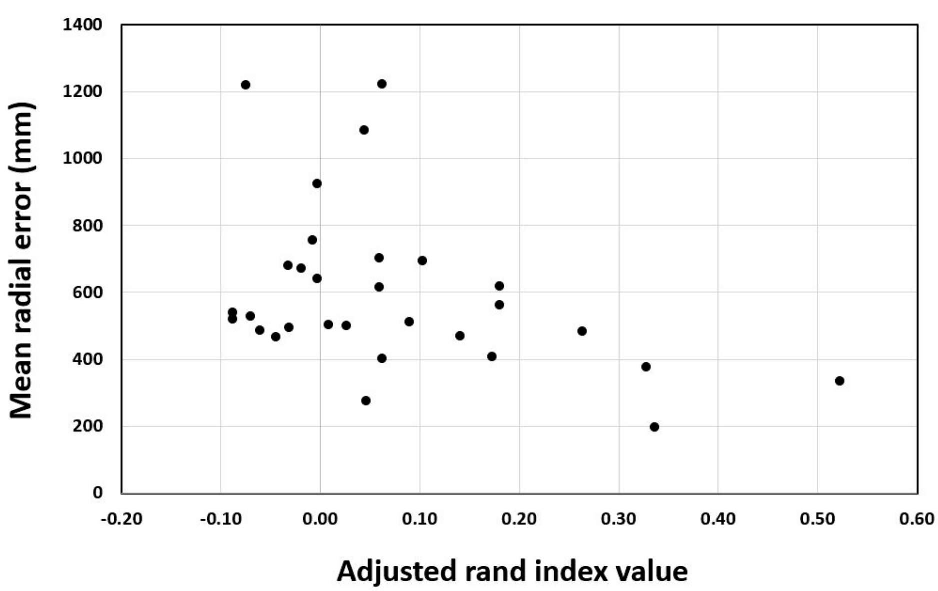


Figure 1.7. Pearson correlation between adjusted rand index and mean radial error over test sessions of the action observation training group

2.4. Discussion

The purpose of the present study was to investigate the influence of action observation training and motor imagery training on the development of mental representation, as well as the performance of motor skills. Specifically, this study was designed to compare the effects of the two cognitive training interventions for both mental representation structure and skill performance, as well as to examine the relationship between the change of mental representation structure and the change of skill performance. In this respect, the present study is an extension of previous research done by Kim, Cruz, & Ha (2011), which have studied the effect of action observation training and motor imagery training on skill performance. It was hypothesized that action observation training would be more effective than motor imagery training, both in the development of mental representation structure and in the improvement of skill performance in the early stage of skill learning. Furthermore, it was expected that the change in mental representation structure would be connected with the change in skill performance. The results of this study support the established hypothesis partially. To be specific, we could find some meaningful improvement in mental representation structure and skill performance over time through both action observation training and motor imagery training. In addition, it was found that changes in mental representation structure and skill performance were positively correlated for the action observation training group.

With regard to mental representation structure of golf putting, it was revealed that the mental representation structures of all practice groups (i.e., motor imagery, action observation, and physical practice) changed over time, leading to more elaborate and structured representations in the direction of the expert reference dendrogram, reflecting well the four-movement phases (i.e., BAC 1–4, BAC 5–7, BAC 8–11 and BAC 12–16; Frank et al., 2013). This result indicates that practice brings about functional changes of task-specific mental representation in long-term memory, which is in line with the results of recent studies on perceptual-cognitive changes (Frank et al., 2014, 2013; Frank, Land, & Schack, 2016).

Related to this, studies focusing on the neurophysiological mechanisms underlying motor imagery and action observation have shown that the two simulation states of action share certain neural representations (Conson, Sarà, Pistoia, & Trojano, 2009; Holmes, Cumming, & Edwards, 2010). For instance, brain regions such as the primary and the premotor cortex, the supplementary motor area, the cerebellum, and the basal ganglia tend to be activated not only during motor imagery but also during action observation in the absence of any overt action (Lorey et al., 2013). In this respect, the changes in mental representation structure in this study may be associated with changes in brain activation that may, in turn, be correlated with motor outcome. The extent to which each simulation state contributes to changes in motor learning-related brain areas, however, has yet to be determined (Frank & Schack, 2017).

Interestingly, it was revealed that the initial status of the mental representation structure differed somewhat between the groups. Specifically, (ARI_{pre} = 0.05, BAC 1, 2, 6; BAC 8, 13; BAC 9, 12; BAC 10, 11), (ARI_{pre} = 0.01, BAC 2, 6, 15; BAC 4, 16; BAC 7, 14; BAC 8, 13), (ARI_{pre} = 0.08, BAC 1, 2, 3, 4, 6, 15; BAC 10, 13), and (ARI_{pre} = 0.02, BAC 1, 2, 3, 6, 15) meaningful clusters (of golf putting) were shown for the pre-test in action observation training, motor imagery training, physical practice, and control groups, in that order. Meaningful clusters represent a group of BACs that are functionally or biomechanically related to movement components and phases for the achievement of action goals (Schack, 2012). Thus, this result indicates that even though participants actually had no previous performance experience with the task, the initial cognitive architecture of the mental representation may have varied depending upon the individual, suggesting that the initial dissimilarity of mental representation structure may lead to different effects for the development of mental representation and performance during the early motor learning phase. However, as Frank et al. (2014) indicated in their article, to date, it is not clear whether the slope of representation development is functionally related to the initial status of representation structure. The rate of change in representation is likely to be different because there are various representation structures in novices. Therefore, future studies should be undertaken to investigate differences in the development of mental representation and skill performance according to the degree of novices' initial representation structure for a better understating of this issue.

Contrary to our expectation, the mental representation structure of the control group developed over time as well. Specifically, (BAC 1, 2, 3, 6, 15) at the pre-test (ARI_{pre} = 0.02), (BAC 1, 2, 3, 6, 15), (BAC 7, 14), (BAC 9, 10) at the post-test (ARI_{post} = 0.03), and (BAC 1, 2, 3, 6, 15), (BAC 8, 9), (BAC 10, 11), (BAC 12, 14, 16) at the retention test ($ARI_{retention}$ = 0.07) were found respectively. The possible explanation for this result is that physical test trials executed during test sessions might have influenced the development of the mental representation structure.

With reference to the cognitive effect of the action observation training and motor imagery training, it was expected that action observation training, associated with a bottom-up mechanism, would be more effective than motor imagery training, associated with a top-down mechanism, in the development of a mental representation structure for novices in the early learning stage (see Holmes & Calmels, 2008 for details on potential mechanisms involved in observation and imagery). However, we could not compare the difference in mental representation structure objectively between the two cognitive training interventions, due to the difference between the initial representation structures. Nevertheless, the result of this study is meaningful in that task-specific representation structure can be developed through practice, which is especially relevant to the perceptual-cognitive perspective (Mechsner et al., 2001), and the cognitive action architecture approach (Schack, 2004), which emphasize the crucial role of mental representation for the generation and control of voluntary movements.

Regarding the ease of the use of the two types of cognitive training interventions, the present result of the post-experimental questionnaire showed that the use score of action observation was significantly higher than that of motor imagery by the second practice day, out of the three days in the practice period. This result indicates that action observation was easier to use than motor imagery for novices who had no previous task experience. For example, Soohoo, Takemoto, & Mccullagh (2001) compared the effect of observation and imagery on the performance of a squat lift skill. In their study, participants were instructed to choose and use their preferred method of the two types of cognitive training (i.e., action observation and motor imagery) for the fifth trial, after they performed the fourth trial of either observation or imagery in each predetermined group. The result of the study demonstrated that many participants preferred to watch the video of an expert model who performed the task. This result shows that novices prefer action observation to motor imagery during the early stage of skill learning. However, there are still individual differences associated with preference. Therefore, in future research, individual preference needs to be considered for the assignment of cognitive training groups.

Concerning performance outcome, first, before the practice phase, there was no difference in the accuracy among the four groups. After three days of training, the three practice groups (i.e., action observation training, motor imagery training, and physical practice group), except for the control group, significantly improved accuracy at the post-test compared to the pre-test. Moreover, such an improvement was maintained at the retention test. This is in line with the research result of (Kim et al., 2011) that investigated the difference in learning effect between action observation and motor imagery of golf putting. Thus, this result pattern supports the previous findings that not only physical practice, but also cognitive training such as action observation training or motor imagery training, can enhance motor skill acquisition and learning (Driskell et al., 1994; Hayes, Hodges, Huys, & Mark Williams, 2007; Schmidt & Lee, 2013; Wulf, Raupach, & Pfeiffer, 2005). In addition, like Frank, Land, Popp, and Schack (2014) mentioned in their article, which investigated functional links between motor memory and motor imagery, the relatively short length of practice may be one reason for the lack of differences among the groups in the performance of golf putting. Therefore, future research on this topic that employs golf putt task needs to consider a longer practice period to prevent possible confounds in statistic results.

Lastly, regarding the relationship between the change of mental representation structure and the change of skill performance, it was revealed that the change in mental representation structure of the training groups was positively related to the change in skill performance, with more elaborate mental representation being linked to better skill performance. This result indirectly supports the perceptual-cognitive perspective, which emphasizes the role of mental representation as a basis for the control of voluntary motor movements (Mechsner et al., 2001; Schack & Mechsner, 2006). Additionally, the positive relationship between the two variables by the group was found to be significant for the only action observation group. This result implies that the mental representation elaborated through action observation training might be more related to the execution of the motor system.

Taken together, the findings of this study provide insights into perceptual-cognitive and performance changes in the process of motor learning through cognitive training. This study is the first to compare the effect of action observation training and motor imagery training on both the development of mental representation and skill performance. Moreover, it is noteworthy that this study has demonstrated that the two simulation states of action led to both cognitive adaptation and skill improvement, and that action observation training resulted in the positive relationship between cognitive-perceptual and performance changes. However, the generalizability of these findings is subject to certain limitations. For instance, although this study was designed to compare action observation and motor imagery as objectively as possible, it was difficult to control all of the factors that can influence the effect of action observation and motor imagery, such as the possibility of imagery during observation or the initial representation status of participants. Thus, more research is required to confirm the findings of the present study. Regarding future research on action observation and motor imagery, future research might investigate the perceptual-cognitive and behavioral patterns of the combined training (i.e., AO + MI training) over the course of learning or relearning in motor skill learning and motor rehabilitation settings rather than their independent use (Eaves et al., 2016).

3. A FUNCTIONAL LINK BETWEEN MENTAL REPRESENTATION IN LONG-TERM MEMORY AND COGNITIVE PERFORMANCE IN WORKING MEMORY

This chapter is based on

Kim, T., Park, H., & Schack, T. (2019). A functional link between mental representation in long-term memory and cognitive performance in working memory. *Advances in Cognitive Psychology, 15*(1), 11-20. doi:10.5709/acp-0252-y

Abstract

Although there have been various attempts to identify the perceptual-cognitive mechanisms underlying the superior performance of skilled players over novices in sports, few studies have examined the relationship between mental representations and cognitive performance according to the skill levels of players. The purpose of this study was to investigate the functional link between mental representations in long-term memory and cognitive information processing ability in working memory by analyzing mental representation structure and cognitive performance according to skill level. Twenty male skilled and 25 male novice tennis players participated in this study. Structural dimensional analysis of mental representation was used to evaluate the mental representation structure of a tennis serve. In addition, cognition and movement chronometry was used to assess the cognitive performance of tennis serve in working memory. Results of the representational analysis showed that the similarity of the skilled players to the standard representation structure was higher than that of novices. Furthermore, results in cognitive performance showed that the skilled players had higher accuracy and shorter response time compared to the novices. Finally, a significant correlation between the adjusted Rand index and cognition movement chronometry accuracy was observed. Taken together, the mental representation structure and cognitive performance of the skilled players were superior to those of the novices, and mental representations were positively correlated with the accuracy of the cognitive information processing. These results imply that the degree of a functional connection between working memory and long-term memory may be used as a perceptual-cognitive factor to explain the improvement in performance.

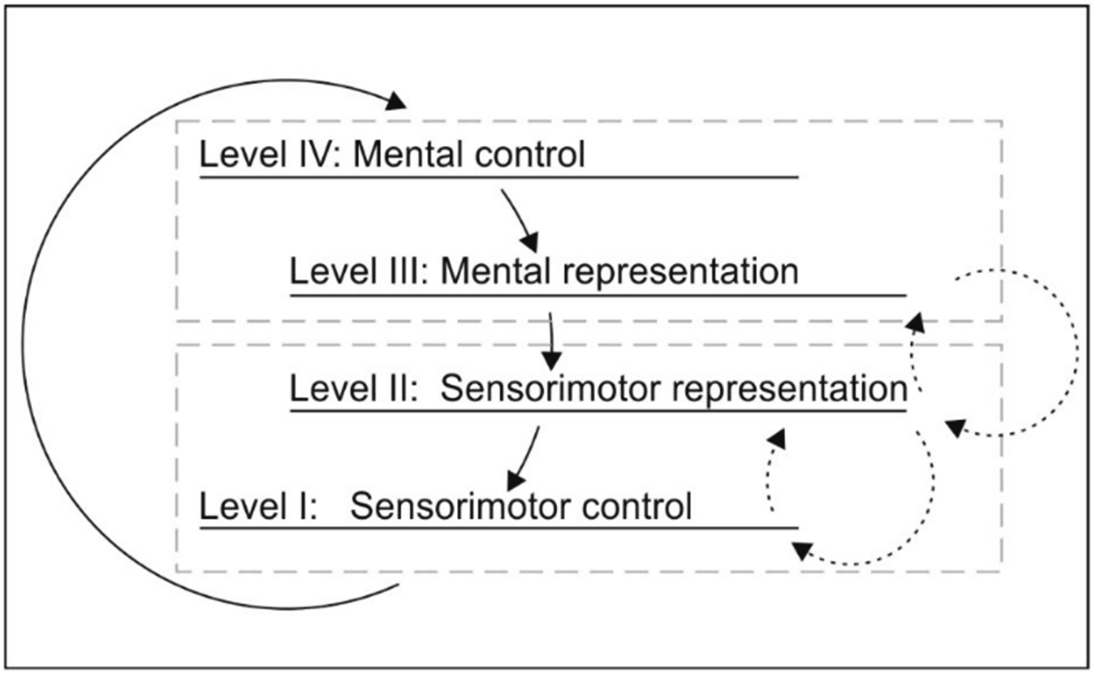
3.1. Introduction

Motor skill learning refers to a relatively permanent change in the ability to perform a given skill (Magill & Anderson, 2017). Such persistent change can be achieved through systematic and continuous training. Studies in the field of sports have shown that skilled performers are superior not only in performance but also in perceptual-cognitive capacity in comparison to novices (Del Villar, González, Iglesias, Moreno, & Cervelló, 2007; Thomas & Thomas, 1994; Ward, Ericsson, & Williams, 2013; Williams & Ericsson, 2005). Regarding perceptual-cognitive capacity, skilled performers have a superior cognitive processing ability to anticipate and make decisions by more quickly and efficiently finding, manipulating, and interpreting information related to task performance in the environment (Del Villar et al., 2007; Ericsson, 2003, 2007; Güldenpenning, Steinke, Koester, & Schack, 2013; Loffing & Cañal-Bruland, 2017; Thomas & Thomas, 1994; Ward et al., 2013; Williams & Ericsson, 2005). Taking this into account, the changes in perceptual-cognitive capacity may be considered as important learning variables that reflect the process of learning the movement. Indeed, as the systematic and continuous training progresses, the mental representational structure of long-term memory (LTM) becomes more elaborate and well-organized (Frank et al., 2014, 2013).

According to the perceptual-cognitive (PC) perspective (Bernstein, 1967), the planning and execution of motor actions are guided by the formation of cognitive representations based on perceptual information about these motor actions. Thus, the PC perspective assumes that cognitive representations and motor actions are functionally connected. The explanatory models supporting the PC perspective include the theory of event coding (Hommel et al., 2001), the action simulation theory (Jeannerod, 2001), and the cognitive action architecture (CAA) approach (Schack, 2004). The CAA approach (Schack, 2004) argues that mental representations are composed of basic action concepts (BACs), which are identified as representation units for motor actions. They play an important role in the planning and execution of motor actions. Specifically, the mental representations serve as a functional cognitive reference for controlling motor actions. In this respect, the CAA approach assumes that well-organized mental representations contribute not only to improving the performance of the motor output level but also to enhancing perceptual-cognitive performance. Previous studies have shown a functional relationship between mental representations and motor outcomes (i.e., skill performance; Kim, Frank, & Schack, 2017; Schack, 2003).

The CAA approach proposes that motor actions are hierarchically organized by the mental and sensorimotor systems (Schack, 2004; Schack & Hackfort, 2012). According to this model (see Figure 2.1.), the mental system consists of a mental control level and a mental representation level. The sensorimotor system consists of a sensorimotor representation level and a sensorimotor control level. Thus, motor actions have been proposed to be organized through these four levels hierarchically, from a high level (i.e., Level IV; mental control) to a low level (i.e., Level I; sensorimotor control). More specifically, at the mental control level, the initial goals and strategies of motor actions are established. At the level of mental representation, mental representations based on BACs serve as cognitive reference points for the execution of set goals and strategies. Then, at the level of sensorimotor representation, the specific sensorimotor representation acts as a perceptual reference, so that planned and prepared actions at the mental system are, in fact, output well. Finally, at the sensorimotor control level, motor actions are executed and the four levels are actively linked during execution. Of particular importance, the CAA approach emphasizes the function of the mental representational level of the mental system, which serves as a cognitive reference.

