Understanding the literacy performance of Chinese children from an embodied cognition approach

by

XU, Zhengye

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Statement of Originality

I, XU, Zhengye, hereby declare that I am the sole author of the thesis and the material presented in this thesis is my original work except those indicated in the acknowledgement. I further declare that I have followed the University's policies and regulations on Academic Honesty, Copyright and Plagiarism in writing the thesis and no material in this thesis has been submitted for a degree in this or other universities.

Abstract

The present study investigated relationships between embodied cognition and children's literacy performance from on-line (i.e., concurrent external task-related information) and off-line (i.e., internalized embodied experience) perspectives. In total, 144 second-grade and 150 fourth-grade Chinese students were recruited to complete three studies.

Study 1 explored specific contributions of visual, motor, and haptic systems of handwriting to Chinese character learning by assigning each child to one of four strategies: reading, visual processing, air writing, or handwriting. Both air writing and handwriting elicited a larger training effect than reading or visual processing; however, there was no difference between the air writing and handwriting groups. The fourth-graders exhibited greater improvement than the second-graders; however, there was no age difference in the facilitative effects of each group.

Study 2 studied the effects of visual and motor modalities in manipulations of reading comprehension, which were investigated by assigning each child to rereading, observing-performed or participant-performed manipulations and comparing their results. There were two training periods: acute enhancement and strategy maintenance. Only the children in the observing-performed manipulation were asked to change their strategy to the participant-performed manipulation in the second period; the other children were asked to keep the strategy to which they were assigned in the first period. For both periods, the facilitative effects of the manipulations were evident only in the fourth-graders. However, the participant-performed manipulation led to greater enhancement than the

observing-performed manipulation in the first period; however, there was no difference between these two groups in the second period.

Study 3 explored off-line embodied cognition and its relationship to children's Chinese character reading and reading comprehension. In addition to the children, 28 adults were asked to complete a sentence-picture verification task (SVT) and a body-object interaction (BOI) task. In the SVT, the participants were asked to judge whether the object in the picture was mentioned in the preceding sentence. The experiment's pictures were either a perceptual match or mismatch with the objects depicted in the paired sentences. In the BOI task, the participants were asked to judge whether a word made sense. The experimental words were rated by the participants in terms of how easily the participants could physically interact with each word's referent. A facilitating role of embodied cognition in language comprehension was observed in both tasks for the children and the adults. Moreover, regarding the perceptual mismatch effect, the relationships were positive in the second-graders whereas the relationships were negative in the fourth-graders. In addition, a positive correlation between the BOI effect and reading comprehension was observed.

The current findings showed 1) the facilitating roles of on-line and off-line embodied cognition in reading acquisition and comprehension; 2) the specific contributions of sensory-motor modalities to literacy performance; 3) the benefits to the younger children of on-line embodied cognition in a relatively easy task (i.e., Chinese character learning) whereas the older children gained advantages from on-line embodied cognition in both tasks; 4) the different associations between off-line embodied

cognition and literacy performance with different embodied indicators; and 5) the development of the link between off-line embodied cognition and literacy performance had a tendency from positive to negative.

Keywords: body-objective interaction; manipulation; mental model; perceptual mismatch effect; sensory-motor

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List of Abbreviations

BOI	Body-Object interactions
IH	Indexing hypothesis
PME	Perceptual mismatch effect
RAN	Rapid automatized naming

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Chapter 1: Introduction

Embodied cognition is a broad term that is used to describe a cluster of theories within cognitive science, many of which emphasize the importance of the sensory-motor experience gained through our bodily interactions with the environment in acquiring and representing conceptual knowledge (Borghi & Cimatti, 2010). Consistent with the view of embodied cognition, a series of studies have found that the sensory-motor system plays a crucial role in language processing (e.g., Engelen, Bouwmeester, de Bruin, & Zwaan, 2011; Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004; Wellsby & Pexman, 2014).

In the field of language and reading development, it has been found that concurrent embodied information can facilitate children's reading performance. For example, a study reported that English-speaking children (i.e., first- and second-graders) who indexed what they were reading about (e.g., farm animals) to playset pieces that they could manipulate remembered more action sentences from the story than children who only reread the story (Glenberg et al., 2004). In addition, it has also been demonstrated that previous sensory-motor experience can be reactivated to facilitate children's language processing. For instance, Engelen et al. (2011) measured children aged 7 to 13 years with a sentence-picture verification task. The children were presented with a picture that was either perceptually matched or mismatched with the shape implied in the sentence. For example, a picture of a whole watermelon would match the shape of a watermelon implied in the sentence, "Keith saw the watermelon in the garden", but not the shape of a watermelon in the sentence, "Keith saw the watermelon in the bowl". The participants were asked to judge whether the object in the picture had been mentioned in the sentence. The results showed that verification was faster when the picture perceptually matched the situation depicted in the sentence, which illustrated a simulation of the sentences' content (i.e., the previous embodied experience was reactivated when reading these sentences).

Taken together, these findings in the language field demonstrate that direct sensory-motor interactions are critical for gaining knowledge and developing cognitive capabilities (Engel, Maye, Kurthen, & König, 2013) and that higher order and off-line cognitive processing (i.e., removed from the environment) involve the reenactment of the bodily states from previous experience (e.g., simulation) (Foglia & Wilson, 2013). That is, both concurrent embodied information (i.e., on-line) and previous embodied experience (i.e., off-line) can affect language processing. However, the literature on embodied cognition in the language comprehension of children, from both the on-line and off-line perspectives, remains scant.

