A Functional Link Between Mental Representation in Long-Term Memory and Cognitive Performance in Working Memory

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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 a 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 a 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 functional connection between working memory and long-term memory may be used as a perceptual-cognitive factor to explain improvement in performance.

KEYWORDS

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, Land, Popp, & Schack, 2014; Frank, Land, & Schack, 2013).

According to the perceptual-cognitive (PC) perspective (Bernstein, 1967), the planning and execution of motor actions is 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, Müsseler, Aschersleben, & Prinz, 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. In fact, previous studies have shown a functional relationship between mental representations and motor outcome (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 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.
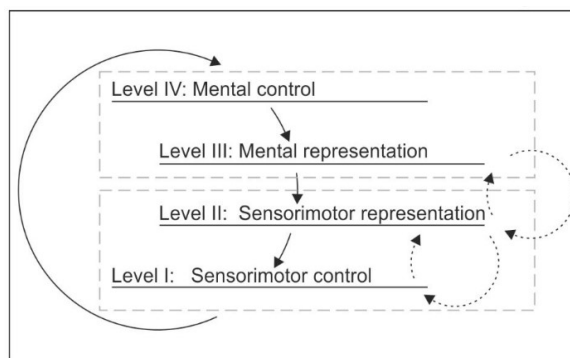
FIGURE 1.

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 the purpose of 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 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 repre-

sentation 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 on the basis of 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.

METHODS

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.

Measurement

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 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 a 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, in order 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.

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 5 s. 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 5 (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.

TABLE 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

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 an 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 were excluded from the analysis. The experiment was conducted in a quiet lab.

Data Analysis

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 in order 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., λ < 0.68) indicated a significant difference between the two groups, while λ ≥ 0.68 indicated that there was no difference between the two groups.

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 col-

lected through the CMC test. The average across Levels 1-5 was used. The significance level was set at 5%.

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.

RESULTS

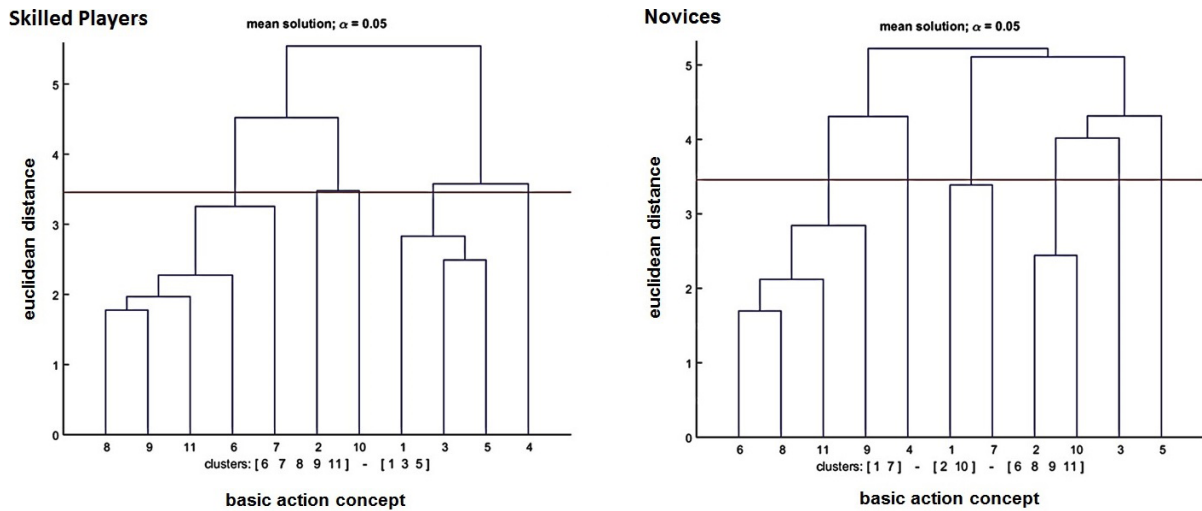## Mental Representation Structure

The cluster analysis showed that statistically significant clusters appeared in both the novice and the skilled group (see Figure 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 clearly significant difference between the groups (λ = 0.46).