Figure 2.1. The levels of hierarchical organization of the motor action system during the early stages of learning (Adapted from Schack (2002), reprinted from Frank (2014))



At the mental representation level, BACs are representational units in LTM for motor control and are linked to functional and biomechanical demands of motor actions (Schack, 2004). Thus, more elaborate and well-structured mental representational structures are expressed as the relations between and functional groupings of meaningful BACs (Schack, 2012), and the mental representational structure of skilled players is more sophisticated and functionally organized than that of novices (Bläsing, Tenenbaum, & Schack, 2009; Schack & Mechsner, 2006). For example, Schack and Mechsner (2006) used the structural dimensional analysis of mental representation (SDA-M) method to investigate differences in mental representational structures according to differences in the expertise in motor skills. The result of the study showed that the mental representational structures of players with high-level expertise were more elaborate and well-organized than those of low-level players and beginners. This implies that the mental representation may serve as a cognitive reference for the control of motor actions. In fact, the mental representational structure has been shown to change to a more functional structure through physical or cognitive training (Frank et al., 2014, Frank et al., 2013; Kim et al., 2017). The results of such previous studies support the CAA approach, which emphasizes the role of such mental representations for action control.

Examining the mental representations of specific motor actions in LTM can help to track the extent of motor learning as well as identify problems with motor planning and control (Braun et al., 2007). The structural dimensional analysis (SDA) method of mental representations in LTM was originally developed by Lander and Lange (1996) for structuring and interpreting the relationships between concepts given in the field of cognitive psychology. Afterward, Schack (2001) adjusted this algorithm to analyze mental representations of motor actions in LTM, which is called the SDA-M method. This method allows for the identification of psychometric mental representations through the knowledge-based decision making for relationships between specific BACs, which are linked to functional and biomechanical components of motor actions (Schack, 2012). The SDA-M method has been primarily employed in the examination of the mental representation structure of actions in athletic domains such as windsurfing (Schack, 1999), ballet (Bläsing & Schack, 2012), golf (Frank et al., 2014; Kim et al., 2017), judo (Weigelt, Ahlmeyer, Lex, & Schack, 2011), tennis (Schack & Mechsner, 2006), climbing (Bläsing, Güldenpenning, Koester, & Schack, 2014), and soccer (Lex, Essig, Knoblauch, & Schack, 2015), among others.

Behavioral studies support the importance of action representations in the control and learning of motor actions (Bläsing et al., 2014; Bläsing & Schack, 2012; Braun et al., 2007; Frank et al., 2013; Kim et al., 2017; Lex et al., 2015; Schack, 2003). For example, Frank et al. (2013) examined the effect of physical training on the development of mental representation structure and the performance of golf putting. In this study, the training group not only showed a functional change of the mental representation structure but also an improvement in putting performance, while the control group showed no change in both variables. In addition, Schack (2003) identified a relationship between kinematic parameters and the mental representational structure for the twisting somersault of gymnastics. The results showed a significant correlation between these two variables. These findings support the hypothesis of the CAA approach that the control and learning of voluntary motor actions are planned and executed based on mental representations, and that the functional change of mental representations developed through training leads to a change in the motor output level, by acting as a cognitive reference (Schack, 2004).

The skill learning model (Fitts & Posner, 1967) argues that skill learning proceeds through three distinct learning stages. In the first stage (the cognitive stage), cognitive performance is required in working memory (WM) to process information such as how to perform tasks and remembering instructions. In the second stage (the associative stage), the association between specific cognitive stimuli and action responses is strengthened, and the need for WM capacity is gradually reduced. At the final stage (the autonomous stage), the cognitive attention capacity required for performing the skill is negligent. Thus, cognitive processing in the WM is especially required in the initial phase of the skill learning process, and it involves retrieving and using the representation of information related to the skills stored in the LTM (Furley & Memmert, 2010; Williams & Ericsson, 2005). It is important to examine the functional link between mental representations in LTM and the performance in WM because it highlights the perceptual and cognitive changes in the skill learning process. It also provides practical insights on the need to develop effective cognitive interventions, such as motor imagery or action observation, to facilitate skill learning.

Despite some previous studies supporting the CAA approach (Bläsing & Schack, 2012; Braun et al., 2007; Frank, Land, & Schack, 2016), there is still a lack of research supporting the link between mental representation level and motor output level. In particular, there has been little research into the relationship between the organization of BACs in LTM and cognitive performance, which reflects the processing efficiency of action information in WM. Therefore, in this study, we examined the relationship between the two parameters, as well as the difference in mental representation structure in LTM and cognitive performance in WM, according to differences in skill level. Based on the CAA approach, we hypothesized that if action representations play an important role as a cognitive reference in the planning and execution of intended motor actions, then skilled players would execute a better cognitive performance, with a more elaborate, well-organized mental representation structure compared to novices. Furthermore, we also hypothesized that there would be a link between mental representations and cognitive performance because mental representations were expected to work from the mental representation level to the motor output level.

3.2. Methods

3.2.1. Participants

Twenty male tennis players from a local university (M_{age} = 22.30 years, SD = 1.30) and twenty-five male novices with no prior experience in tennis (M_{age} = 21.84 years, SD = 1.57) took part in the present study. They were classified into skilled and novice groups. The average training period of the skilled players was 11.05 years. All participants gave their written consent indicating their agreement to participate in the study. Participants were required to self-report that they were healthy, and had no current cognitive and neurological problems. The experiment was conducted in accordance with the ethical standards stated in the 1964 Declaration of Helsinki.

3.2.2. Measures

3.2.2.1. Mental Representation Structure

The SDA-M was used to measure the mental representation structure. Schack (2012) modified the SDA (Lander & Lange, 1996) that is well established and used in cognitive psychology to identify the structure of relationships in a given set of concepts. The SDA-M method consists of four steps. The first step is a splitting procedure to obtain distance scaling data on the proximity between the representational units (BACs) associated with a particular motor action in LTM. The second step is a hierarchical cluster analysis that transforms the set of BACs into a hierarchical structure. The third step is a factor analysis to reveal the feature dimensions of the established representational structure. The fourth step is an invariant analysis to verify the differences between the established cluster solutions within and between groups.

In this study, eleven BACs for the tennis serve, described in a previous study, were used (Schack & Mechsner, 2006; see Table 2.1.). They were as follows: throwing the ball (BAC 1), forward movement of the pelvis (BAC 2), bending of the knees (BAC 3), bending of the elbow (BAC 4), upper body rotation (BAC 5), racket acceleration (BAC 6), whole-body stretch motion (BAC 7), hitting the ball (BAC 8), wrist flap (BAC 9), forward bending of the body (BAC 10), and follow-through with the racket (BAC 11). The BACs were classified into a preliminary phase, a striking phase, and a swing phase, with the phases differing from each other in functional and biomechanical aspects. BAC 1, BAC 2, BAC 3, and BAC 4 comprised the preliminary phase, BAC 5, BAC 6, BAC 7, BAC 8 comprised the striking phase, and BAC 9, BAC 10, and BAC 11 comprised the swing phase.

Accordingly, as a first step, a splitting task was performed in a laboratory setting to collect psychometric data on the representational distance between the selected BACs. Among the eleven BACs for the tennis serve action, two BACs were presented to participants in text form. One of the two BACs was presented in red text on the computer monitor as an anchor (i.e., the reference concept) and the other BAC was randomly presented in black text on the right side of the anchor. The participants were asked to judge whether the other concept (i.e., the one presented in black) was "functionally close" to the anchor concept while performing the movement. Functionally close refers to the mobilization of body segments and muscles for a specific goal, such as preparation, striking, or finishing during the execution of a motor action. With each BAC serving as an anchor, the remaining 10 BACs were randomly compared; each BAC served as an anchor once. Thus, in this way, participants were asked to make a total of 110 judgments (11 anchors × 10 comparisons). Subsequently, the sum (i.e., the algebraic sum) of the number of negative and/or positive decisions for a particular reference concept was determined. It was then transformed into Z values for standardization. Finally, they were merged into a Z-matrix to form the starting point for all further analysis. The SDA-M is a method to reveal the structure of representations by means of knowledge-based decisions in an experimental environment instead of asking for explicit statements regarding their mental representation structures.

In the second step, the Z-matrix was transformed into a Euclidean distance matrix using the average linkage method for hierarchical cluster analysis. This allowed the 11 BACs to form individual cluster solutions in a dendrogram. Each cluster solution was established by determining a critical Euclidean distance (d_{crit}), which served as the criterion for determining whether each cluster solution was significant at the 5% significance level on the y-axis of the dendrogram. Each cluster solution was located below or above the critical distance value. Clusters below the critical distance value were interpreted as significant.

The third step, a factor analysis, was not performed, because the feature dimensions of the mental representation structure were already predetermined as reference criteria in this study.

In the fourth step, an invariant analysis was performed using an invariant measure λ, which determines the structural invariance, to verify the structural homogeneity of cluster solutions between groups. Its value was determined by the number of pairwise cluster solutions, the number of concepts in the cluster solution, and the average number of clusters. The λ value ranged from 0 to 1, with 1 indicating the most identical structure of the two cluster solutions. In this study, the statistical threshold for invariance between two structures was set to 0.68, as prescribed by Lander (1991, 1992).

In addition, the analysis of the adjusted rand index (ARI; Rand, 1971; Santos & Embrechts, 2009) was used to verify the similarity between the representation structure of the predetermined standard and that of the novice or skilled group in this study. The ARI value ranges from -1 to +1, with +1 indicating that the two representation structures are identical, while -1 indicates that the two representation structures are completely different. The ARI analysis counters a limitation of the hierarchical cluster analysis. The hierarchical cluster analysis provides information on changes in specific representation structures established within and between groups, or within and between individuals. However, when the number of significant cluster solutions of two representational structures is similar, it does not provide numerical information on which cluster solutions are more elaborate or organized into the standard structure. The ARI analysis thus compensates for such a limitation by providing numerical information on the degree of similarity between the standard representation structure and the observed representation structure, here, of the novice and the skilled group. Additionally, as the number of significant cluster solutions increases and the value of ARI approaches +1, the mental representation structure becomes more elaborate and organized.

Table 2.1. Basic action concepts of the tennis serve action

Movement phase	**Number**	**Basic action concept**
Preparation	1	Throwing the ball
	2	Forward movement of the pelvis
	3	Bending of the knees
	4	Bending of the elbow
Strike	5	Upper body rotation
	6	Racket acceleration
	7	Whole body stretch motion
	8	Hitting the ball
Final swing	9	Wrist flap
	10	Forward bending of the body
	11	Follow-through with the racket

3.2.2.2. Cognitive Performance

A cognition movement chronometry (CMC) test was used to measure the accuracy and speed of information processing related to the tennis serve in WM. The CMC test was developed by Schack (2002) to expand an experimental paradigm developed by Sternberg (1969) to analyze the processing of memory in the field of cognitive psychology. Some of the 11 BAC images for the tennis serve performed by a tennis player were presented on a computer monitor. Participants were asked to remember the images, which appeared for 5s. The CMC test consisted of five levels. Participants were instructed to remember one BAC image at Level 1 and five BAC images at Level 5. After 5 s, the images disappeared from the screen, and eight of the 11 BAC images were presented one by one in random order on the monitor. Participants were asked to determine as quickly and accurately as possible whether each of the eight images, presented in a random order, was one of the images that they initially attempted to memorize. In this way, the same procedure was repeated five times from Level 1 (i.e., remembering one BAC image) to Level 5ive (i.e., remembering five BAC images). The CMC program was made using an open-source program (Mathôt, Schreij, & Theeuwes, 2012), and the accuracy and reaction time of each participant's judgments were measured and saved on a computer.

3.2.3. Procedure

This experiment was carried out individually for each participant, and all of the participants signed an informed consent form after hearing an outline of the experiment. Next, the splitting task was performed to measure the mental representational structure of the participants. For the splitting task, participants sat in a chair in front of a computer monitor. Then, after hearing explanations from the experimenter regarding the meaning of words comprising each of the 11 BACs for the tennis serve as well as the splitting task, they performed the task. There was no time limit because the participants had to make judgments based on the information stored in LTM. On average, this task took about 25 minutes to complete. Afterward, there was a 10-minute break. Participants then received instructions on performed the CMC test to measure cognitive performance. The CMC test was required to be performed as quickly and accurately as possible. It took approximately five minutes to complete the task. If the response time for each stimulus exceeded 10 s, the particular data for the participant was excluded from the analysis. The experiment was conducted in a quiet lab.

3.2.4. Data Analysis

3.2.4.1. Mental Representation Structure

A cluster analysis of the dendrogram was performed using the data collected from the splitting task. The purpose of the cluster analysis was to examine whether there were statistically significant clusters at the 5% significant level among the skilled or novice groups and to examine how well the mental representation structure of each group was organized (Schack, 2012). In the cluster analysis, a significance level of 5% corresponded to a critical value (d_{crit}) of 3.46 (i.e., d_{crit} = 3.46) for the horizontal line on the y-axis of the dendrogram. Thus, clusters that formed below the horizontal line were considered to be significant. In addition, the ARI was analyzed to assess the degree of similarity between the reference dendrogram, which reflected the three phases well (i.e., the preliminary, striking, and swing phases) and the dendrogram of the novice or skilled group (Santos & Embrechts, 2009). The larger the ARI value (from -1 to +1), the greater the degree of similarity between the reference dendrogram and the dendrogram of either the skilled or novice groups. Therefore, as the number of significant clusters increases and the ARI value approaches +1, the mental representation structure becomes more elaborate and organized in the direction of the standard representation structure. Further, an invariant analysis was conducted to analyze whether there was a difference in mental representation structure between the skilled players and the novices (Schack, 2012; Schack & Mechsner, 2006). For the invariant analysis, a critical value (λ) less than 0.68 (i.e., $\lambda < 0.68$) indicated a significant difference between the two groups, while $\lambda \geq 0.68$ indicated that there was no difference between the two groups.

3.2.4.2. Cognitive Performance

A one-way analysis of variance (ANOVA) was performed to test for a statistical difference between the skilled players and the novices for the accuracy and reaction time of the cognitive performance data collected through the CMC test. The average across Levels 1-5 was used. The significance level was set at 5%.

3.2.4.3. Correlation

A correlation analysis was performed to determine the relationship between the mental representation structure and cognitive performance using Pearson's r coefficient, with a two-tailed test. Specifically, the ARI value (described above), which reflects the similarity in clusters between the mental representation structure of the skilled players or novices and that of a standard reference, and the cognitive performance measures (i.e., accuracy and response time), which reflect the capacity of WM, were used for the analysis of the relationship between the parameters. The level of significance for all analyses was set at 0.05.

3.3. Results

3.3.1. Mental Representation Structure

The cluster analysis showed that statistically significant clusters appeared in both the novice and the skilled group (see Figure 2.2.). More specifically, the clusters were (BAC 1, 7), (BAC 2, 10), and (BAC 6, 8, 9, 11) for the novices, and (BAC 1, 3 5) and (BAC 6, 7, 8, 9, 11) for the skilled group. In addition, the ARI was used to assess the degree of similarity between the clusters for each group and the clusters for the standard dendrogram (i.e., the standard representation structure). The standard dendrogram consisted of three phases (i.e., preliminary, BACs 1-4; striking, BACs 5-8; and swing, BACs 9-11). The ARI analysis showed that the representation structure of the skilled players ($ARI_{skilled}$ = 0.48) was more elaborate and more similar to the standard representation structure than that of the novices (ARI_{novice} = 0.14). Lastly, the invariance analysis indicated that there was a significant difference between the groups (λ = 0.46).