Moreover, it should be noted that literacy performance is the result of a series of interactions between the internal cognitive system and external stimuli (e.g., external environment, linguistic stimulus), and, considering the role of embodied cognition in language processing, we assumed that there is a relationship between embodied cognition (i.e., on-line and off-line) and children's literacy performance. However, the current research on literacy development mainly focuses on the internal associations among symbolic factors such as the associations between metalinguistic skills (e.g., phonological awareness, morphological awareness, and syntactic awareness) and literacy abilities (Huang & Hanley, 1995; Nation & Snowling, 2000; Saiegh-Haddad & Geva, 2008; Ziegler, & Goswami, 2005) or the importance of cognitive abilities (e.g., executive functioning, visual processing, and reasoning) for reading development (McCandliss, Cohen, & Dehaene, 2003; van der Sluis, de Jong, & van der Leij, 2007). The possible roles of on-line and off-line embodied cognition in children's literacy performance have not been explored. Studies on Chinese children's embodied cognition and its association with literacy performance are also rare. Chinese orthography has some unique features (which are introduced in the following sections) at both the character/word level and the sentence level that may highlight the role of embodied cognition in children's literacy performance. These features will be further discussed in later sections.

Furthermore, both literacy performance and embodied cognition develop with age (Carlisle, 2000; Wellsby & Pexman, 2014). Hence, the relationship between embodied cognition (i.e., on-line and off-line) and literacy performance might vary with age. The present study tested Chinese children in two grades, i.e., grades 2 and 4, because the reading ability and embodied cognition of children are well developed at this stage but have not yet reached the ceiling (Carlisle, 2000; Wellsby & Pexman, 2014), which could ensure sufficient variance in the relevant measures. However, to comprehensively study the possible roles of on-line and off-line embodied cognition in children's literacy performance, the present study examined both word reading and reading comprehension, which are two major aspects of children's reading development (Ouellette, 2006) and represent reading abilities at both the word level and the passage level, respectively. Children cannot become successful and independent readers without these two abilities (Cain & Oakhill, 2004). Investigating the role of embodied cognition from the on-line and off-line perspectives on Chinese children's literacy performance can enrich our understanding of Chinese children's literacy abilities, particularly by considering factors outside the box of cognition. Practically, the findings of the current research can provide some suggestions for developing effective strategies for improving children's literacy performance.

To summarize, the objective of the current study was to investigate the development of embodied cognition (i.e., from both the on-line and off-line perspectives) and its possible relationship with literacy performance (i.e., from the word reading and reading comprehension perspectives) in Chinese children. To accomplish this objective, three research questions were raised: 1) How does on-line embodied cognition affect Chinese children's Chinese character learning, and does the impact differ based on age? 2) How does on-line embodied cognition influence Chinese children's reading comprehension, and does the impact differ based on age? 3) What is the relationship between off-line embodied cognition and Chinese children's literacy performance, and is this relationship moderated by age? Accordingly, three studies were conducted to investigate the relationship between embodied cognition and literacy performance from three perspectives. While the three studies share the same objective, there is no hierarchical relationship among them.

The structure of this dissertation is as follows. First, embodied cognition and its on-line and off-line versions are described and clarified. Then, a section on "The roles of on-line and off-line embodied cognition in literacy performance" elaborates the three focuses of the current study: on-line embodied cognition in Chinese character learning, on-line embodied cognition in children's reading comprehension, and off-line embodied cognition in children's literacy performance. After the Introduction, descriptions of the three studies, which correspond to these three research questions, are provided, including method, results, and discussion. Then, a general discussion demonstrates the comprehensive relationship between embodied cognition and Chinese children's literacy performance based on the three studies. Finally, the theoretical and educational implications, the limitations of the current study, directions for future studies, and conclusions are discussed.

What is embodied cognition?

Conventional cognitive theories and disembodied cognition in particular treat cognition as a symbolic-based semantic memory system and claim that cognition is divorced from the body (Lakoff & Johnson, 1999). According to the view of disembodied cognition, human cognitive processes are similar to computational algorithms (Rogers & McClelland, 2004): the symbols of human cognition are thought to be context invariant, static, and manipulated by rules (specifically, the if-then operations of computer programs, which are equated with learned rules, associations, and production in humans). That is, cognition should not be influenced by our body and bodily interactions with the environment.

However, several studies have revealed contradictory findings (e.g., Casasanto, 2011; Havas, Glenberg, Gutowski, Lucarelli, & Davidson, 2010). For example, Proffitt's (2006) work on visual perception demonstrated that perceived distance is affected by the energy demands needed for the body to traverse the distance. The same distance appears to be longer when one is tired, wearing a heavy backpack, or in poor physical condition. The crucial roles of body and bodily interactions with the environment have also been found in other cognition areas such as attention (e.g., Campos et al., 2000; Smith & Gasser, 2005) and memory (e.g., Brunel, Labeye, Lesourd, Versace, 2009; Yang, Gallo, Beilock, 2009). Based on these findings, the term embodied cognition was proposed to emphasize the importance of cognition in the sensory-motor experiences gained through our bodily interactions with the environment. Unlike the traditional cognitive theories that emphasize the internal symbolic cognitive system, embodied cognition focuses on the importance of action and the perceptual information acquired by the body, specifically, the interactions among our mind, body and the external environment to understand the world and ourselves (Barsalou, 2008).

It has been demonstrated that embodied cognition is related to the development of cognitive skills (e.g., Engelen et al., 2011; Glenberg et al., 2004; Wellsby & Pexman, 2014). For example, the development of visual attention has been found to be strongly ordered by the development of the sensory and motor systems, which are two crucial embodied modalities. At birth, audition and vision are independent, and infants cannot understand the link between them (e.g., the link between the image of a dog and the sound of a dog). With the accumulation of related experience (e.g., the concurrence of specific objects and sounds), infants can look at the visual event that matches what they hear (Mendelson, Haith, & Gibson, 1976; Spelke, 1979). More importantly, it has been found that because deaf children lack experience matching auditory information with visual images, they show more disorganized visual attention (Smith, Quittner, Osberger, & Miyamoto, 1998).