Cognitive Performance

The analysis of the accuracy of the cognitive performance showed a significant effect of group (skilled players vs. novices) was significant, $F(1, 43) = 4.581$, $p = .038$, $r = .313$ (see Figure 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), 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.
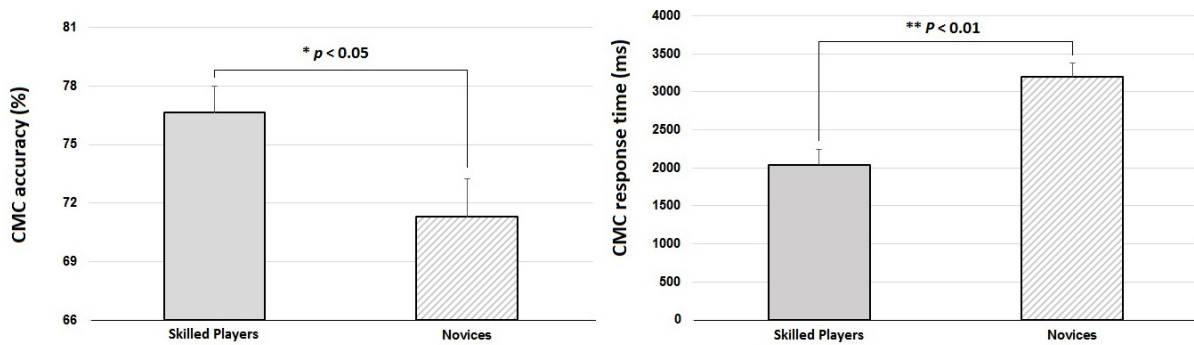
Correlation

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 4). In contrast, the correlation between the mental representation structure and the speed of the cognitive performance was not significant, $r = -.244$, $p = .106$.
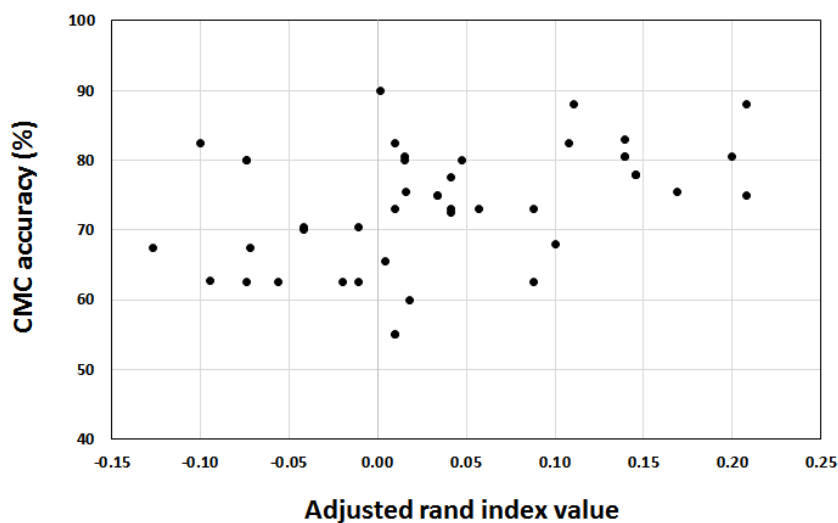
FIGURE 2.

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% ($p < .05$). Clusters appearing below the horizontal line are statistically significant, while clusters above the horizontal line are not.

FIGURE 3.

Accuracy and speed of cognitive performance by skill level. Error bars indicate *SE*s.

FIGURE 4.

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

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, was 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 nonclimbers 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 in order 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. With regards to 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 outcome, 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 the 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 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 carry out the experiment after 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.

CONCLUSION

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.

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