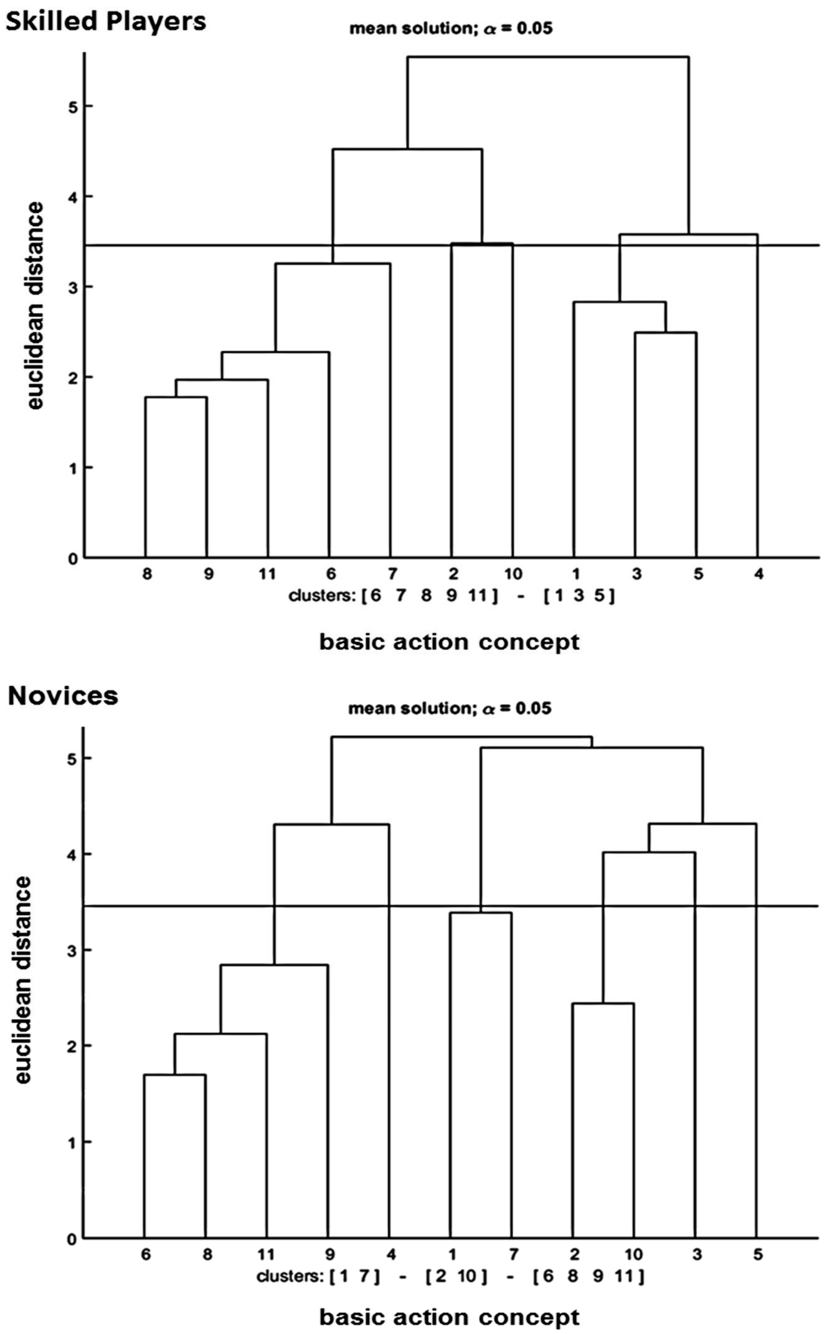


Figure 2.2. Mean dendrograms indicating the mental representation structure of the skilled players and novices. The horizontal line indicates the critical Euclidean distance. The critical value of the Euclidean distance (d_{crit}) was 3.46 at an α level of 5% (p<0.05). Clusters appearing below the horizontal line are statistically significant, while clusters above the horizontal line are not

3.3.2. Cognitive Performance

The analysis of the accuracy of the cognitive performance showed a significant effect of group (skilled players vs. novices) was significant, $F_{(1,43)}$ = 4.581, *p* = 0.038, *r* = .313 (see Figure 2.3.). According to the results of the post hoc test of the main effect, skilled players had significantly higher accuracy than the novices. In addition, the main effect of group was also significant in the analysis of the response time of the cognitive performance, $F_{(1,43)}$ = 18.054, *p* < .001, *r* = .538, (see Figure 2.3), and the post hoc test of the main effect results showed that the mean response time of skilled players was significantly shorter than that of the novices.

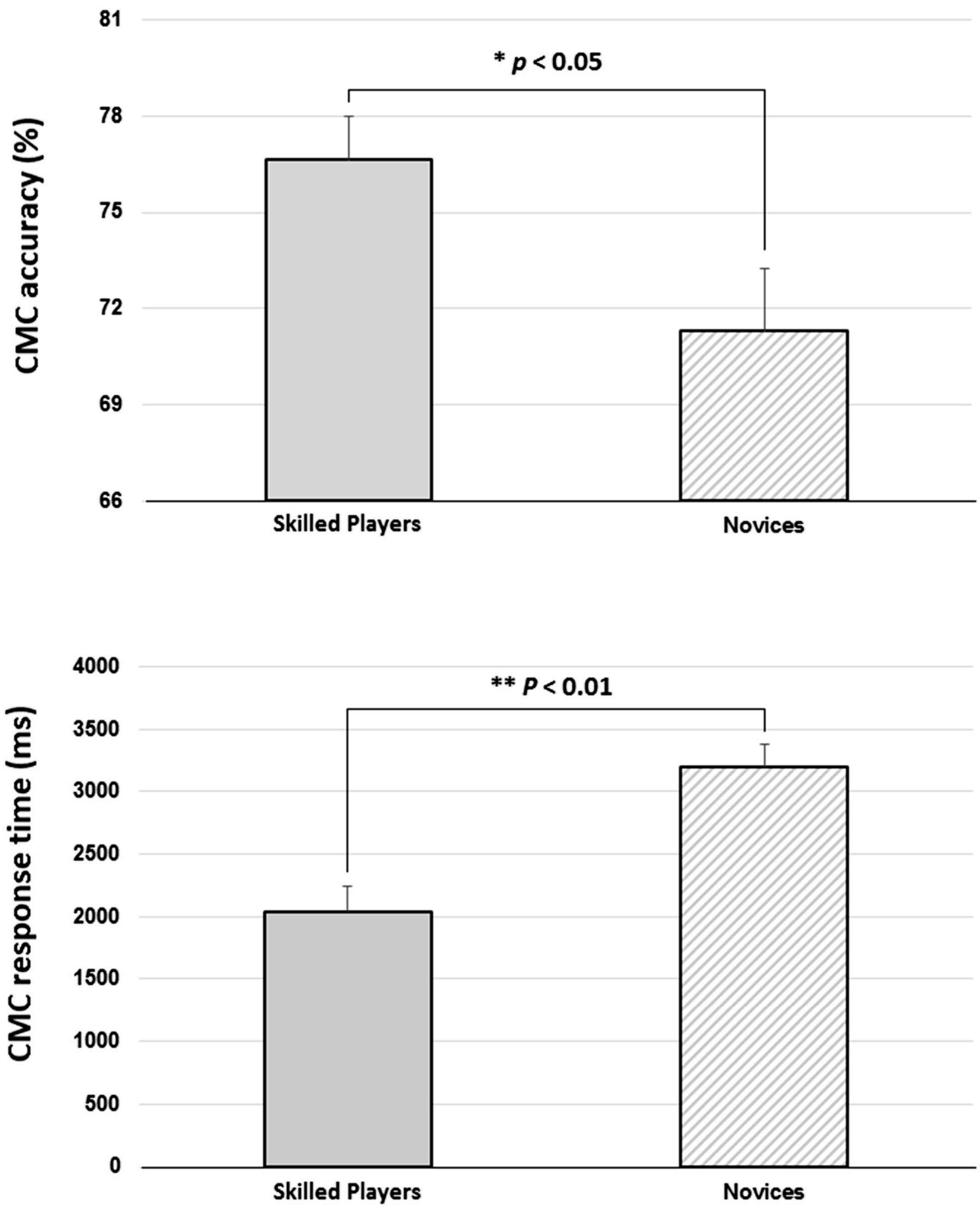


Figure 2.3. Accuracy and speed of cognitive performance by skill level. Error bars indicate standard errors

3.3.3. Correlation

The Pearson correlation analysis showed that the mental representation structure was positively correlated with the accuracy of the cognitive performance, $r = .415$, $p = .005$ (see Figure 2.4.). In contrast, the correlation between the mental representation structure and the speed of the cognitive performance was not significant, $r = -.244$, $p = .106$.

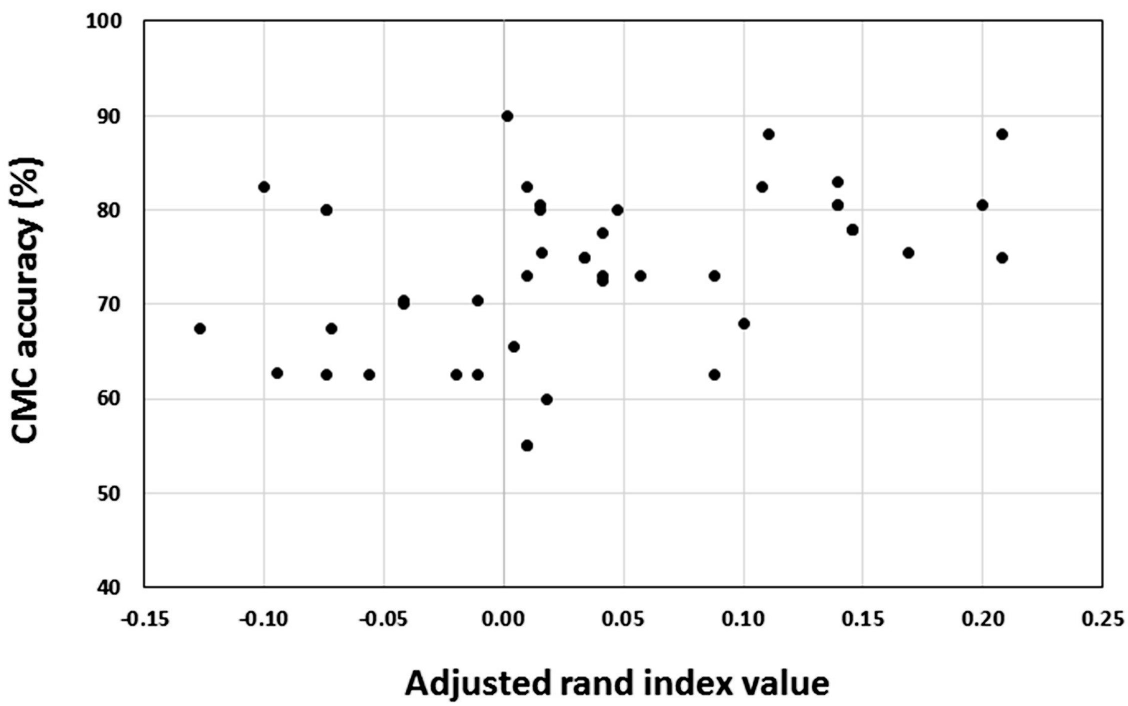


Figure 2.4. Pearson correlation between adjusted rand index and mean CMC accuracy across skill level

3.4. Discussion

The purpose of this study was to examine a functional link between mental representations and cognitive information processing by analyzing mental representational structures and cognitive performance according to skill level. We hypothesized that the mental representational structure and cognitive performance of skilled tennis players would be more elaborate and well-organized than in novices. In addition, it was hypothesized that the relationship between mental representations and cognitive performance would be functionally related. The results of the present study support this set of hypotheses. Specifically, the mental representation structures of the skilled players, stored in LTM, were more elaborate and well-organized than those of the novices. In addition, the cognitive performance of the skilled players was superior to that of the novices, and their mental representational structure in the LTM showed a positive correlation with the accuracy of the cognitive information processing in WM.

With regard to the mental representational structure of the tennis serve skill, the cluster and ARI analyses showed that the clusters of the skilled players' group were functionally better bundled, and the similarity with the standard reference, which reflected the three-movement phases well (i.e., BAC 1-4, BAC 5-8, and BAC 9-11), was also higher than that of the novice players group. As the value of ARI for the skilled group approached +1, compared to the novices, the mental representational structure of the skilled players in LTM was more elaborate and better organized (Kim et al., 2017; Rand, 1971; Santos & Embrechts, 2009). More specifically, this means that the BACs associated with the functional and biomechanical demands of the tennis serve skill were better structured and adapted in skilled players compared to novices. Therefore, this result suggests that skilled players can generate more accurate and consistent action representations than the novices, based on the skilled players' prior experience in the tennis serve skill.

According to the closed-loop theory of motor learning (Adams, 1971), in the early stages of motor learning, information about perceived errors in the last movement is used as the reference for error detection and correction in the ongoing movement. This reference is a memory of a past movement, which is also the basis of learning. This reference mechanism is called a perceptual trace or image. As the practice of a skill to be learned is repeated, feedback on each trial continues to function as a reference for the next trial, and the quality of the perceptual trace as a reference is also continuously enhanced. Thus, when a new skill is learned, there is almost no discrepancy between the reference and the ongoing performance. Considering the fact that perceptual images (i.e., mental representations) are strengthened when motor learning occurs, the result of this study, in which skilled players showed better organization of the mental representation structure than the novices, is supported by the closed-loop theory of motor learning.

The present findings are consistent with previous studies (Bläsing et al., 2014; Bläsing & Schack, 2012; Bläsing et al., 2009; Lex et al., 2015; Schack & Mechsner, 2006). For example, Bläsing et al. (2014) examined the effects of indoor rock climbing experience on the mental representational structure and perceptual judgment of task-related objects. The representation structures of experienced climbers were significantly better organized than those of untrained non climbers and were consistent with standard reference (specifically, the four climbing grip types). This result showed that motor expertise facilitates the development of precise action representations, and supports the above explanation.

In relation to cognitive performance, the accuracy and speed (i.e., response time) of cognitive performance were measured in the present study to examine the processing capacity of information related to the tennis serve action, as processed in WM. Our results show that the accuracy and speed of information processing were significantly better among the skilled players as compared to the novices. Indeed, there are differences in cognitive capacity between the skilled players and the novices. Previous studies using a cross-sectional research design have attempted to identify the characteristics that define a skilled player as compared to a novice (Del Villar et al., 2007; Gabbett & Abernethy, 2013; Güldenpenning et al., 2013; McPherson, 2000; Thomas & Thomas, 1994). These studies have reported that skilled players have more comprehensive knowledge than novices. Concerning their cognitive capacity, skilled players have a superior cognitive processing ability required to make decisions more efficiently than novices by finding, manipulating, and interpreting information related to task performance in the environment more quickly and accurately. (Del Villar et al., 2007; Ste-Marie, 1999; Thomas & Thomas, 1994). The results of this study, thus, support the results of previous studies that have shown differences between the skilled players and novices at the cognitive level.

The most interesting research question in this study was the relationship between mental representations and cognitive performance. The CAA approach proposed by Schack (2004) suggested that BACs, which are functionally connected with the elementary components of motor actions, are organized into a hierarchical cognitive representation structure in LTM. These representational structures serve as a cognitive reference for motor control and execution. In relation to learning, mental representations are functionally more organized and adapted through physical or cognitive training (i.e., action observation training or motor imagery training) during the skill learning process (Frank et al., 2014; Kim et al., 2017). For example, Kim et al. (2017) examined the effects of action observation training and motor imagery training on the development of the mental representation structure and the skill of golf putting. The results showed that the mental representational structure became more elaborate and golf putting improved after three days of training, in both cognitive training groups. These results also indirectly highlight the close relationship between mental representations and motor outcomes, as well as the importance of mental representations.

The present study examined the relationship between mental representation structure in LTM and cognitive performance, reflecting the processing of task-related information in WM. It was revealed that there was a significant positive correlation between mental representation structure and accuracy of cognitive performance. This result indicates that as the mental representational structure becomes more elaborate, the accuracy of the information processing in WM increases. In this regard, the present findings provide evidence that mental representation is deeply involved in the efficiency of the cognitive decision process for the control of voluntary motor actions.

In this study, however, there was no significant correlation between mental representation structure and speed of cognitive performance. Although there is a difference in degree, the trade-off between speed and accuracy is well known in the performance of motor skills (Etnyre, 1998; Fitts, 1954; Indermill & Husak, 1984; Schmidt, Zelaznik, Hawkins, Frank, & Quinn 1979). That is, emphasizing speed decreases accuracy, and vice-versa. Participants in this study were instructed to perform the cognitive task as quickly and accurately as possible. In the situation where both speed and accuracy are required, participants are likely to prioritize information related to the accuracy, because they have to remember visual stimuli and process the task. Hence, the relationship between mental representations and cognitive accuracy would have been strengthened more than the relationship between mental representations and cognitive speed, even though it was revealed that skilled players had superior mental representations, accuracy, and speed of cognitive performance than novices. Therefore, the findings of this study imply that accuracy may be prioritized if the instructions for speed and accuracy are simultaneously required in the performance of cognitive-motor tasks involving visual components.

The generalizability of these results is subject to certain limitations. None of the participants reported neurological or cognitive problems, but individual differences such as initial mental representation, cognitive ability, and intelligence may have had some effect on the outcome of the experiment. Therefore, in the future, it is necessary to experiment with eliminating participants who show extreme individual differences that can affect the results through a preliminary analysis.

The current study thus provides insight into the importance of perceptual and cognitive aspects, as well as typical changes in motor performance in the motor learning process, by highlighting the differences in mental representations and cognitive performance according to the players' skill level. In particular, the functional link between mental representations and cognitive performance suggests the importance of mental representation level in the skill learning process. In this respect, the findings of this study call for the study of cognitive interventions such as motor imagery and action observation, which promote the formation of mental representations (Frank, Kim, & Schack, 2018; Frank et al., 2014). In addition, the findings of this study have a practical implication, in that it may be effective for practitioners to construct a program so that learners can form mental representations of skills to be learned in the initial skill learning stage.