On-line and off-line embodied cognition. There are two basic views of embodied cognition. One view emphasizes the influence of action and body on concurrent cognitive processing. That is, we must utilize our bodies and actions to acquire sensory-motor information from the external world (Barsalou, 2008). Another view highlights the role of simulation. For instance, when knowledge is needed to represent a category such as a car, multimodal representations captured during experience with its instances (cars) are reactivated to simulate how the brain represents perception, action, and introspection associated with the category (Goldman & de Vignemont, 2009; Kiverstein & Clark, 2009).

The former view of embodied cognition suggests that the formation of cognition is constrained by the specific type of body we possess, and the key notion of embodied cognition is action (Gallese & Lakoff, 2005; Glenberg, 1997). Through interactions among the body, action, and the world, cognition can be formed. For example, pulling movements of the arm are associated with approaching desired objects, and pushing movements of the arm are associated with avoiding objects. Typically, the goals of these two actions are to gain or refuse corresponding items. The second view of embodied cognition suggests the important role of the sensory-motor system and assumes that sensory-motor information could offer grounding through various methods such as simulations, situated action, and bodily states. For example, once an individual has the experience of eating a lemon, the taste of sour will be simulated/activated even when only seeing a slice of lemon in the future. Integrating these two views, embodied cognition recognizes the importance of the sensory-motor experience gained through our bodily interactions with the environment for acquiring and representing conceptual knowledge (Borghi & Cimatti, 2010).

From another perspective, these two views reveal different aspects of embodied cognition: on-line and off-line. The first view emphasizes the on-line (concurrent) information gained from interactions among action, the body, and the environment; thus, the process involves a continuous transaction between current states of the brain, body, and environment (Clark, 2008). The second view focuses on previous sensory-motor experience, which can be reused to process current stimuli (Pouw, van Gog, & Paas, 2014). The on-line format treats cognitive activity as a continuous transaction among current states of the mind, body, and environment (Clark, 2008) and focuses on how we use our body and the world during the unfolding of cognitive processes. The impacts of embodied cognition on on-line processing are common in daily life. For example, young children use their fingers to count. In this case, finger tracing could be treated as a type of interaction with the external environment utilized by children to reduce working memory load. The on-line mode of embodied cognition refers to the utilization of the external environment and the current interaction between it and the body to facilitate cognitive processing. However, the off-line studies have focused more on how previous sensory-motor information is reenacted for internal cognitive processing (Pouw et al., 2014). For example, it would be easy to ask someone to imagine a “golden apple” if he or she has relative perceptual information about both “gold” and” apple”.

In brief, on-line embodied cognition focuses more on the contemporary interactions among cognition, action, and the environment while off-line embodied cognition is more concerned with the influence of previously embodied information on current cognitive processing. Understanding embodied cognition from these two perspectives (i.e., on-line and off-line) can help us systematically explore the development of embodied cognition. As described above, it has been found that both on-line (e.g., Glenberg et al., 2004) and off-line (e.g., Engelen et al., 2011) embodied cognition are involved in language processing.

The roles of on-line and off-line embodied cognition in literacy performance

In the following three sections, the roles of on-line and off-line embodied cognition in Chinese children's word recognition and reading comprehension are discussed.

On-line embodied cognition in Chinese character learning. The first aim of the current study was to investigate the role of on-line embodied cognition in word processing (i.e., Chinese character learning), which refers to the interactions among the external environment, the sensory-motor system and the cognitive processing of a target word. For example, when reading a word aloud, the light and temperature of the room as environmental factors, the movement of the mouth and tongue as sensory-motor experiences (i.e., action and auditory information), and the processing of the word in the cognitive system will interact with each other as components of on-line embodied cognition.

Therefore, the involvement of embodied modalities should influence word processing. It has consistently been found that compared with unisensory input (e.g., visual sensory), stimuli from multisensory input (e.g., visual and acoustic sensory) assists infants in acquiring more words (Roy, 2003; Smeets & Bus, 2012). That is, readers acquire related information about words through multimodalities for word processing, and the embodied information benefits this acquisition (Barsalou, 1999). One embodied theory (i.e., dual coding theory) claims that with the embodied approach, the verbal code of a word is associated with codes from other nonverbal (i.e., sensory-motor) modalities. These codes are separate but interdependent information-processing systems, the combination of which will lead to more durable storage and retrieval than either type of code separately (Paivio, 2006; Sadoski & Paivio, 2004).

However, a facilitating role of handwriting in reading has been found in the literatures on both alphabetic languages (e.g., Longcamp et al., 2008; Longcamp, Zerbato-Poudou, & Velay, 2005; Naka, 1998) and Chinese (e.g., Guan, Liu, Chan, Ye, & Perfetti, 2011). For example, a study in French found that handwriting training was the most effective means to improve young children's quality of word reading and writing (Vinter & Chartrel, 2010). Regarding the Chinese language, Tan et al. (2005) examined children's writing and reading skills and found that skilled reading was highly correlated with the ability to write. From the embodied perspective, handwriting is an effective way to implement interactions among the external environment, sensory-motor system, and cognitive process (Bara & Gentaz, 2011; Graham &Weintraub, 1996). Specifically, to write, people must negotiate perceptual and motor information with arbitrary symbol information. First, people acquire the appearance of words/characters through the visual system and then write down the words/characters by controlling the motor system and the muscles of the arm and fingers; in addition, haptic information during handwriting such as how to grasp the pen, influences the outputs (i.e., legibility and speed) (Bara & Gentaz, 2011). Thus, handwriting can be treated as a strategy of on-line embodied cognition that consists of, at least, visual, motor, and haptic components.