Taken together, the present study investigated the functional link between the action representations of LTM and the cognitive performance of WM. Firstly, it was revealed that the mental representation structure of skilled players was more elaborate and better organized than that of novices. Secondly, the cognitive performance (i.e., accuracy and speed) of skilled players was shown to be superior to novices. Thirdly, it was found that there was a positive correlation between the mental representation structure in LTM and the accuracy of information processing in WM. Therefore, the findings from the present study suggest that the functional relationship between the mental representation of LTM and the cognitive process of WM exists. However, such a claim must be further substantiated. To this end, it is worth examining in future studies the relationship between mental representation, cognitive performance, and skill performance during skill learning.

4. THE EFFECT OF ALTERNATE TRAINING OF ACTION OBSERVATION AND MOTOR IMAGERY ON COGNITIVE AND SKILL PERFORMANCE

This chapter is based on

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Abstract

The purpose of this study was to investigate the effect of alternate action observation and motor imagery training on cognitive performance in working memory and skill performance. Forty-eight beginners with no experience in Taekwondo participated in the experiment. They were randomly assigned to one of four groups: action observation (AO) training group, motor imagery (MI) training group, alternate AO+MI training group (i.e., MI after AO), and a control group. Cognitive performance was measured before and after three days of training, and one day after completion (retention test). After the retention test, all participants performed three blocks of Taekwondo roundhouse kick. Results showed that alternate AO+MI training overall was more effective in improving cognitive performance and skill performance after cognitive training than independent AO and MI training. Taken together, the findings suggest that alternate AO+MI training may be considered a more effective training method as compared to AO and MI training alone.

4.1. Introduction

Action observation (AO) and motor imagery (MI) are simulation states of action (Jeannerod, 2001) that are functionally equivalent to action execution (Filimon, Nelson, Hagler, & Sereno, 2007; Grezes & Decety, 2001; Lotze et al., 1999). Along these lines, AO training and MI training have been used as effective cognitive training methods facilitating motor performance and learning (Driskell, Copper, & Moran, 1994; Ste-Marie et al., 2012).

Action observation refers to a dynamic state that simulates the observed actions and outcomes through the observation of actions performed by other people (Sale et al., 2014). In particular, in the early stage of skill learning, action observation goes through external stimulus-oriented processing because the information source required for the formation of action representations is provided by external stimuli away from the body (Eaves, Riach, Holmes, & Wright, 2016; Holmes & Calmels, 2008). External stimuli through such action observation influence the formation of action representations and changes in neurophysiological factors (Grezes & Decety, 2001; Kim et al., 2017). Actually, action observation training has been typically used as an effective cognitive training method for the change of social behaviors as well as improvement of motor skill, strategy, and mental preparation (see meta-analysis by Ashford, Bennett, & Davids, 2006; Bandura, 1986; see Ste-Marie et al., 2012 for review).

Motor imagery refers to rehearsing motor actions mentally without overt physical execution (Jeannerod & Decety, 1995). Motor imagery is subjected to an internal stimulus-oriented process that depends on the internal stimulus of the body since action representations are formed based on the action information in long-term memory (Holmes & Calmels, 2008; Kim et al., 2017). The mechanism of such motor imagery affects not only neurophysiological factors but also the formation of action representations (Decety, 1996; Frank, Land, Popp, & Schack, 2014). Motor imagery training has also been used as an effective cognitive training to enhance the performance and learning of motor skill (see meta-analysis by Driskell et al., 1994; Feltz & Landers, 1983; see Mizuguchi, Nakata, Uchida, & Kanosue, 2012; Murphy, 1994 for review).

Recently, neurophysiological studies on the simultaneous use of AO and MI (AO+MI) showed that the simultaneous AO+MI condition increased the activation of motor-related brain regions and enhanced motor output more than AO condition or MI condition alone (Eaves, Behmer,

& Vogt, 2016; Taube et al., 2015; Wright, Williams, & Holmes, 2014). AO goes through the process of external stimulus-oriented bottom-up, in which the information source needed for the formation of action representations is provided externally (Holmes & Calmels, 2008). On the other hand, MI is involved in the processing of the internal stimulus-oriented top-down, in which the information source necessary for the formation of action representations is internally generated (Holmes & Calmels, 2008). In this regard, for beginners who have not had previous task experience, it may be difficult to expect a learning effect through MI since there is no action information stored in long-term memory, which is necessary for motor planning and execution (Mulder et al., 2004). In addition, the effectiveness of AO may be reduced by having difficulty in forming action representations due to the lack of intent to memorize or imitate (Wright et al., 2016). Given these points, MI during AO may be a way to complement those limitations. Specifically, AO provides visual information about the task needed for MI. As such, MI may contribute to enhancing the intent to remember or imitate during AO. Regarding simultaneous AO+MI, recent works suggested that simultaneous AO+MI training may work more effectively in the early stages of motor skill acquisition than AO or MI training alone (Eaves et al., 2016; Vogt, Rienzo, Collet, Collins, & Guillot, 2013).

However, it is likely that the activation of increased motor-related brain regions during simultaneous AO+MI was actually due to some degree of rotation or transformation of the observed images for MI, rather than functional activities related to the execution of the action (Eaves et al., 2016). As a way to reduce the cognitive confrontation of such simultaneous AO+MI to carry out motor imagery whilst observing, alternate AO+MI that perform AO followed by MI may be considered an effective training schedule. More specifically, learners first perceive the information related to task performance from the outside through AO. More specifically, the learners perform MI after sufficient preparation for the rotation or the transformation of the observed images necessary for MI. As such, learners can concentrate their attention more effectively that needs during MI. The repetition of such a process is expected to contribute to the elaboration of mental representations and increase the efficiency of cognitive activities. Despite this possibility, the effectiveness of alternate AO+MI training has not been systematically tested.

Given that the neural activity of the brain is related to the functional activity of mental representations (DeCharms & Zador, 2000), increased neural activity through AO+MI training may indicate a functional enhancement of mental representations. According to the perceptual-cognitive perspective (Hommel et al., 2001; Zentgraf et al., 2009) and cognitive action architecture (CAA) approach (Schack, 2004), mental representations of motor actions stored in long-term memory serves as a cognitive reference like a mental blueprint that guides the execution of actions by engaging in the planning and control of intended motor actions. In particular, from the CAA's viewpoint, the basic action concepts, which are units of action representations linked to the functional and biomechanical demands of motor movements at the level of mental representation, are hierarchically structured and closely linked to the sensory-motor system. It is more likely that the more elaborate the mental representations composed of the conceptual building blocks, the basic motion concepts, the better the motor outcome. Indeed, the mental representations of experts were shown to be more elaborate and well organized than those of beginners (Bläsing, Güldenpenning, Koester, & Schack, 2014; Bläsing & Schack, 2012; Bläsing, Tenenbaum, & Schack, 2009; Lex, Essig, Knoblauch, & Schack, 2015). In addition, in the early stage of motor learning, the mental representational structures of beginners are functionally adapted through physical training or motor imagery training (Frank et al., 2014, 2013, 2016).

In terms of mental representations in long-term memory, motor learning can be considered a continuous and functional change of perceptual-cognitive representations. Some previous studies have examined the effect of AO training or/and MI training on the development of mental representation structure and skill performance in the early motor learning stage (Frank et al., 2018b, 2014; Kim et al., 2017). In addition, working memory is responsible for keeping task information temporarily, retrieving information stored in long-term memory, or integrating and processing information to suit the current situation (Baddeley, 2003; Daneman & Carpenter, 1980). In terms of the capacity of working memory in relation to motor learning, the cognitive ability to quickly and accurately interpret and process important information related to action execution in working memory is improved as the learning process progresses (Ste-Marie, 1999; Thomas & Thomas, 1994). In this respect, changes in long-term memory and working memory are likely to be connected, reflecting the process of skill learning.

There have been a few studies examining the changes in mental representation structure according to AO or MI training (Frank et al., 2018b, 2014; Kim et al., 2017). To date, however, no studies have investigated the effect of alternate AO+MI training on cognitive performance in working memory and skill performance. In this study, we extended the study of Kim et al. (2017), which compared the effect of AO training and MI training on the development of mental representation structure and skill performance. Specifically, based on the neurophysiological evidence of simultaneous AO+MI and the discussion on an effective combination of AO and MI (see Eaves et al., 2016 for review), we examined the effect of alternate AO+MI training on the improvement of cognitive performance in working memory and skill performance. In this study, it was hypothesized that alternate AO+MI training would lead to greater improvement in the cognitive performance as well as in the skill performance compared to independent AO and MI training since it was expected that AO and MI would complement each other's strengths and weaknesses as mentioned above. In addition, we were interested in a relationship between changes in cognitive performance and changes in skill performance according to different training methods (i.e., AO, MI, alternate AO+MI). Finally, for skill development, we hypothesized that the performance would develop more after cognitive training as compared to no training (Frank et al., 2018).

4.2. Methods

4.2.1. Participants

Forty-eight participants (36 females, 12 males; M_{age} = 26.38, *SD* = 5.10) were recruited from the local university. The participants were all novices with no previous experience in Taekwondo. They were randomly assigned into four groups according to the statistical random table using sequence and gender: action observation (AO) training group (n = 12, M_{age} = 25.17, *SD* = 4.00, 3 males), motor imagery (MI) training group (n = 12, M_{age} = 25.08, *SD* = 3.11, 3 males), alternate training group of AO and MI (n = 12, M_{age} = 28.00, *SD* = 6.37, 3 males), no training group (n = 12, M_{age} = 27.25, *SD* = 6.15, 3 males). The study was performed in accordance with local ethical guidelines and the ethical standards of the Helsinki Declaration. All participants signed informed written consent prior to participation in the study.

4.2.2. Measures

4.2.2.1. Imagery Ability

The revised version of the Movement Imagery Questionnaire (MIQ-R; Hall & Martin, 1997) was used to determine if participants had adequate visual imagery ability and kinesthetic imagery ability to participate in cognitive training. The MIQ-R is composed of eight items, four items for visual imagery ability and four items for kinesthetic imagery ability, with high internal reliability (Monsma et al., 2009). For each of the items, participants executed each of the movements themselves watching one of the eight movements described in the questionnaire on the monitor. Then they were instructed to imagine the movement visually or kinesthetically without any physical movement. Subsequently, participants were asked to rate how easy the visual or kinesthetic imagery was on a Likert scale, ranging from 1 (i.e., very difficult to see or feel) to 7 (i.e., very easy to see or feel).

4.2.2.2. Cognitive Performance

As a measure of working memory, the cognition movement chronometry (CMC) test was used. Schack (2002) developed the CMC test to expand an experimental paradigm developed by Sternberg (1969) in cognitive psychology to sports psychology. In the present study, the CMC test provided data on processing speed and accuracy of information about Taekwondo roundhouse kick in working memory. More specifically, eight Taekwondo roundhouse kick stills were selected based on the basic action concept, which is distinguished from each other functionally and biomechanically. The selected stills were the Taekwondo roundhouse kick participants watched, but the model was different. The purpose of this task was to evaluate how quickly and accurately the participants perceive and judge randomly presented stills. Participants were asked to memorize the images for five seconds. After five seconds, the presented images were not visible on the screen. Subsequently, the eight images were presented on the screen one by one in random order. Participants were asked to judge as quickly and accurately as possible whether each of the presented images belongs to those that they had attempted to memorize for five seconds. Specifically, participants were instructed to press the left or right key on the keyboard as quickly and accurately as possible when the images were presented on the computer screen. Their accuracy and response time were automatically stored on the computer. The same procedure was repeated five times from level one to level five, with an increasing number of images to be memorized (i.e., level one: one image; level five: five images). The CMC test program used in this experiment was created by an open-source experiment builder (Mathôt et al., 2012) to track the accuracy of the judgment and the response time.

4.2.2.3. Skill Performance

All participants performed ninety trials of Taekwondo roundhouse kick over three blocks. Their performance was video-recorded. Two experts from South Korea with 5th Dan black belt (i.e., more than ten years of experience) in Taekwondo watched the recorded scenes and rated the accuracy of the performance according to specific criteria (see Table 3.1 for rating criteria). The two raters were kept blind regarding the identity of the group and test block, and the recorded video clips were provided in random order. The Taekwondo roundhouse kick was divided into preparation step, kicking step 1, kicking step 2, and finishing step. Each step was scored from a minimum score of 1 (very poor) to a maximum score of 5 (very good).

Table 3.1. Evaluation criteria for the Taekwondo roundhouse kick (Lee, 2006)

Action phase	**Assessment items**				
	Very good	**Good**	**Moderate**	**Poor**	**Very poor**
	5	**4**	**3**	**2**	**1**
Preparation	1. The left foot is stepped toward a target 2. Both knees are bent about 15 degrees 3. The right pelvis and shoulders are angled 45 degrees toward a target 4. Both fists are placed in front of the chest 5. The gaze is toward a goal				
Strike 1	1. The right heel is lifted from the ground 2. The left supporting sole does not move on the ground 3. The right shoulder and pelvis simultaneously rotate 110 degrees toward a target 4. Both arms do not go far beyond the centerline of the torso 5. The upper body is not bent				
Strike 2	1. The supporting left heel rotates counterclockwise by 160 degrees 2. The right foot and knee are folded close to the knee of the left support foot 3. The right knee that kicked is kneeling down inside and the pelvis and torso rotate forward 160 degrees at the same time 4. The knee and ankle are extended at the same time as turning to a target 5. The hip does not fall back, and the instep is extended at a 130-degree angle				
Recovery	1. The kicking foot is pulled and folded forward the support foot 2. The landing of the kicking foot is one step ahead 3. The spacing of the feet after landing is not too wide or narrow 4. The fists of both arms are located in front of the chest 5. The gaze is toward a goal				

4.2.2.4. Post-Experimental Questionnaire

Participants in the training groups during the three-day training period were asked to complete a post-training questionnaire after each day's training. The main purpose of the post-training questionnaire was to examine participants' motivation and the ease to perform the training according to the instructions. In other words, the main purpose of the questionnaire was to exclude data from participants who had very low motivation and very high difficulty based on the scores of the questionnaire. Specifically, participants were asked to respond on 7-point Likert scales indicating their level of motivation during the training (i.e., 1 = very demotivated, 7 = very motivated, "How motivated did you feel during the practice") and how easy or difficult it was to perform the training (i.e., 1 = very easy, 7 = very difficult, "How easy was it for you to perform action observation or motor imagery or alternate action observation and motor imagery").

4.2.3. Procedure

The procedure of this study included a pre-test, a treatment period, a post-test, and a retention test (see Table 3.2.).

Table 3.2. Experimental procedure by group and measurement time

Group	Pre-test Day 1	Training Day 2 Day 3 Day 4	Post-test Day 4	Retention test Day 5
Alternate AO+MI (n = 12)	CMC MIQ	AO+MI training 90 times per day (AO 45 + MI 45)	CMC	CMC Skill test
AO (n = 12)	CMC MIQ	AO training 90 times per day	CMC	CMC Skill test
MI (n = 12)	CMC MIQ	MI training 90 times per day	CMC	CMC Skill test
Control (n = 12)	CMC MIQ	No training	CMC	CMC Skill test

Note. CMC (Cognition and Movement Chronometry): the psychometric method for measuring the accuracy and speed of cognitive performance. MIQ (Movement Imagery Questionnaire): the imagery questionnaire to assess visual, kinesthetic, and overall imagery abilities of participants. Skill test: physical performance of Taekwondo roundhouse kick

4.2.3.1. Pre-Test

First, all participants were asked to complete the MIQ-R (Hall & Martin, 1997) to verify that they had adequate visual and kinesthetic movement imagery abilities to participate in cognitive training. A pre-test was conducted the day before the experimental treatment to assess the initial level of cognitive performance for the Taekwondo roundhouse kick. Specifically, in the pre-test, all participants read and signed the informed consent form. Then participants performed a CMC (Cognition and Movement Chronometry) test to measure their cognitive performance, specifically the processing speed and accuracy of the information in working memory associated with the roundhouse kick (Schack, 2004).

4.2.3.2. Experimental Treatment

Participants in the experimental groups took part in either observation training or imagery training, or an alternate training for 90 trials a day for three days. The control group did not take part in any training.

4.2.3.2.1. Action observation training group

Participants assigned to the action observation training group sat in a chair in front of a computer monitor (21 inch LCD monitor with 1280 × 1024 resolution) and were asked to observe the scene of the roundhouse kick of Taekwondo shown on the monitor as attentive as possible during action observation without any actual movement. The video for the observation consisted of a scene in which a skilled male model of similar age to the participants correctly performed the roundhouse kick. The model was a black belt Taekwondo player with more than 10 years of Taekwondo training. The video was displayed in real-time from a frontal and third-person perspective that the model and observer were facing each other. Participants have trained 90 trials a day for three days.

4.2.3.2.2. Motor imagery training group

Participants assigned to the motor imagery training group also sat on the chair in front of the computer monitor and heard from the experimenter about their tasks. Then, participants were asked to imagine the roundhouse kick as clearly and vividly as possible without any actual movement according to the instructions on the monitor. Specifically, when the monitor showed the instruction "Be ready", participants prepared the imagery and pressed the start button as soon as ready. Then, they started the imagery with eyes closed at their own pace and pressed the stop button after finishing the imagery. In this way, participants performed 90 trials a day for three days.