Considering that the embodied components of handwriting are related to word processing, they might uniquely contribute to reading (Guan, et al. 2011; Shadmehr & Holcomb, 1997). To illustrate, first, visual skills are necessary to produce word forms. Writers should be able to use the visual system to perceive both the shape of the standard and the deviation between it and their own handwriting products (Bara & Gentaz, 2011). Second, fine motor skills are required for successful handwriting because accurately formed words can be produced only through proper timing and the force control of coordinated arm, hand, and finger movements (Tseng & Chow, 2000). In addition, the haptic information related to the movement trajectory and amplitude specific to each word plays a critical role in handwriting (Bara & Gentaz, 2011). In brief, handwriting integrates the perceptual (i.e., visual and haptic) and motor representations of words, which in turn aids reading performance.

Although there is no direct evidence to support the causal effect of on-line embodied sources on word reading, several studies have found that visual, haptic, and motor skills are related to handwriting performance (Bara & Gentaz, 2011). Regarding the role of visual information in handwriting, an intervention study conducted in children with difficulties in learning to write found that these children had greater gains than the control group (i.e., character without other information) after seeing a copy containing numbered arrows that contained stroke order information (Berninger et al., 1997). Additionally, it has been found that finger-function tasks (e.g., touching the thumb with each finger in sequential order with viewing) are quite reliable and valid for assessing handwriting (Bara & Gentaz, 2011), which suggests the critical role of the motor system in handwriting. A study in French assessed the role of visual-motor integration (i.e., the coordination between visual perception and finger movement) in handwriting. The study found that training that involved visual-motor integration was the most effective way to improve 5-year-old children's handwriting compared with trainings involving only visual or motor activities (Vinter & Chartrel, 2010).

Furthermore, another study in French children found that visual, haptic and motor training together were helpful for reading and writing, even without integrating perceptual and motor information for handwriting. To illustrate, after training involving visual (i.e., by looking at the letters), haptic and motor (i.e., by exploring the letter with the fingers) information about the letters, 5-year-old kindergarten children exhibited a greater improvement in both letter recognition and handwriting quality than children who attended a training involving only visual information (Bara & Gentaz, 2011). Taken together, the evidence above suggests that there are three critical elements in handwriting, specifically, visual, motor, and haptic processing. However, it is still not clear which aspects of handwriting (i.e., visual, motor, or haptic processing or a combination of them) are critical in contributing to reading prediction.

Moreover, Chinese has some unique features that may highlight the crucial role of handwriting in reading (Tan et al., 2005; Tan, Xu, Chang, & Siok, 2013). First, the visual form of morphosyllabic Chinese characters is comparably complex, which leads to stress on processing in the visual modality in word reading. Chinese characters are composed of strokes in two-dimensional space; on average, a simplified Chinese character has 10.3 strokes (Srihari, Yang, & Ball, 2007). Second, Chinese characters are usually composed of two or more components. The structures of the characters can involve a left-right structure, a top-bottom structure, or an enclosed structure, which requires spatial relation assignment within characters in handwriting (Lam et al., 2004). Successful spatial relation assignment requires not only good planning and execution of the motor system but also negotiation between the visual and motor systems. Therefore, investigating the role of handwriting in word reading from the embodied cognition perspective can help us not only explore the relationship between on-line embodied cognition and reading at the word level but also understand the underlying mechanism of handwriting in word reading in a morphosyllabic writing system (Shu, 2003).

The facilitative effect of the integration of the visual, haptic, and motor processing of handwriting in word reading in Chinese was found in a previous study that asked children to copy unfamiliar language scripts (i.e., Hebrew, Korean, and Vietnamese); this integration significantly predicted third- and fourth-grade Hong Kong Chinese children's reading of Chinese words even after controlling for metalinguistic skills (McBride-Chang, Chung, & Tong, 2011). However, the specific roles of visual, motor, and haptic processing in word reading have not been explored. To address this issue, the present study investigated the facilitative effect of handwriting on word reading from three perspectives: visual (with stroke order), visual + motor (i.e., air writing, no haptic), and visual + motor + haptic (i.e., real handwriting); three training conditions were designed accordingly. In addition, a control condition (i.e., reading holistic characters) was added to measure the facilitative effects.

In the control condition, the children were presented with pictures of holistic characters. In the training condition focusing on visual processing, the children were presented with a video to show them how a given Chinese character is written. It should be noted that although both the control and visual processing trainings involved only visual processing, a previous study on letter recognition found that visual representation with stroke order provided an additional benefit beyond viewing the overall shape (Berninger et al., 1997). It is possible that visual information about stroke order requires more oculomotor control, that is, more involvement of on-line embodied cognition. Distinguishing between visual information about a holistic character and stroke orders can help us explore the role of visual processing in handwriting to more comprehensively benefit word reading. In the visual and motor skill training condition, the children were asked to follow the video and write the Chinese character with their index finger in the air while excluding the haptic experience (i.e., the friction between pen and paper and the way of holding a pen). Finally, in the handwriting training condition, the children were asked to write the Chinese character with a pen on paper and thus could integrate the visual, motor, and haptic information.

Comparing the effectiveness of these three training conditions with the control condition, the study examined whether and to what extent different levels of sensory-motor information are important for learning Chinese characters. According to the view of embodied cognition (Barsalou, 1999) and the findings of the previous studies (e.g., Roy, 2003; Smeets & Bus, 2012), and considering that handwriting involves the richest sensory-motor resources, it was expected that handwriting would show the strongest facilitative effect.