4.2.3.2.3. Alternate AO+MI training group

Participants in the alternate AO+MI training group sat on a chair in front of the monitor and listened to the task from the experimenter, just like participants in other training groups. Action observation training and motor imagery training were performed alternately. Specifically, participants were asked to observe the scene of Taekwondo roundhouse kick displayed on the monitor as attentive as possible without any physical movement, and then imagine the roundhouse kick action as clearly and vividly as possible. Participants performed 90 trials (i.e., 45 trials of observation and 45 trials of imagery) daily for 3 days.

4.2.3.2.4. Control group

Participants in the control group visited the lab for three days and read books that were not related to Taekwondo for the same amount of time as the training time of participants in the training group.

4.2.3.3. Post-Test and Retention Test

The post-test was conducted immediately after the end of the three-day training, and the retention test was carried out the next day after the post-test. The procedure and measurement variables were the same as the pre-test. In addition, participants' performance of the roundhouse kick was assessed after the retention test. Participants performed three blocks of 30 roundhouse kicks, with a 5-minute break in between blocks. Their performance was video-recorded for further analysis.

4.2.4. Data Analysis

4.2.4.1. Imagery Ability

One-way ANOVA on MIQ-R scores was performed to examine differences in visual imagery ability, kinesthetic imagery ability, and overall imagery ability among the four groups, respectively. For post-hoc testing, pairwise comparisons with Bonferroni correction were used. The significance level of all analysis was 5%.

4.2.4.2. Cognitive Performance

Two-way ANOVA (four groups x three test sessions) was performed on the accuracy and response times of cognitive performance with repeated measures of the second factor. In addition, further analysis was conducted with a one-way ANOVA to investigate differences between groups by test sessions and vice versa. The Bonferroni correction for the threshold was performed.

4.2.4.3. Skill Performance

The accuracy of the Taekwondo roundhouse kick was analyzed using the average data of the scores evaluated by the two experts based on the specific evaluation criteria (Lee, 2006). To analyze the accuracy, two-way ANOVA (four groups × three blocks) was performed with repeated measures on the second factor. For post-hoc testing of a significant interaction, a one-way ANOVA was performed to examine differences between groups by block and vice versa. The Bonferroni correction for multiple comparisons was performed. The significance level for all analyses was set at 5%.

4.2.4.4. Post-Training Questionnaire

Two-way ANOVA (three training groups × three test sessions) on motivation and ease to follow the instructions were performed with repeated measures of the last variable. The significance level for data analysis was set at 5%.

4.2.4.5. Correlation

Two-tailed Pearson's correlation analysis was performed to examine a correlation between the change in cognitive performance and the change in skill performance across the whole test session by training type. The accuracy value of cognitive performance and the accuracy score of skill performance were used for the correlation analysis. The significance level of the data analysis was set at 5%.

4.3. Results

4.3.1. Imagery Ability

For visual imagery ability, ($F_{(3,44)}$ = 1.279, p = 0.293, η_p^2 = 0.080), and kinesthetic imagery ability, ($F_{(3,44)}$ = 2.768, p = 0.053, η_p^2 = 0.159), the main effect of group was not significant. For overall imagery ability, the main effect of group was also not significant, ($F_{(3,44)}$ = 2.471, p = 0.074, η_p^2 = 0.144). Overall, all groups showed an average of five or more on the three imagery ability scales. These results indicate that there was no difference in visual, kinesthetic, and overall imagery abilities between the four groups. Furthermore, considering that a score of five points means "somewhat easy to see or feel", the results show that participants in each group had adequate movement imagery abilities to participate in cognitive training (Smith & Collins, 2004; Smith, Wright, & Cantwell, 2008). No one was dropped from the experiment due to the lack of imagery ability scores.

4.3.2. Post-Training Questionnaire

For motivation, there was no interaction effect, ($F_{(4,66)}$ = 0.320, p = 0.864, η_p^2 = 0.019), no main effect of group, ($F_{(2,33)}$ = 0.155, p = 0.857, η_p^2 = 0.009), and no main effect of test session, ($F_{(2,66)}$ = 3.026, p = 0.055, η_p^2 = 0.084). The mean score of each training group was 5.33 (i.e., rather motivated; alternate AO+MI training), 5.36 (i.e., rather motivated; AO training), and 5.44 (i.e., rather motivated; MI training). In addition, for ease, there was also no interaction effect, ($F_{(4,66)}$ = 0.628, p = 0.644, η_p^2 = 0.037), no main effect of group, ($F_{(2,33)}$ = 3.070, p = 0.060, η_p^2 = 0.157), and no main effect of test session, ($F_{(2,66)}$ = 1.441, p = 0.244, η_p^2 = 0.042). The mean score for each training group was 5.03 (i.e., rather easy; alternate AO+MI training), 6.00 (i.e., easy; AO training), and 5.20 (i.e., rather easy; MI training).

4.3.3. Cognitive Performance

For accuracy, a two-way analysis of variance (ANOVA) was used. The two-way ANOVA revealed a statistically significant interaction ($F_{(6,88)}$ = 2.236, p = 0.047, η_p^2 = 0.132) meaning that the differences in accuracy between the groups may have varied depending on the test session, or vice versa (see Table 3.3. and Figure 3.1.). First, the result of the post-hoc test on the differences between the groups by test session showed that there was no statistically significant difference between the groups in the pre-test (p = 0.954). However, the accuracy of alternate AO+MI training group was statistically higher than the control group in both the post-test (p = 0.021, η_p^2 = 0.289) and retention test (p = 0.020, η_p^2 = 0.296). Second, the result of the post-hoc test on the differences between the test sessions by the group showed that the accuracy of alternate AO+MI training group was statistically higher in the post-test (p = 0.043, η_p^2 = 0.433) and retention test (p = 0.014, η_p^2 = 0.530) than in the pre-test. The accuracy of the MI training group was statistically higher in the retention test than in the pre-test (p = 0.020, η_p^2 = 0.505). However, both the AO training group (p = 0.062) and the control group (p = 0.599) did not show any statistically significant difference in accuracy between the test sessions (i.e., pre-test, post-test, and retention test). In addition, the main effect of test session ($F_{(2,88)}$ = 15.562, p < 0.001, η_p^2 = 0.261) was statistically significant. The post-hoc test on the main effect of test session (i.e., pre-, post-, and retention test) showed that the accuracy of the post-test (p = 0.003, η_p^2 = 0.195) and the retention test (p < 0.001, η_p^2 = 0.331) was statistically higher than that of the pre-test. The main effect of group ($F_{(3,44)}$ = 2.167, p = 0.105, η_p^2 = 0.129) was not statistically significant.

For response time, a two-way analysis of variance showed that the main effect of group was not statistically significant ($F_{(3,44)}$ = 0.800, p = 0.501, η_p^2 = 0.052) whereas the main effect of test session ($F_{(2,88)}$ = 13.566, p < 0.001, η_p^2 = 0.236) was statistically significant. The post-hoc test on the main effect of test session (i.e., pre-, post-, and retention test) showed that the response time of the retention test was statistically shorter than that of the pre-test (p < 0.001, η_p^2 = 0.231) and post-test (p < 0.001, η_p^2 = 0.323). In addition, there was no statistically significant interaction between the two factors ($F_{(6,88)}$ = 1.136, p = 0.348, η_p^2 = 0.072).

Table 3.3. Descriptive data on the accuracy of cognitive performance by group and session

Variable	Group	Session	Mean	Standard Deviation	Corresponding 95% Confidence Interval	
					Lower Bound	Upper Bound
Accuracy (Score)	AO	Pre	73.542	6.864	67.372	79.711
		Post	77.083	6.895	71.623	82.544
		Retention	80.833	9.905	75.740	85.926
	MI	Pre	75.208	8.010	69.039	81.378
		Post	80.000	10.923	74.540	85.460
		Retention	82.708	5.786	77.615	87.801
	AO+MI	Pre	72.792	16.904	66.622	78.961
		Post	86.875	8.266	81.415	92.335
		Retention	88.167	7.111	83.074	93.260
	Control	Pre	73.958	7.266	67.789	80.128
		Post	75.125	10.825	69.665	80.585
		Retention	76.542	11.153	71.449	81.635

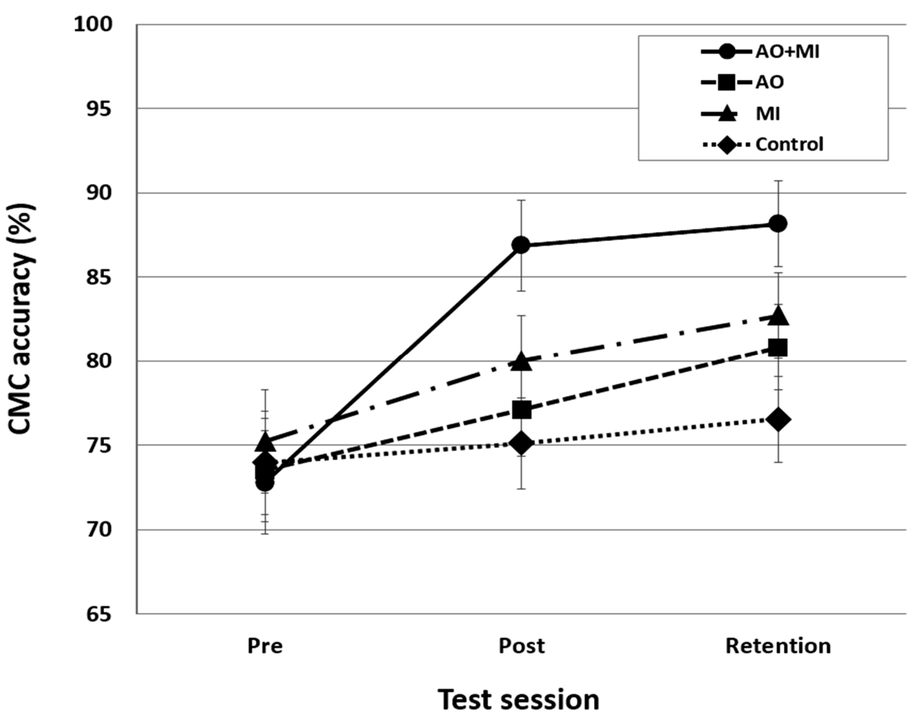

Figure 3.1. The accuracy of cognitive performance across group and test session. Error bars

indicate standard errors

4.3.4. Skill Performance

For the accuracy of Taekwondo roundhouse kick, a two-way analysis of variance showed that both the main effect of group ($F_{(3,44)}$ = 4.089, p = 0.012, η_p^2 = 0.218) and the main effect of block ($F_{(2,88)}$ = 22.407, p < 0.001, η_p^2 = 0.337) were statistically significant. The post-hoc test on the main effect of group showed that the accuracy of alternate AO+MI training group was statistically higher than that of the MI training group (p = 0.047, η_p^2 = 0.218) and the control group (p = 0.024, η_p^2 = 0.243). In addition, the post-hoc test on the main effect of block showed that the accuracy was statistically higher in block 2 than in block 1 (p = 0.004, η_p^2 = 0.164) and in block 3 compared to block 2 (p < 0.001, η_p^2 = 0.261). However, the interaction of group and block was also statistically significant ($F_{(6,88)}$ = 2.320, p = 0.040, η_p^2 = 0.137) meaning that the differences in accuracy between the groups may vary depending on the block, or vice versa (see Table 3.4. and Figure 3.2.). First, the result of the post-hoc test on the differences between the groups by block showed that there was no statistically significant difference between the groups in block 1 (p = 0.109). However, the accuracy of alternate AO+MI training group was statistically higher in block 2 than the MI training group (p = 0.001, η_p^2 = 0.478) and the control group (p = 0.002, η_p^2 = 0.416). In block 3, there was no statistically significant difference between groups (p = 0.120). Second, the result of the post-hoc test on the differences between the blocks by the group showed that the accuracy of alternate AO+MI training group was statistically higher in block 2 than in block 1 (p = 0.001, η_p^2 = 0.679) and such improvement was maintained in block 3 (p = 1.000). The accuracy of the AO training and MI training group was statistically higher in block 3 than in block 1 (p = 0.015, η_p^2 = 0.524), (p < 0.001, η_p^2 = 0.748) and in block 3 than block 2 (p = 0.015, η_p^2 = 0.476), (p < 0.001, η_p^2 = 0.800), respectively. However, the control group did not show any statistically significant difference in accuracy between the blocks (p = 0.225).

Table 3.4. Descriptive data on skill performance by group and session

Variable	Group	Session	Mean	Standard Deviation	Corresponding 95% Confidence Interval	
					Lower Bound	Upper Bound
Skill Performance (Score)	AO	Block1	2.149	0.511	1.865	2.433
		Block2	2.273	0.581	1.975	2.572
		Block3	2.660	0.721	2.243	3.077
	MI	Block1	1.754	0.491	1.470	2.038
		Block2	1.847	0.550	1.548	2.145
		Block3	2.523	0.762	2.106	2.940
	AO+MI	Block1	2.200	0.568	1.916	2.484
		Block2	2.743	0.558	2.444	3.041
		Block3	2.836	0.766	2.419	3.253
	Control	Block1	1.928	0.360	1.644	2.212
		Block2	1.909	0.320	1.611	2.208
		Block3	2.138	0.607	1.720	2.555

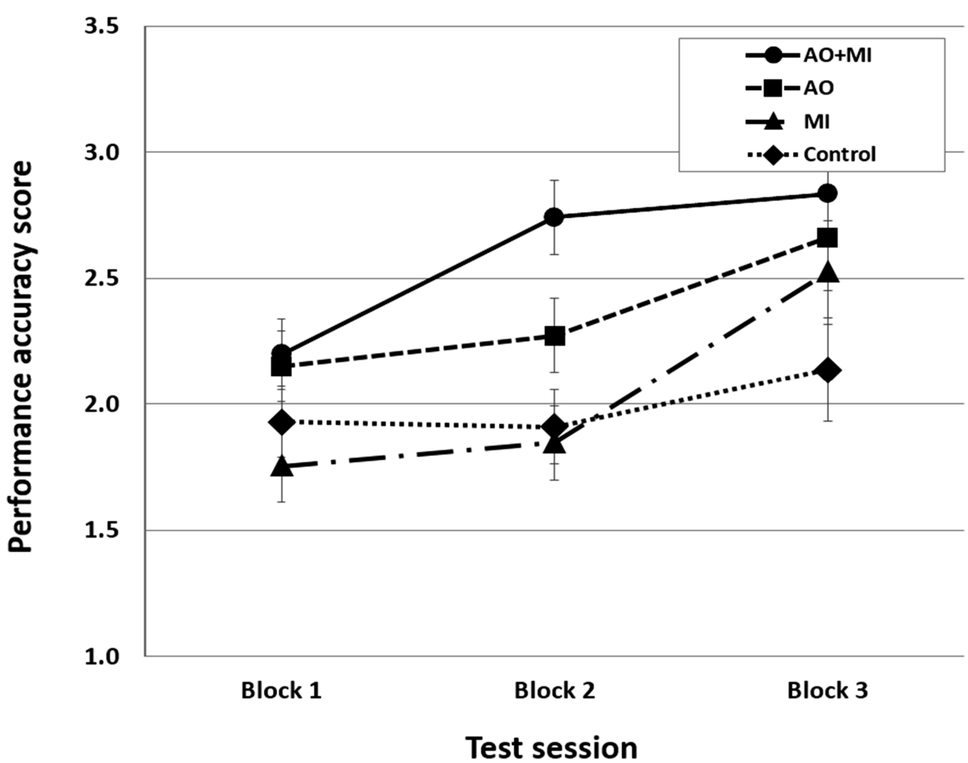

Figure 3.2. The accuracy of skill performance across group and test session. Error bars indicate standard errors

4.3.5. Correlation

For alternate AO+MI training group, the Pearson correlation the change in the accuracy of cognitive performance and the change in the accuracy of skill performance (r = 0.423, n = 36, p = 0.010) was significant. For the AO training group, it was also revealed that the correlation between changes in cognitive performance and skill performance (r = 0.30, n = 36, p = 0.009) was significant. However, in the case of the MI training group and the control group, there was no significant correlation between changes in the two performances.

4.4. Discussion

The purpose of this study was to examine the effect of alternate AO+MI training on cognitive performance in working memory and skill performance. It was hypothesized that alternate AO+MI training would lead to greater improvement in cognitive performance as well as skill performance than independent AO and MI training due to the complementary nature of AO and MI training. In addition, we hypothesized that the relationship between changes in cognitive performance and skill performance across test session may vary according to the method of cognitive training and that the skill performance would develop more after cognitive training as compared to no training. Overall, the results of the present study support set hypotheses.

First of all, regarding the cognitive performance, the present results showed that the interaction between the group and the test session (i.e., pre-, post-, and retention test) was significant in the accuracy of the cognitive performance. More specifically, the accuracy of the alternate AO+MI training group was significantly improved in the post-test compared to the pre-test, and such improvement was maintained in the retention test. In the case of the MI training group, the accuracy of the retention test was significantly higher than that of the pre-test. In contrast, the AO training and control group did not show any difference between the measurement times. However, the AO training group showed a somewhat stronger effect size (η_p^2 = 0.397, p = 0.080) compared to the control group (η_p^2 = 0.046, p = 0.599). Comparing AO with MI, the result of this study implies that MI may be more effective in the efficiency of information processing in working memory than AO. In addition, it was found that only alternate AO+MI training group was significantly more accurate than the control group in the post-test and retention test. Present findings show that cognitive training, such as alternate AO+MI and MI training, can be effective in the accuracy of processing information related to task performance in working memory. In addition, we found the potential applicability of AO training, which showed larger effect sizes than the control group.

With regards to the response time of the cognitive performance, the interaction between the group and test session was found to be not significant. Many studies that have attempted to study the expert-novice paradigm to define characteristics of experts as compared to novices have shown that experts possess broader and more complete knowledge than novices (Abernethy, Thomas, & Thomas, 1993; Del Villar, González, Iglesias, Moreno, & Cervelló, 2007; Iglesias, Moreno, Santos-Rosa, Cervelló, & Del Villar, 2005; Ste-Marie, 1999). Regarding cognitive capacity, experts have more accurate, organized, and structured knowledge than novices and have the cognitive ability to make quicker and more appropriate decisions based on that knowledge (see meta-analysis by Mann, Williams, Ward, & Janelle, 2007). Considering this fact, the reason for no interaction of response time in this study is probably that three days of training may not be sufficient for the novice learners to significantly improve the speed of decision making through training. However, the accuracy result of cognitive performance shows that cognitive training is increasingly improving the cognitive capacity of novice learners.

Concerning the outcome of skill performance (i.e., the accuracy of Taekwondo roundhouse kick), skill performance across three blocks (i.e., thirty trials per one block) after retention test was assessed to measure the development of performance after previous cognitive training. It was found that the accuracy of the alternate AO+MI training group was significantly higher in the second block than the MI training group and the control group. These results suggest that alternate AO+MI training may be relatively more effective in learning skills. A possible explanation for the effect of alternate AO+MI is that the change of cognitive capacity in working memory, which was improved effectively due to alternate AO+MI training, may have some influence on the level of motor output. The results of the cognitive performance through alternate AO+MI training in this study support such an assertion.

Lastly, the correlation between cognitive performance and skill performance was examined. The results showed that there was a significant positive correlation between the two variables (i.e., CMC accuracy and skill performance score) in the alternate AO+MI training group. AO training group also showed a positive correlation between cognitive performance and skill performance. In contrast, it was revealed that for the MI training group and the control group, the correlation between the two variables was not significant. This difference in the results of AO and

MI can be interpreted as the difference in the degree of sophistication or organization of the functional link between cognitive and physical aspects. In other words, if the practice period is longer, it can be interpreted that the potential learning effect of AO might be greater than that of MI. Therefore, these results imply that AO-related training, such as alternate AO+MI training or AO training, may have contributed to a functional link between cognitive capacity in working memory and motor output. Considering that the participant's task was to perform Taekwondo roundhouse kick accurately, AO-related training, which externally provided visual images, may be more effective in performing the skill rather than MI training, which may be difficult for novice learners to form action representations (Tsukazaki, Uehara, Morishita, Ninomiya, & Funase, 2012), As such, it seems that cognitive performance and skill performance are functionally well connected by AO-related training.

AO and MI are different types of motor simulation (Jeannerod, 2001). AO is external stimulus-oriented, which is dependent on external environmental information, whereas MI is internal stimulus-oriented, which depends on internal body information (Holmes & Calmels, 2008). Both simulations activate the motor-related brain regions that are involved in the actual execution of the imaged or observed action without movement (Filimon et al., 2007; see meta-analysis by Hardwick, Caspers, Eickhoff, & Swinnen, 2018; Lorey et al., 2013; Lotze et al., 1999). Concerning the combination of AO and MI, the cognitive effect of alternate AO+MI in this study can be indirectly supported by the results of previous neurophysiological studies of simultaneous AO+MI (Wright et al., 2018). Neurophysiological activation increased by simultaneous AO+MI was found to be greater than that by independent AO or MI (Sakamoto, Muraoka, Mizuguchi, & Kanosue, 2009; Taube et al., 2015). Furthermore, simultaneous AO+MI showed stronger electrophysiological activity in the rostral prefrontal cortex compared to other conditions (i.e., static AO+MI, pure AO, and pure MI; Eaves et al., 2016). Given that the rostral prefrontal cortex is most likely involved in cognitive information processing to align dual-action simulations (Burgess et al., 2007; Eaves et al., 2016), the simultaneous AO+MI may be more effective for the efficiency of cognitive information processing. However, considering that simultaneous AO+MI can undergo cognitive confrontation, which requires simultaneous mental rotation or transformation of the observed images for MI (Eaves et al., 2016), alternate AO+MI of this study could give learners abundant time to prepare the images required for subsequent MI after observation. As such, the procedure has likely contributed to the cognitive and behavioral effects of alternate AO+MI training.

Taken together, the findings of this research provide insight into the effect of alternate AO+MI training as well as a link between the changes in perceptual-cognitive level and in motor outcome by showing the influences of AO, MI, and alternate AO+MI training on cognitive performance in working memory and skill performance. One of the main findings to emerge from this study was that alternate AO+MI training overall was more effective in improving cognitive performance and skill performance than independent AO and MI training, showing a strong connection between the two parameters (i.e., CMC accuracy and skill performance accuracy). Therefore, the findings of the present study suggest that alternate AO+MI training may be considered an effective method for facilitating improvements in perceptual-cognitive and skill performance as compared to AO and MI training alone. To our knowledge, the present study is the first to examine the effects of alternate AO+MI training on the development of cognitive and skill performance in motor action and the relationship between them. Nevertheless, there are some limitations in generalizing the findings of this study. First, it was difficult to confirm the change in skill performance directly because the skill test was carried out after the retention test of cognitive performance. Second, not only the training period was short, but also the consideration of the gender of participants, the skill level of the model, the direction of modeling, and the viewing perspective of motor imagery were somewhat insufficient. Third, if two evaluators of skill performance have different opinions, some bias may be caused. Therefore, future research needs to consider these limitations more clearly and verify current findings. In addition, regarding the study on the different AO+MI training schedules, Romano-Smith et al. (2018) have examined the effects of simultaneous and alternate AO+MI training on aiming performance. For additional behavioral evidence, further research needs to examine the effects of different training schedules of AO and MI (i.e., simultaneous AO+MI, alternate AO+MI, and intensive AO+MI) on perceptual-cognitive performance and skill performance throughout motor skill learning or relearning.

5. THE EFFECT OF DIFFERENT SCHEDULES OF ACTION OBSERVATION TRAINING AND MOTOR IMAGERY TRAINING ON THE CHANGES IN MENTAL REPRESENTATION STRUCTURE AND SKILL PERFORMANCE

This chapter is based on

Kim, T., Frank, C., & Schack, T. (accepted for publication). The effect of different schedules of action observation training and motor imagery training on the changes in mental representation structure and skill performance. *International Journal of Sport Psychology.*

Abstract

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.

5.1. 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 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, to the best of our knowledge, no studies have compared 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.

5.2. Methods

5.2.1. 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).

5.2.2. Measures

5.2.2.1. 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).

5.2.2.2. 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 representational 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 representational 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 4.1), and the mental representational structure was measured. A splitting task was performed to collect data for the analysis of mental representational structures. Each of the 17 basic actions as an anchor was compared with each of the 16 basic 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.

Table 4.1. 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.

5.2.2.3. 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.

5.2.2.4. 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").

5.2.3. 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 4.2.).

Table 4.2. 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	SDA-M Skill test	SDA-M Skill test

		AO + 15 MI)		
Alternate AO+MI (*n* = 10)	MIQ SDA-M Skill test	Alternate AO+MI training 30 times per day (15 AO + 15 MI)	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 + 15 MI)	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.

5.2.3.1. 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.

5.2.3.2. 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.

5.2.3.2.1. 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.

5.2.3.2.2. 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.

5.2.3.2.3. 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 alternate training groups. After the daily training, participants completed the post-training questionnaire.

5.2.3.2.4. 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.

5.2.3.3. 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.

5.2.4. Data Analysis

5.2.4.1. 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%.

5.2.4.2. 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 mean Euclidean distance of the Taegeuk il-Jang was closer to zero. In addition, two-way ANOVAs (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%.

5.2.4.3. 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.

5.2.4.4. 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%.

5.2.4.5. 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%.

5.3. Results

5.3.1. Imagery Ability

Analysis of visual imagery ability, ($F_{(3,36)}$ = 1.043, p = 0.385, η_p^2 = 0.080), kinesthetic imagery ability, ($F_{(3,36)}$ = 0.493, p = 0.690, η_p^2 = 0.039), and overall imagery ability, ($F_{(3,36)}$ = 0.719, p = 0.547, η_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 et al., 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.

5.3.2. Mental Representation Structure

Cluster analysis for the simultaneous AO+MI training group showed that significant clusters increased over time (see Figure 4.1.). 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 4.2.). 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 4.3.). 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 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 4.4.). 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, η_{p}^2 = 0.973), and the main effect of the measurement time, ($F_{(2,72)}$ = 957.937, p = 0.000, η_{p}^2 = 0.964), were significant. The post-hoc test on the main effect of the 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, η_{p}^2 = 0.913, see Figure 4.5.), 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).

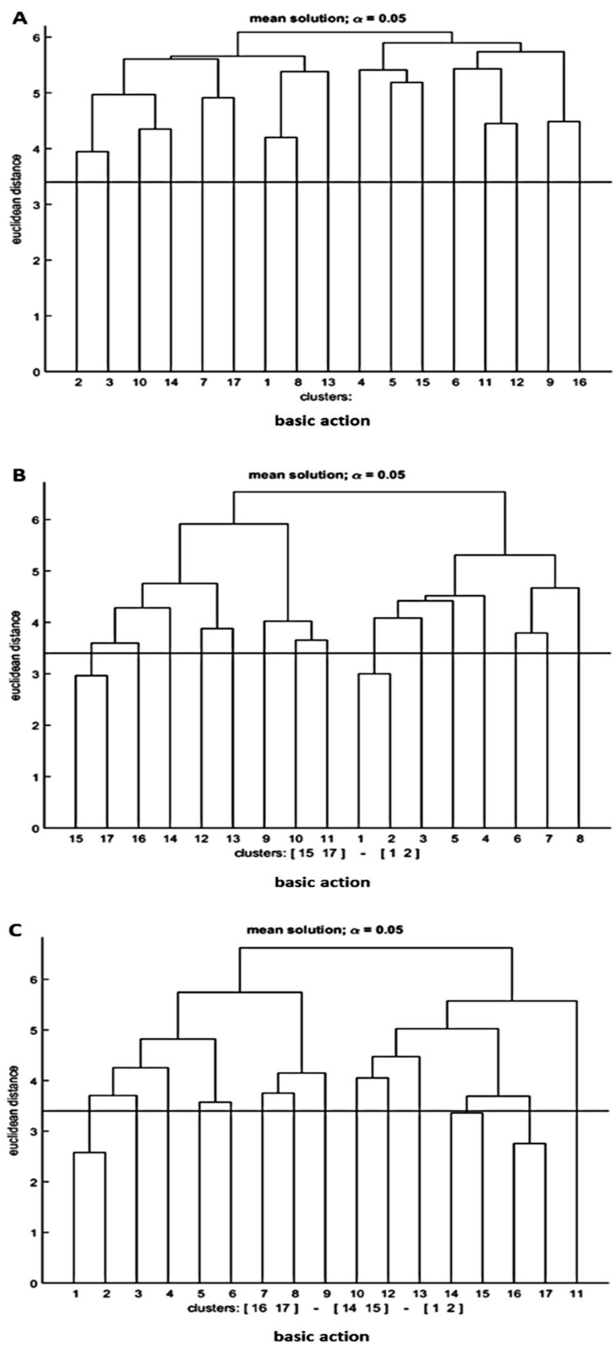

Figure 4.1. Mean dendrograms indicating mental representation structure of simultaneous AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test. The horizontal line indicates the critical Euclidean distance. The critical value of the Euclidean distance (d_{crit}) was 3.40 for an α level of 5%. Clusters below this line indicate statistically significant, while clusters above this line indicate statistically insignificant.

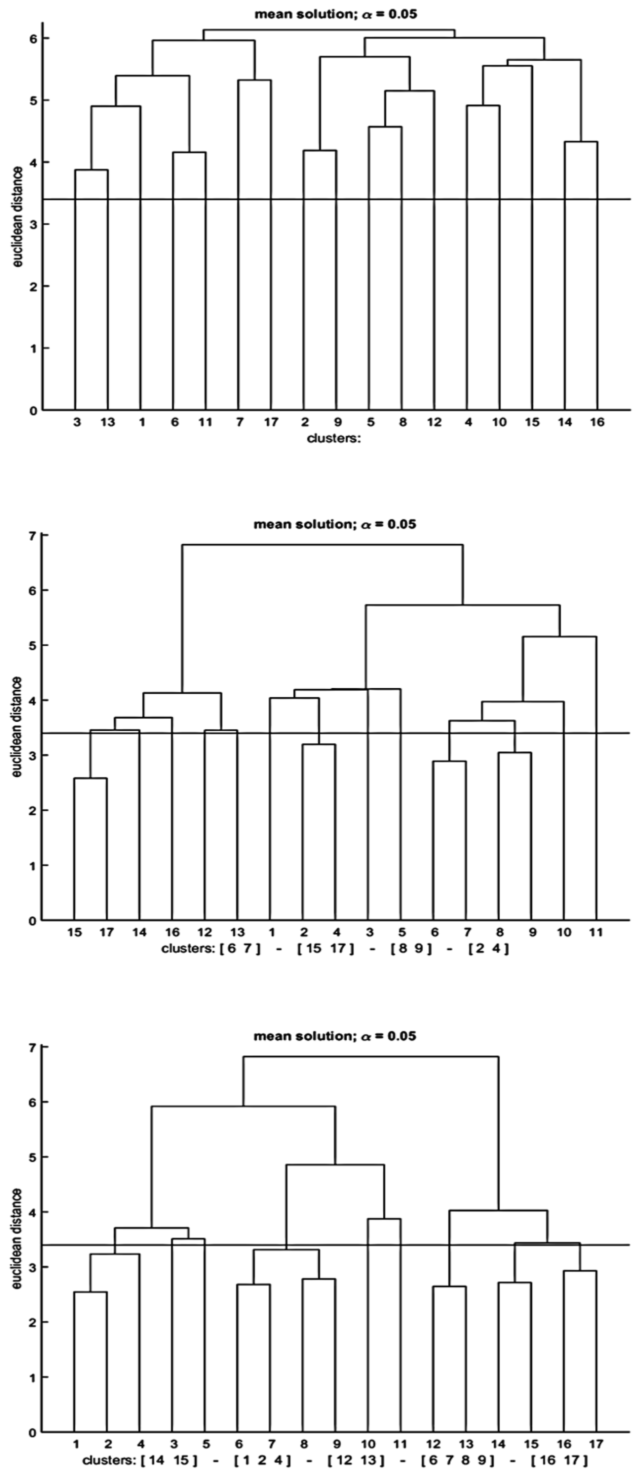

Figure 4.2. Mean dendrograms indicating mental representation structure of alternate AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.40).

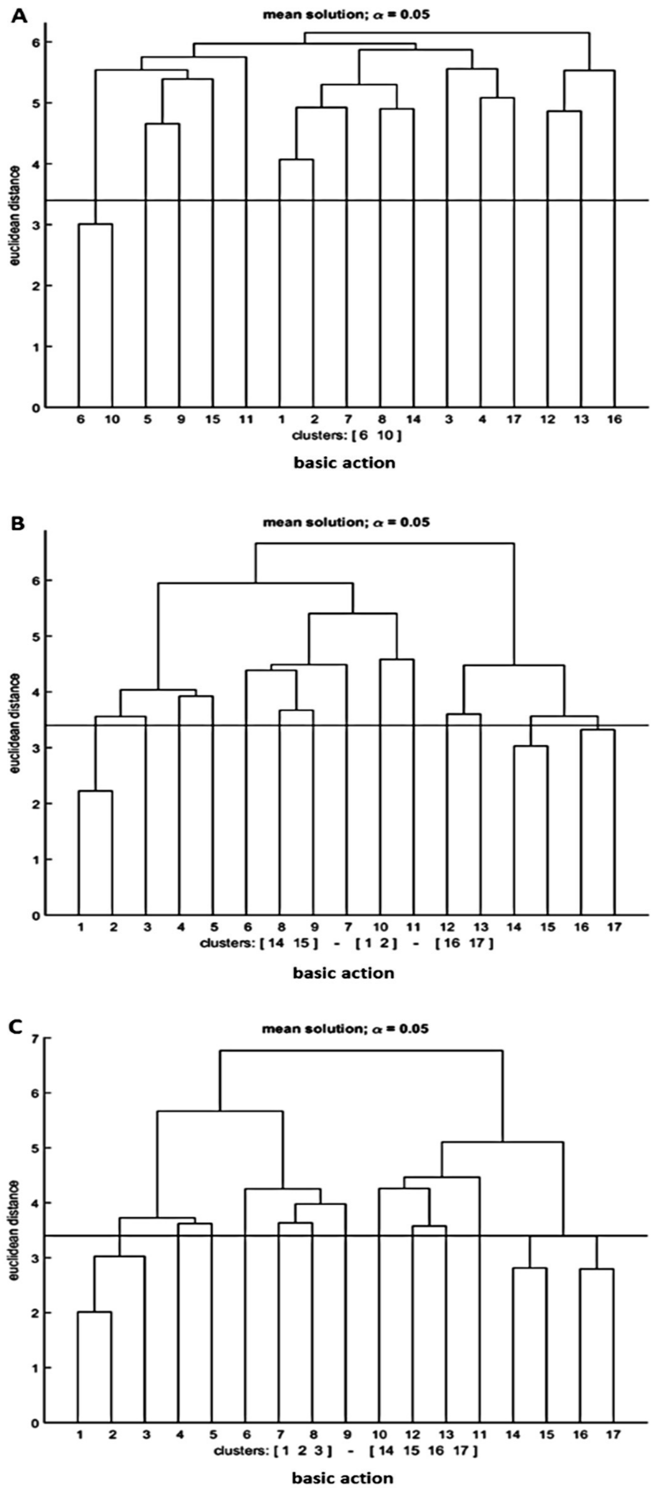

Figure 4.3. Mean dendrograms indicating mental representation structure of blocked AO+MI training group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.40).