At the same time, the present study explored the developmental issue of the relationship between on-line embodied cognition and Chinese character learning. Investigating the possible influence of age on the facilitative effect of on-line embodied cognition in Chinese character processing can help us determine in which age group(s) of children embodied cognition is more closely related to reading in Chinese. To the best of our knowledge, the literature on the interactions among age, on-line embodied cognition, and word reading is still limited. However, it has been found that children with high letter-naming scores also had high scores in letter handwriting (Molfese, Beswick, Molnar, & Jacobi-Vessels, 2006). That is, there is a positive correlation between children's language knowledge and handwriting acquisition (Bara & Gentaz, 2011; Karlsdotti & Stefansson, 2002). This link has been presumed to be a complementary link that supports the development of the alphabetic knowledge needed for word-decoding skills. Alphabetic knowledge can assist children in making an association between letter names and letter sounds.

The interaction between language knowledge and handwriting acquisition (Bara & Gentaz, 2011; Karlsdotti & Stefansson, 2002) is consistent with the symbol interdependency hypothesis (Louwerse, 2011), which suggests that lexical representations comprise embodied and symbolic systems. That is, despite external embodied information, internalized language knowledge may also assist children in learning new lexical information. To illustrate, internalized language knowledge may enable children to easily determine a connection between new characters/words and those in their mental lexicon, which can enhance learning efficiency. Considering the positive correlation between handwriting and word reading (e.g., McBride-Chang et al., 2011; Tan et al., 2005, 2013), we assumed that the sensory-motor components of handwriting would result in a larger benefit for older children than for younger children, who typically have less language knowledge.

To summarize, the first research question of the present section was whether and how on-line embodied cognition influences word reading (i.e., Chinese character learning) in Chinese children (i.e., second- and fourth-graders). To explore this question, a Chinese character learning training was conducted. Specifically, the roles of visual, motor, and haptic skills in handwriting in Chinese character learning were explored. Three training conditions were involved by considering the three key components of handwriting in terms of embodied cognition, i.e., visual processing, motor skills, and haptic skills. It was assumed that the real handwriting condition would be more effective in facilitating the learning of Chinese characters because it contained the richest elements of embodied cognition compared to the other two training conditions. Moreover, consistent with a previous study (Karlsdottir & Stefansson, 2002), we proposed that older children (i.e., fourth-graders) would benefit more from on-line embodied training than younger children (i.e., second-graders).

Children's age, nonverbal intelligence, and other abilities that may influence children's Chinese character learning, i.e., rapid automatized naming (RAN), working memory, Chinese character reading, phonological awareness, morphological awareness, and orthographic knowledge, were taken into account as control variables. Nonverbal intelligence refers to children's reasoning ability and was evaluated by Raven's Standard Progressive Matrices (Raven, 1996). RAN refers to the ability to name visually presented familiar symbols (i.e., digits, letters, and colors) as quickly as possible; RAN has a strong correlation with reading (Georgiou, Parrila, Cui, & Papadopoulos, 2013) and was tested by the RAN digit task. Working memory capacity is the ability to retain and manipulate information during a short period of time (Klingberg, Forssberg, & Westerberg, 2002), and it was measured by the backward digit recall test. Chinese character reading was used to examine children's reading ability at the word level (Liu & McBride-Chang, 2010), which can influence children's acquisition of new characters. Phonological awareness refers to the ability to manipulate and reflect on sound representations of one's language (Kuo & Anderson, 2010), and it was measured by the syllable deletion and onset deletion test. Morphological awareness was defined by Carlisle (2000) as "children's conscious awareness of the morphemic structure of words and their ability to reflect on and manipulate that structure" (p. 194). In the present study, it was measured by the morphological production task (Liu, Li, & Wong, 2017). Orthographic knowledge is defined as children's awareness of conventional rules in structuring Chinese characters and the ability to identify or distinguish real Chinese characters from a set of pseudocharacters, noncharacters, and symbols (Ho, Yau, & Au, 2003), and it was measured by a Chinese character decision task.

In addition, considering the properties of the training conditions, the children's writing and visual-spatial processing ability were also controlled. A copying task (McBride-Chang et al., 2011) was utilized to measure the children's writing ability while two visual tasks were applied to measure their visual processing (Gardner, Kornhaber, & Wake, 1996). However, from the stimuli perspective, characters' properties could also influence learning results such as the complexity and presentation order of stimuli (Averell & Heathcote, 2011; Hayes, 1987). Thus, both item complexity and item order were controlled in the data analysis. There were two objectives in the present study: first, to investigate the specific roles of the visual, motor, and haptic systems of handwriting in Chinese children's character learning, and, second, to explore the possible influence of age on the relationships between the specific embodied components of handwriting and character learning.

On-line embodied cognition in children's reading comprehension. The second focus of the current study was the role of on-line embodied cognition, which was conducted through manipulation training on Chinese children's reading comprehension. As mentioned above, it has been found that manipulating objects of reading enhances children's reading performance (e.g., Glenberg et al., 2004; Glenberg, 2011; Marley & Szabo, 2010). In studies with English speakers, the typical manipulation strategy is that children are required to manipulate toy objects (e.g., for stories in a farm setting, a toy barn, chicken, pig) that correspond with the events described in the sentences if the sentences were presented with a green light (e.g., Ben gets eggs from the chicken.). These green-light sentences are critical for comprehending the text and generally include verbs. A series of developmental studies have found that this type of manipulation strategy, compared with the reread strategy (i.e., children are asked to read and reread text), can facilitate children's reading comprehension (e.g., Glenberg, Brown, & Levin, 2007; Glenberg et al., 2004; Marley, Levin, Glenberg, 2007). From the embodied cognition perspective, manipulation assists children in acquiring on-line sensory-motor information by manipulating toys or the images of toys corresponding with the story's content; thus, the approach can be treated as an on-line embodied strategy. The findings of studies related to manipulations have been attributed to the indexical hypothesis (IH), which asserts that meaning arises when words and phrases are indexed, or mapped, onto relevant experience and those experiences are integrated, or meshed, with the guidance of syntax (e.g., Glenberg et al., 2007; Glenberg & Kaschak, 2002; Glenberg & Robertson, 1999; Kaschak & Glenberg, 2000). To illustrate, through manipulation, a story can be concreted, which can reinforce the connection between the story and its embodied representations and thus improve children's memorization of the story. A better memory can lead to better comprehension (Cain, Oakhill, & Bryant, 2004). In addition, in a manipulation, children must act out the sentences of a story. That is, they must physically instantiate the syntax of the sentences, specifically, who does what to whom, in their own actions. Thus, manipulation helps children illustrate how written texts can be meaningful and aids them in uncovering that meaning (Glenberg, 2011). In brief, manipulations can benefit children's memory of the text and help them derive the inferences that are necessary to construct integrated mental models for language comprehension (Moreno & Mayer, 1999; Rubman & Salatas Waters, 2000).

The facilitating role of manipulations on children's performance in passage reading has been documented in English in a few studies (e.g., Glenberg et al., 2007: Glenberg et al., 2004; Marley & Szabo, 2010). To the best of our knowledge, the role of manipulations in reading comprehension has not been thoroughly explored among Chinese children. As described above, in addition to Chinese characters, Chinese has some unique features at the word and sentence levels that may highlight the role of manipulations in facilitating reading. For example, in general, Chinese has no plural form of nouns. Characters such as 狗/gou3/, 椅/yi3/, 菜/cai4/ can denote either the singular or plural form—dog/dogs, chair/chairs and vegetable/vegetables. Therefore, when reading a passage, it is difficult for children to determine whether nouns are singular or plural by processing only the character/word of a concept. To identify the number of objects, children must further process the quantifiers, which may be linked with nouns such as 一只/yi1 zhi1/ (one), 一些 /yi1 xie1/ (some), 许多/xu3 duo1/ (many). In contrast, through manipulation, children can obtain visual information about an object's number, which may facilitate their understanding.

Chinese also involves broad flexibility in the word order of sentences. Specifically, Chinese is a topic-prominent language (Chao, 1968; Li & Thompson, 1981). When the topic is an object noun/phrase, two specific types of object-subject-verb word order—"BA [把] sentence structure" and "BEI [被] sentence structure"—are used: 我摔碎了妈妈新买的杯子 (I broke mother's new cup) is a subject-verb-object sentence and can be converted to BA and BEI sentence structures 我把妈妈新买的杯子摔碎了 (I BA mother's new cup broke) and 妈妈新买的杯子被我摔碎了 (Mother's new cup BEI I broke), where 妈妈新买的杯子 (Mother's new cup) becomes the topic. For children, especially early readers, it is easy to be confused by the relationships among the concepts implied in the BA and BEI sentences (Chik et al., 2012). By manipulating the objects based on the sentence (i.e., in the sentence *I BA mother's new cup broke,* readers must move the object *I* toward the object *mother's new cup*), children can concretize the relationship between objects (i.e., I broke mother's new cup). Therefore, manipulations should be particularly helpful for children in comprehending Chinese content.

However, it should be noted that from the perspective of on-line embodied cognition, manipulation consists of two critical aspects: perceptual and motor processing. According to the IH (Glenberg et al., 2004), either of these two types of embodied information (i.e., visual features of corresponding concepts and reader's body and actions) contributes to the facilitative effect of manipulation on reading comprehension. In other words, in addition to visual information, the involvement of the motor system in the manipulation elicits a specific effect on reading comprehension. It has been consistently suggested that sentences are understood by creating a simulation of the actions that underlie them (Glenberg & Robertson, 1999). For instance, a study (Glenberg & Kaschak, 2002) found that English-speaking adults responded faster to the sentences that implied compatible actions (e.g., Close the drawer) with their actual ones (e.g., the hand moved away from the body). Accordingly, IH asserts that the underlying mechanism of manipulations in facilitating children's reading is related to readers' visual and motor systems.

In contrast, two studies found that the provision of concrete dynamic visual representations of story events provided a comparable degree of facilitation to that of participant-performed manipulation (Glenberg et al., 2007; Marley et al., 2007). These findings suggest that visual indexing alone may account for reading enhancement. To illustrate, one study in English trained children in small (three-child) reading groups. The participants were assigned to (participant-performed) manipulation groups and rereading groups (Glenberg et al., 2007). With the same background information, the children in each group were asked to read the three successive critical sentences one-by-one. In the manipulation condition, each child was asked to read the sentence aloud and then manipulate the objects. Thus, in the manipulation condition, each child performed physical manipulations and observed others' manipulations. For the reread condition, one child read and reread the critical sentence, followed by the next child, and so on.

Children in the manipulation condition were substantially more accurate in answering 10 forced choice questions about the texts than those in the reread condition. More importantly, the children displayed a similar level of improvement on all the questions pertaining to critical sentences, both those manipulated by themselves and those manipulated by the other children. In other words, observing a peer manipulate objects that correspond to sentences may be as effective as manipulating the objects oneself. However, it should be noted that in the study by Glenberg et al. (2007), each child in the manipulation condition combined observation and physical manipulation strategies when reading one story. Thus, there may have been mutual interference in the effects of the observing-performed and participant-performed manipulations.