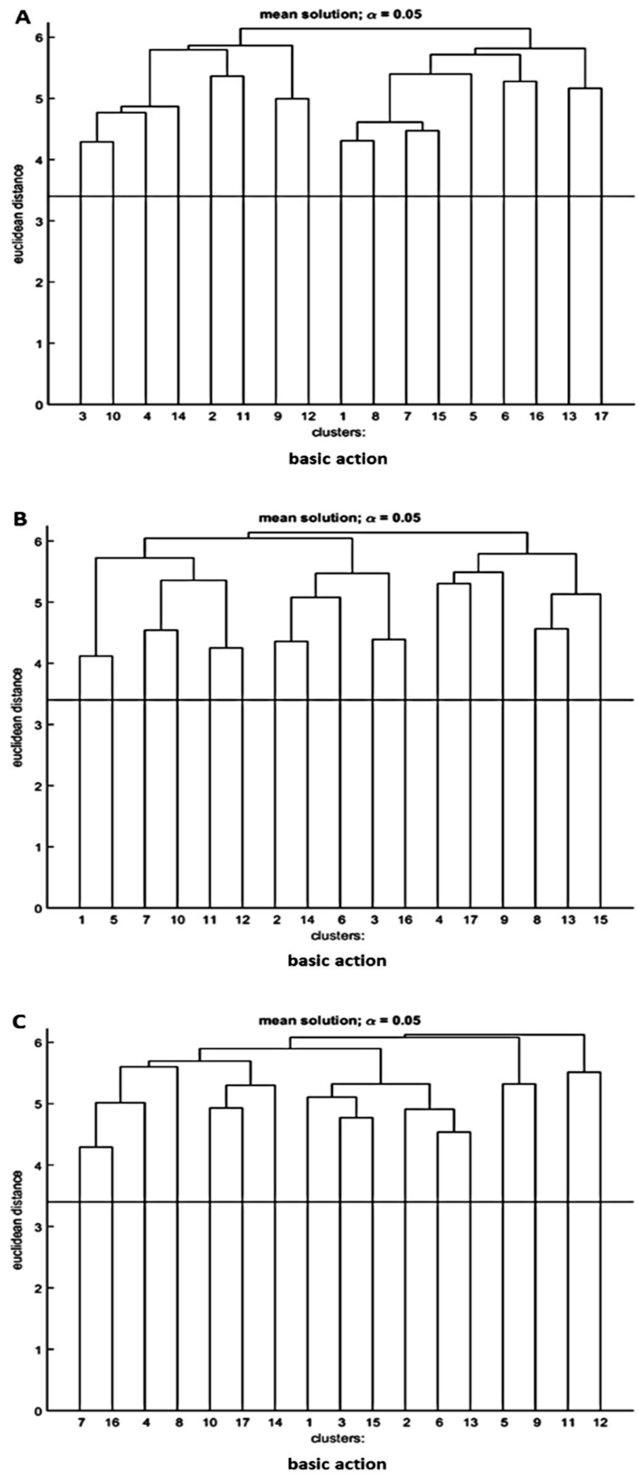

Figure 4.4. Mean dendrograms indicating mental representation structure of control group at (A) pre-test, (B) post-test, and (C) retention test (α = 0.05; d_{crit} = 3.40).

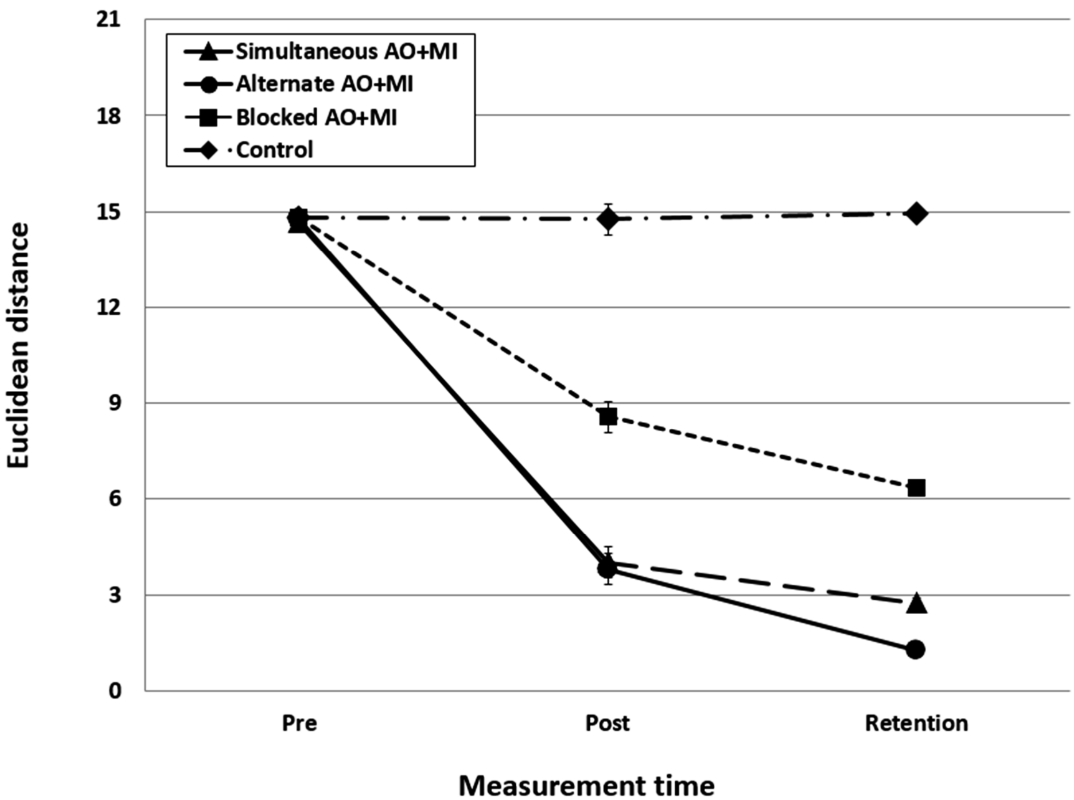

Figure 4.5. Changes in Euclidean distance across group and measurement time. Error bars indicate standard errors.

5.3.3. 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, η_p^2 = 0.203), indicating that the differences between the groups may have varied depending on the measurement times, or vice versa (see Figure 4.6.). 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 the 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).

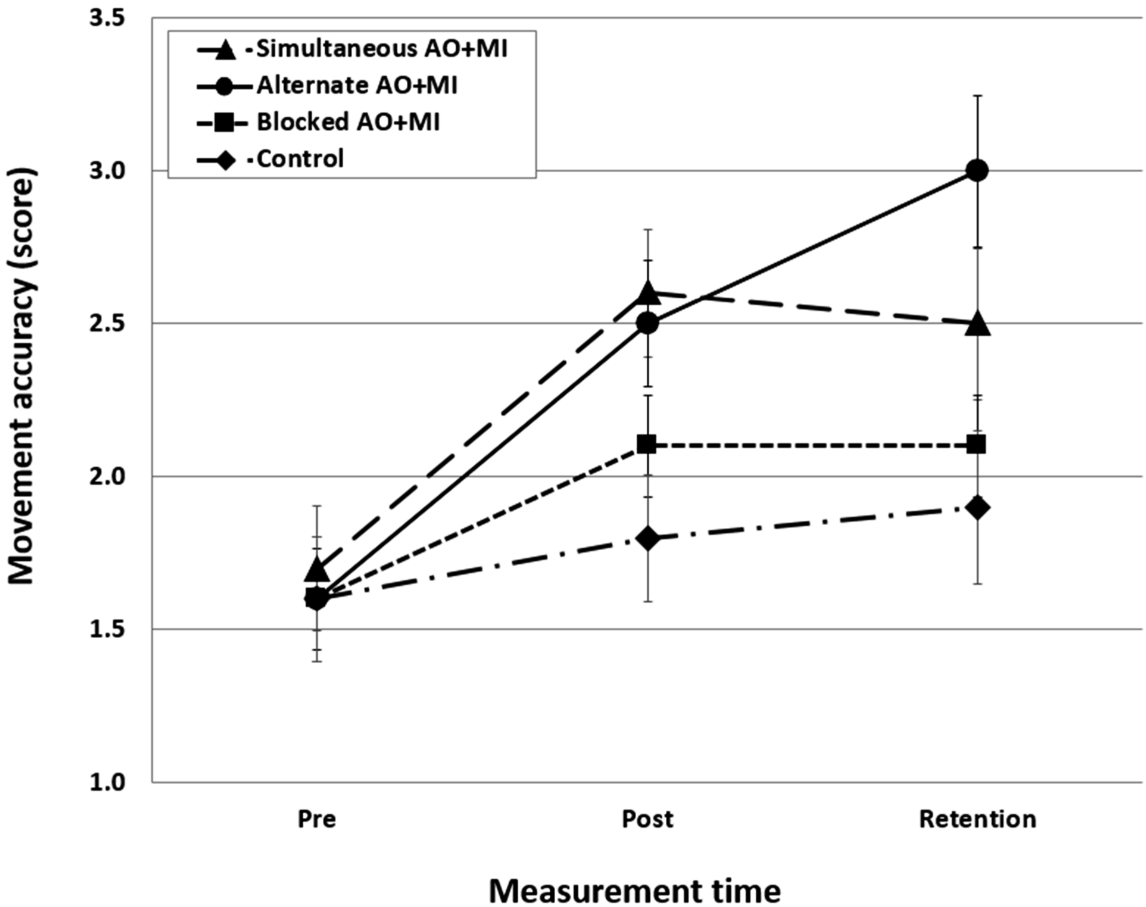

Figure 4.6. The movement accuracy of skill performance across group and measurement time. Error bars indicate standard errors.

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, η_p^2 = 0.591), meaning that the differences between the groups can be changed according to the measurement time, or vice versa (see Figure 4.7.). 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 the alternate AO+MI group (p = 0.000) and blocked AO+MI group (p = 0.019) was higher than that of the 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 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).

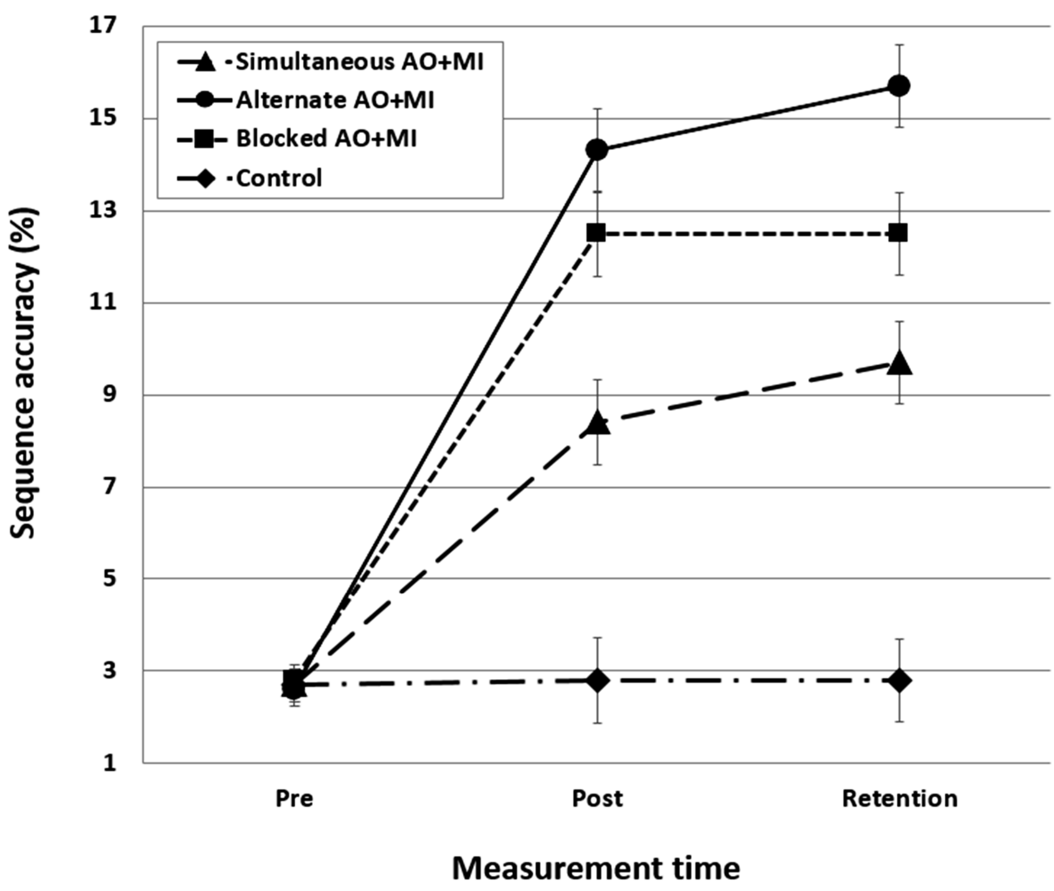

Figure 4.7. The sequence accuracy of skill performance across group and measurement time. Error bars indicate standard errors.

5.3.4. 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, η_p^2 = 0.088), the main effect of training day, ($F_{(2,54)}$ = 2.341, p = 0.106, η_p^2 = 0.080), and the interaction of the two variables, ($F_{(4,54)}$ = 0.473, p = 0.756, η_p^2 = 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 the training day, ($F_{(2,54)}$ = 13.141, p = 0.000, η_p^2 = 0.327), was significant. However, it was revealed that the main effect of group, ($F_{(2,27)}$ = 0.623, p = 0.544, η_p^2 = 0.044), and the interaction of the two variables, ($F_{(4,54)}$ = 1.745, p = 0.154, η_p^2 = 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.

5.3.5. 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.

5.4. 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.

6. GENERAL DISCUSSION

6.1. Key findings

The purpose of the first study was to examine the effects of action observation (AO) training and motor imagery (MI) training on the development of mental representational structure and golf putting performance as well as the relationship between changes in mental representation structure and skill performance in the initial learning stage. Both AO training and MI training were expected to lead to a functional change of mental representation structure as well as a performance improvement. In addition, a hypothesis was established that there would be a positive correlation between the change in mental representation structure and the change in skill performance, and the degree of the correlation would depend on the training method. The results of the study showed that not only the accuracy of golf putting performance but also the mental representation structure improved over time through AO training and MI training. In addition, there was a significant positive correlation between changes in mental representation structure and skill performance in AO training group. Taken together, these findings suggest that cognitive adaptation and performance enhancement may occur through training by motor simulations such as action observation and motor imagery and that perceptual-cognitive changes are related to changes in skill performance.

The purpose of the second study was to examine the functional link between mental representations in long-term memory and cognitive performance. It was expected that if mental representations play an important role as a cognitive reference in the planning and execution of intended motor actions, then skilled players would execute a better cognitive performance, with a more elaborate, well-organized mental representation structure compared to novices. In addition, we also hypothesized that there would be a connection between mental representations and cognitive performance. The results of the study showed that the mental representation structure and cognitive performance of the skilled players were superior to those of the novices, and mental representations correlated positively with the accuracy of the cognitive performance. Taken together, these findings imply that the degree of a functional link between long-term memory and working memory may be used as a perceptual-cognitive factor to reflect an improvement in performance.

The purpose of the third study was to examine the effect of alternate training of action observation and motor imagery on cognitive performance in working memory and skill performance. It was expected that alternate AO+MI training would lead to greater improvement in cognitive performance as well as skill performance compared to independent AO or MI training. In addition, we hypothesized that there may be a significant positive correlation between changes in cognitive performance and skill performance and that the degree of such correlation would vary with training methods (i.e., AO, MI, and alternate AO+MI training). The results of the study showed that alternate AO+MI training was more effective in improving cognitive performance and skill performance than independent AO and MI training, showing a significant correlation between the changes in the accuracy of cognitive and skill performance. Taken together, these findings suggest alternate AO+MI may be considered as a more effective training method as compared to AO and MI training alone.

The purpose of the fourth study was 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. It was expected 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. 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, these findings suggest that simultaneous, alternate, and blocked AO+MI can be used as effective training schedules to enhance the learning of a procedural motor skill, and in particular that alternate AO+MI schedule may be most effective.