To distinguish the observing- and participant-performed manipulations, another study on listening comprehension among academically at-risk Native American children included an additional observing-performed manipulation condition (Marley et al., 2007). The children were assigned to three conditions: a listening condition and observing- and participant-performed manipulations. In the observation group, the participants watched a complete situation that was manipulated by the experimenter as directed by the text. Consistent with Glenberg et al. (2007), the study found that the participant-performed manipulation elicited better performance in terms of recalling stories than the listen-only condition; however, no significant difference was found between the observing- and participant-performed manipulations. The results suggest that observing the outcome of the experimenter's manipulations was as beneficial as the child's own manipulations.

A possible reason for the achievement of reading enhancement through the observation of others' manipulations is related to the mental model, i.e., a representation of what a text is about (Glenberg et al., 2012). A mental model is constructed from modal representations of experience similar to those described by a text (Barsalou, 1999), and it is critical for language comprehension (Glenberg et al., 2012). Although the IH suggests that physical manipulation is an effective method for acquiring the required sensory-motor information for the mental model, it has been found that after 3 years of age, children can understand and gain meaningful visual features and actions by observing the actions of others (i.e., gestures) (e.g., Dargue & Sweller, 2018; Kimbara, 2008; Stanfield, Williamson, & Özçalişkan, 2014; Macoun & Sweller, 2016). For example, it has been found that the understanding of Piagetian conservation increased two-fold for first graders who viewed a conservation lesson accompanied by iconic gestures in comparison with a lesson taught through speech alone (Church, Ayman-Nolley, & Mahootian, 2004). In line with the findings of behavioral studies, it has been shown that the observation of actions performed with different effectors (i.e., hand, foot, and mouth) recruits the same motor representations that are active during the actual execution of those same actions (Buccino et al., 2001). Thus, through observing-performed manipulations, children can use sensory-motor information to simulate content and construct a mental model, thereby aiding comprehension.

The inconsistency between the IH and the findings for the observing-perform manipulation (i.e., Glenberg et al., 2007; Marley et al., 2007) leads to a question: Does the information acquired from the motor modality of manipulation make a unique contribution to the improvement of reading comprehension among typical Chinese children? In other words, is the underlying mechanism of manipulation (on-line embodied cognition) in enhancing children's reading due to the construction of the mental model, the involvement of readers' bodies (i.e., operating manipulatives), or both? To examine this question, the present study involved three reading strategies: a reread condition, an observing-performed manipulation, and a participant-performed manipulation. The two manipulations provided perceptual (i.e., visual) and motor information that was required for constructing a mental model of the corresponding story. However, only the participant-performed manipulation involved readers' bodies and actions.

According to the prediction of the IH (Glenberg et al., 2004), because of the additional perceptual and action information, children in both manipulation conditions should show greater improvement than children in the reread condition; however, it is possible that the participant-performed manipulation will provide more benefits than the observing-performed manipulation. According to the view of embodied theories (Barsalou, 1999), compared with the observing-performed manipulation, the additional motor experience in the participant-performed manipulation might elicit a larger facilitative effect. The involvement of the motor system provides an additional modality (i.e., motor system) to process related information, which offers a more detailed embodied representation and a more elaborate memory trace. However, it is also possible that, consistent with Glenberg et al. (2007) and Marley et al. (2007), there will be no significant difference between the observing- and participant-performed manipulations. The visual representations of objects and correct information about how to use the objects may be enough for children to construct a complete mental model for language comprehension. The involvement of readers' bodies may not lead to further and unique enhancement.

Moreover, the current study also explored whether children can learn how to manipulate objects effectively from manipulations and whether there is a difference between observing- and participant-performed manipulations during strategy maintenance. Learning effective manipulation methods, specifically, how to move objects correctly guided by text, is a precondition that children can develop as an effective fundamental reading strategy (e.g., reading with an imagined manipulation rather than physical manipulation). Thus, after reading one passage using their assigned reading strategies (i.e., observing- and participant-performed manipulations), the present study provided a new playset to the children and asked them to manipulate the new playsets according to the new story. Comparing the observing- and participant-performed manipulations on the level of strategy maintenance can help us develop a more effective way to teach manipulation to children.

Regarding the developmental issue, a previous study found that younger children can benefit more from manipulation strategy than older children (Marley & Szabo, 2010). To illustrate, kindergarten and first-grade children were asked to listen to a story and free recall with their assigned strategies: picture/control condition (i.e., listened to the story content and viewed pictures of actors and objects in final positions as described by the text) and manipulation (i.e., listened to the story and moved and manipulated as directed by the stories). The results showed that although there was improvement in both the kindergarten and first-grade children, the improvement observed in the first-grade children was significantly less than that observed in the kindergarten children. Younger children, who have relatively more difficulties reading than older children, may rely more on the cues provided by external concrete embodied information. Consistent with the study by Marley and Szabo (2010), we presumed that younger children (i.e., second-graders) might benefit more from manipulation and/or observation than older children (i.e., fourth-graders).

To summarize, the research question for Study 2 examined the role of on-line embodied cognition in Chinese children's reading comprehension. Thus, second- and fourth-grade students were recruited to complete two reading comprehension tasks after reading using their assigned strategies (i.e., rereading condition and observing- and participant-performed manipulations). The difference between the two tests for the reading comprehension task was utilized as the indicator of each child's improvement. Children's age, nonverbal intelligence, and other abilities related to children's reading comprehension, i.e., RAN, working memory, Chinese character reading, phonological awareness, and morphological awareness, were included as control variables (the details of these control measures were described in the preceding section). There were three objectives in this study. First, we explored whether there was a difference between the observing- and participant-performed manipulations in terms of enhancing reading comprehension among Chinese children. Second, we investigated strategy maintenance in the observing- and participant-performed manipulations. Third, we examined whether there were age differences in acute improvement and strategy maintenance between the observing- and participant-performed manipulations.