6.2. Implications

6.2.1. Perceptual-cognitive and behavioral changes through AO, MI, and AO+MI

Motor learning can be defined as a change in skill performance that is relatively permanent (Magill & Anderson, 2017). Such motor learning is generally accomplished through systematic and continuous physical practice (Coker, 2004). However, a cognitive training such as action observation (AO) training or motor imagery (MI) training can also be applied to strengthen skill learning either alone or in combination with physical practice (Hodges and Williams, 2012). Actually, Action observation (AO) training and motor imagery (MI) training are cognitive training methods that have been widely used to facilitate motor learning, performance, and rehabilitation (Caligiore et al., 2017; Driskell et al., 1994; Feltz & Landers, 1983; Holmes & Calmels, 2008; Ste-Marie et al., 2012).

Action observation (AO) is defined as a dynamic state that simulates the observed actions and outcomes by observing actions performed by oneself or a model (Sale et al., 2014). Motor imagery (MI) is defined as a dynamic state that simulates specific actions mentally (Decety, 1996; Jeannerod & Decety, 1995). In this regard, both AO and MI are motor simulations performed in the absence of movement execution (Jeannerod, 2001). There is a considerable amount of behavioral evidence supporting that AO and MI enhance skill learning and performance (Breslin et al., 2005; Hayes et al., 2008; Horn et al., 2007; Jones & Stuth, 1994; Lotze & Halsband, 2006; Martin et al., 1999; Mizuguchi et al., 2012; see Murphy, 1994 for MI review; see Ste-Marie et al., 2012 for AO review). Furthermore, previous neuroscientific studies have proposed that AO and MI are functionally equivalent in that they similarly activate motor-related brain areas that are active during the actual execution of the observed or imaged action (Buccino et al., 2001; Filimon et al., 2007; Gazzola & Keysers, 2009; see meta-analysis by Hardwick et al., 2018; Lotze et al., 1999). The activation of the motor-related brain areas may reflect changes in action representation formation for action preparation (Holmes et al., 2010).

With regard to perceptive-cognitive change (i.e., change in action representation structure) through cognitive training, the findings of the first study provide deeper insights into the motor learning process by examining both changes in action representation formation as well as changes in skill performance through action observation (AO) training and motor imagery (MI). The findings showed that action representation structure became more elaborate and structured over time through AO training and MI training, and that the performance of complex motor skills (i.e., accuracy of golf putt) was also significantly improved by the two training methods. Thus, this study suggests that both AO training and MI training as independent cognitive training methods can effectively promote the formation of action representation and skill performance.

Action observation (AO) and motor imagery (MI) have been considered for a long time as independent cognitive interventions to improve skill learning and performance (Driskell et al., 1994; McCullagh, Law, & Ste-Marie, 2012). More recently, studies have been conducted with more interest in a combined application of AO and MI (see Eaves et al., 2016; Vogt et al., 2013 for review). AO undergoes an external stimulus-driven process that the formation of action representations are guided externally in working memory by observing actions in an environment such as a live demonstration, recorded video, or virtual reality (Wright et al., 2014). In contrast, MI goes through an internal stimulus-driven process, which generates action representations based on the information stored in long-term memory (Holmes & Calmels, 2008; Murphy, 1994). AO can help learners form action representations by externally providing visual information related to a skill to be learned during the early stages of skill acquisition (Frank et al., 2018). With the help of AO, it is likely to form more robust action representations by focusing on visual or kinesthetic simulation through MI. Actually, previous neurophysiological and behavioral studies on combined methods of AO and MI have shown that the combined application of AO and MI may be more effective than either AO or MI alone (Battaglia et al., 2014; Bek et al., 2016; Berends et al., 2013; Eaves et al., 2016 for review; Eaves et al., 2014; Mouthon et al., 2015; Nedelko et al., 2012; Ohno et al., 2011; Romano-Smith et al., 2018; Sakamoto et al., 2015; Scott et al., 2018; Sun et al., 2016; Taube et al., 2015; Taube et al., 2014; Villiger et al., 2013; Vogt et al., 2013 for review; Wright et al., 2018; Wright et al., 2014).

More recently, there has been increasing interest in how to deliver such AO+MI, that is, the effectiveness of AO+MI training schedule. Most of the neurophysiological and behavioral studies on AO+MI cited above relate to simultaneous AO+MI that performs MI during AO. Simultaneous AO+MI goes through a dual simulation process (Eaves et al., 2016). It rehearses mentally the observed action simultaneously while processing visual stimulus information related to an action to be performed or learned, obtained externally through AO. This can be one of the effective AO+MI schedules (Romano-Smith et al., 2018). However, if the visual action information obtained through AO contains too complex mental rotations or long procedural sequences, it may exceed the limited capacity of working memory. As a result, the efficiency of simultaneous AO+MI may decrease due to the increased cognitive processing load in working memory. Therefore, AO+MI schedule needs to be changed according to the characteristics of the action or skill to be learned.

Another form of AO+MI schedule, alternate AO+MI, is that motor imagery (MI) is performed after action observation (AO). The alternate AO+MI may be more effective than other types of AO+MI schedules to learn too complex or long procedural motor skills by reducing the cognitive processing load in working memory. Specifically, learners first obtain the action information necessary for forming action representations through AO. Subsequently, learners go through 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 AO. Then, during MI, learners are more likely to be able to develop the formation of action representations more efficiently by focusing on their attention within the limited capacity of working memory (Buszard et al., 2017; Engle, 2010; Williams & Ericsson, 2005). Despite increasing interest in the effectiveness of various AO+MI training schedules, this research is in its infancy. In this regard, the third and fourth studies provide a deeper understanding of the effect of AO+MI training schedule.

The third study examined the effect of alternate AO+MI training on the cognitive and skill performance of Taekwondo roundhouse kick. The results showed that cognitive and skill performance was improved by alternate AO+MI, AO, and MI training. In particular, alternate AO+MI training was relatively more effective than AO and MI training. The fourth study investigated the effects of different AO+MI training schedules (i.e., simultaneous, alternate, and blocked AO+MI) of Taekwondo Poomse on the changes in the formation of action representation structure in long-term memory and skill performance variables. The results showed that simultaneous, alternate, and blocked AO+MI training improved mental representation structure and skill performance. In particular, alternate AO+MI training was found to be more effective in developing mental representation structure in the initial learning process than simultaneous and blocked AO+MI training.

Regarding the relationship between perceptual-cognitive and behavioral changes, according to the perceptual-cognitive (PC) perspective (Bernstein, 1967), the planning and execution of motor actions are guided by the formation of cognitive representations based on perceptual information about these motor actions. Thus, the PC perspective assumes that cognitive representations and motor actions are functionally connected. The explanatory models supporting the PC perspective include the theory of event coding (Hommel et al., 2001), the action simulation theory (Jeannerod, 2001), and the cognitive action architecture (CAA) approach (Schack, 2004). Among them, the CAA approach (Schack, 2004) proposes that mental representations are composed of basic action concepts (BACs), which are identified as representation units for motor actions. They play an important role in the planning and execution of motor actions. Specifically, the mental representations serve as a functional cognitive reference for controlling motor actions. In this respect, the CAA approach assumes that well-organized mental representations contribute not only to improving the performance of the motor output level but also to enhancing perceptual-cognitive performance. The results of the first and fourth studies showed an overall positive correlation between changes in mental representation structure and changes in skill performance, although there were differences in the degree of correlation according to training method (i.e., AO, MI, AO+MI), training schedule (i.e., simultaneous AO+MI, alternate AO+MI, blocked AO+MI), and skill characteristics (i.e., complex motor skill, sequential motor skill).

In addition, the skill learning model (Fitts & Posner, 1967) argues that skill learning proceeds through three distinct learning stages. In the first stage (the cognitive stage), cognitive performance is required in working memory (WM) to process information such as how to perform tasks and remembering instructions. In the second stage (the associative stage), the association between specific cognitive stimuli and action responses is strengthened, and the need for WM capacity is gradually reduced. At the final stage (the autonomous stage), the cognitive attention capacity required for performing the skill is negligent. Thus, cognitive processing in the WM is especially required in the initial phase of the skill learning process, and it involves retrieving and using the representation of information related to the skills stored in long-term memory (LTM) (Furley & Memmert, 2010; Williams & Ericsson, 2005). In this regard, there is likely a functional link between the change in mental representations in LTM and the change in cognitive performance in WM as the skill learning process progresses. The result of the second study showed there was a positive correlation between the mental representation structure in LTM and cognitive performance in WM. The findings of four studies imply that changes in perceptual cognition and motor outcome are functionally linked.

6.3. Limitations and future directions

The three studies (i.e., 1st, 3rd, and 4th studies) examined the effects of AO training, MI training, or AO+MI training on mental representations in long-term memory, cognitive capacity in working memory, and skill performance during initial learning stages. In the second study, the functional link between mental representations in long-term memory and cognitive performance in working memory was examined. The findings of the studies provide insights into perceptual-cognitive and behavioral changes through cognitive training (i.e., AO, MI, or AO+MI). Although some of the key research questions set out in the studies have been resolved to some extent, there remain many questions about the effectiveness of cognitive training, such as AO, MI, or AO+MI training. This section discusses limitations derived from the studies, as well as future research directions that take into account such limitations.

First, one of the limitations derived from the first study is that, unlike our expectation, the mental representation structure of the control group became more structured over time. On the other hand, the control group did not show any difference in skill performance between test sessions (i.e., pre-, post- and retention test). A possible explanation for the result is that novice learners may have gained information about how to do golf putting roughly through golf putting trials performed during each test session, which may have affected the change in mental representation structure. Another explanation is that although participants were novice learners who had not previously performed golf putting, most participants knew what a golf putting was. Furthermore, because they had seen golf putting scenes indirectly through the media, there may have been some information on putting in long-term memory. As a result, their indirect experience may have influenced mental representations by working with actual putting attempts during each test session. Differences in mental representation structure between groups in the pre-test support the argument that prior knowledge of golf putting in participants' long-term memory may be different. However, the difference in skill performance was different. In the pre-test, there was no difference between the groups. Specifically, the performance of AO training group and MI training group improved over time, while the control group showed a slight improvement in performance, but there was no significant difference between the test sessions. These results imply that the change in mental representations may be more sensitive to cognitive training than the change in skill performance. In future research, it is necessary to classify beginners who have some prior knowledge and indirect experience about the task and beginners who do not. It is then necessary to examine the effects of individual differences in mental representation structure on perceptual-cognitive and behavioral changes during the learning process. It is hoped that the study will contribute to a better understanding of the mechanism of mental representations in long-term memory.

Second, another limitation derived from the studies (i.e., 1st, 3rd, and 4th studies) is that although the studies examined the learning effects of AO, MI, or AO+MI training, it is still early to generalize the results. In fact, the effectiveness of AO is influenced by various factors such as learner's skill level, model's proficiency, task characteristics, modeling delivery method, viewing perspective, etc (see Ste-Marie et al., 2012 for review). The effectiveness of MI can also be affected by various factors such as the expertise of learners, task characteristics, imagery perspective, age, etc (see Driskell et al., 1994 for meta-analysis). Thus, the effects of AO and MI may vary depending on the specific combination of such conditions. Furthermore, the combined effects of AO and MI can also vary depending on how the various conditions are combined. With regard to AO+MI training, which has received a lot of attention recently, future studies need to find optimal AO+MI training schedules considering various combination conditions of AO+MI. More specifically, it is necessary to compare the difference in effects of simultaneous AO + MI, alternate AO + MI, and blocked AO + MI according to the model and participants' skill level, skill characteristics (i.e., closed motor skill vs. open motor skill or complex motor skill vs. sequential motor skill), angle and speed at which modeling is shown, and imagery perspectives (i.e., internal perspective vs. external perspective), etc.

Third, an additional limitation derived from the studies (i.e., 1st, 2nd, and 4th studies) is that only visual stimuli were used to measure mental representations in long-term memory. For the measurement of mental representations, learners were asked to judge the functional relationship of the basic action concepts associated with performing a specific skill provided in the text. The current studies have shown that cognitive training such as AO, MI, and AO+MI made mental representations more structured and organized. However, mental representations need to be measured along with auditory or kinesthetic stimuli as well as visual stimuli such as text and image, because mental representations can be formed based on information from various sensory resources (Barry & Burgess, 2014). It is expected that the measurement of mental representations based on various sensory stimuli would provide more in-depth insight into changes in perceptive-cognitive aspects by cognitive training in the motor learning process. Therefore, future studies need to compare changes in mental representations based on visual, auditory, and kinesthetic stimuli through cognitive training.

Finally, another limitation derived from the studies (i.e., 1st, 2nd, 3rd, and 4th studies) is on the relationship between mental representations in long-term memory, cognitive performance in working memory, and skill performance. The studies examined the relationship between mental representations and skill performance (i.e., 1st & 4th studies), mental representations and cognitive performance (i.e., 2nd study), and cognitive performance and skill performance (i.e., 3rd study). The studies showed that there was an overall positive correlation between the variables although there was a difference in the degree of the relationship according to the method of cognitive training. However, the relationship was not a one-to-one relationship. This implies that there may be action control processes not yet revealed among the factors. Therefore, to deepen the insight into the motor learning process, future research needs to examine in detail the relationship between mental representations, cognitive performance, various neurophysiological factors, and motor outcome.

6.4. Conclusion

In summary, action observation (AO) training and motor imagery (MI) training have been used independently as effective cognitive training to promote the learning and performance of motor skills. However, there is a difference in the operating mechanism between AO and MI. Specifically, AO goes through an external stimulus-driven process in which the information necessary for the formation of action representations is provided externally. On the other hand, MI undergoes an internal stimulus-driven process that forms action representations based on internal information already stored in long-term memory. Given that, combined training of AO and MI may be more effective than AO or MI training alone, although the effectiveness of AO+MI varies depending on the training method (i.e., simultaneous AO+MI, alternate AO+MI, and blocked AO+MI). In the initial learning stage, learners acquire the information necessary for the formation of action representations externally through AO. Subsequently, or at the same time, they focus on rehearsing mentally observed actions based on information obtained through AO. This increases the likelihood that action representations become more elaborate and robust, thus increasing the likelihood of being more effective in skill learning.

With regard to AO, MI, and AO+MI training, three studies (i.e., 1st, 3rd, and 4th studies) were conducted, and a cross-sectional study (i.e., 2nd study) was conducted regarding the functional link between long-term memory and working memory. In the first study, we examined the effect of AO training and MI training on mental representation structure in long-term memory and golf putting performance. In the second study, we examined the functional link between mental representations in long-term memory and cognitive performance in working memory. In the third study, we examined the effect of alternate training of AO and MI on cognitive performance in working memory and Taekwondo roundhouse kick performance. Finally, in the fourth study, we examined the effects of different training schedules of AO+MI on mental representation structure in long-term memory and sequential skill performance.

Most previous studies have focused on neurophysiological and behavioral changes following AO, MI, and/or simultaneous AO+MI training. For a more in-depth study, in the present four studies, we examined not only changes in mental representation structure in long-term memory, cognitive performance in working memory, or skill performance by AO training, MI training, and different AO+MI training (i.e., simultaneous AO+MI, alternate AO+MI, blocked AO+MI) but also the relationship between those factors. Based on the results of the studies, the conclusions are as follows.

First, AO training and MI training act as effective cognitive training in the development of mental representations in long-term memory, cognitive performance in working memory, and skill performance. Second, simultaneous, alternate, and blocked AO+MI training can be effective in improving mental representations in long-term memory and sequential skill performance. In particular, alternate AO+MI training, which performs MI after AO, may be more effective for sequential skill learning. Finally, the relationship between mental representations in long-term memory, cognitive performance in working memory, and skill performance is likely to be strengthened as skill learning progresses, and the degree of the link can vary depending on the method of practice. Thus, the four studies provide insights into changes in perceptual-cognitive and skill performance following AO, MI, and AO+MI training and the relationship between perceptual-cognitive and behavioral changes.

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FURTHER SCIENTIFIC CONTRIBUTIONS

Journal contributions

Kim, T., Frank, C., & Schack, T. (2020). The effect of alternate training of action observation and motor imagery on cognitive and skill performance. *International Journal of Sport Psychology.* 51(2), 101-121. doi:10.7352/IJSP.2020.51.101

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Conference contributions

Kim, T., Frank, C., & Schack, T. (2018). The effect of different training schedule of action observation and motor imagery on the perceptual-cognitive performance. *Presented at the 8th Congress of the Asian-South Pacific Association of Sport Psychology (ASPASP),* from June, 29th to July, 3rd, Keimyung University, Daegu, South Korea.

Kim, T., Frank, C., & Schack, T. (2018). The effect of different training schedules of action observation and motor imagery on the changes in mental representation structure, cognitive and skill performance. *Presented at the Annual Meeting of the ‚Research on Imagery and Observation (RIO) group* from April 12th to 13th, Bielefeld University, Germany.

Kim, T., Frank, C., & Schack, T. (2017). Mental representation and cognitive training: the influence of combined training of action observation and motor imagery on the changes in perceptual-cognitive and skill performance. *Presented at the 13th Conference of European Network of Young Specialists in Sport Psychology (ENYSSP),* Bratislava, Slovakia.

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