Off-line embodied cognition in children's literacy performance. The influence of embodied cognition on literacy performance is not limited to the on-line mode; embodied cognition also affects the off-line mode. As described above, previous sensory-motor experiences stored in long-term memory (i.e., off-line embodied cognition) can be reused to affect current cognitive processing (Barsalou, 2008). A previous study found that infants with higher scores on motor exploration variables at 5 months of age had higher scores on intellectual and academic measures at 4-, 10-, and 14 years of age (Bornstein, Hahn, & Suwalsky, 2013). This indicates that there is a correlation between off-line embodied cognition and literacy performance; however, the mechanism of this association has not been clarified.

One focus of the current study was the relationship between off-line embodied cognition and word reading, which is a critical part of children's literacy performance. A previous study found a positive correlation between off-line embodied cognition and word reading (Wellsby & Pexman, 2014). This correlation might be related to the role of embodied cognition in word acquisition; that is, the acquisition of words could be affected by the corresponding embodied information involved in the words. Typically, it is easier for children to gain embodied experiences of concrete concepts (e.g., hat, wave) than of abstract concepts (e.g., idea, respect). For example, a mother will say, "here is your hat" and give the baby its hat, or a father will say, "wave bye-bye" and use the waving gesture. From these embodied interactions, symbols are grounded in bodily actions and perceptual experience (i.e., sensory-motor experience) (Glenberg & Gallese, 2012); thus, sensory-motor experience could facilitate children's word acquisition.

In addition, another explanation for the role of off-line embodied cognition in word reading might be that the sensory-motor experience contributes significantly to concept development and organization from infancy onward (Antonucci & Alt, 2011). Specifically, in the case of concrete concepts based on related sensory-motor information, children who have a better ability to utilize past experience should have a better method of categorization. For example, after gaining some experience with balls, children can summarize the same properties of individual balls such as shape and size. Then, they will be able to categorize objects that have the same critical properties as “balls”. Thus, they could save their mental resource to learn other words. At the same time, through the conceptual metaphor, concrete concepts could be helpful for children in learning related abstract concepts. For example, in the English saying, “Time is money”, money is the concrete concept that could help children understand the abstract concept of time. Through the metaphor, children could comprehend that there is something in common between the two concepts (e.g., valuable). In Chinese, the word 手足/shou3 zu4/ (sibling) is combined by the morpheme 手/shou3/ (hand) and 足/zu4/ (foot). Hand and foot are both important to our body; through the metaphor, children can recognize that 手足/shou3 zu4/ (sibling) could represent a person who is important and close to them. Taken together, off-line embodied cognition (i.e., previous sensory-motor experience) has a critical role in conceptual acquisition and mental lexicon development and thus benefits word reading.

At the same time, it has also been found that off-line embodied cognition is related to reading comprehension (Wellsby & Pexman, 2014): children with more developed off-line embodied cognition, measured through the simulation of concepts, exhibited better performance on reading comprehension. The research has found that when reading is effortful, readers construct a simulation of the described concepts/events (Wellsby & Pexman, 2014). Simulation is defined as the reaction of the internalized previous sensory-motor experience when processing the corresponding concept again

(Barsalou, 2008). The empirical evidence has shown that during reading, readers simulate the implied shape and orientation of objects (Engelen et al., 2011) and many other perceptual features of a situation such as the direction of motion (Glenberg & Kaschak, 2002; Zwaan, Madden, Yaxley, & Aveyard, 2004), the axis along with which an action took place (Richardson, Spivey, Barsalou, &, McRea, 2003), and the rate and length of fictive motion (Matlock, 2004).

Simulation might be the reason that off-line embodied cognition facilitates reading comprehension. The symbol interdependency hypothesis (Louwerse, 2011) suggests that concept representation could be both embodied and symbolic. That is, language comprehension can be symbolic through interdependencies of amodal linguistic symbols; however, it can also be embodied through the references obtained by these symbols for perceptual representations. Children with more embodied experience might be good at reactivating the related embodied information for conceptual processing, thereby facilitating comprehension. Furthermore, the procedure of reactivating past embodied information during reading (i.e., simulation) is useful for integrating symbolic and embodied information (Antonucci & Alt, 2011). Thus, children with this experience could build a comprehensive understanding more easily than children who lack this experience.

Two effects were utilized as indicators of off-line embodied cognition in the present study. One is called the body-object interaction (BOI) effect, and the other is the perceptual mismatch effect (Engelen et al., 2011; Siakaluk et al., 2008). The BOI effect is related to the different embodied degrees of concepts. In our daily life, different objects have different embodied properties due to the various chances of interactions between such objects and our bodies. For example, compared with “ship”, people have a greater possibility of producing a bodily interaction with “watch” because we have more interactions with “watch” than “ship” in daily life.

Based on this difference, Siakaluk et al. (2008) identified how easily a human body can physically interact with an object through BOI. BOI measurement focuses on previous experience interacting with objects; for instance, necklace, glove, and ring are high BOI words while vase, ship, and cloud are low BOI words. It is believed that objects with a higher frequency of connecting with the body in real life provide more embodied experience and would therefore be easier to understand and recognize (Siakaluk et al., 2008). Consistent with this prediction, it has been found that participants respond with greater speed and accuracy to high BOI words than to low BOI words (i.e., a BOI effect) on various tasks such as lexical decision tasks, phonological lexical decision tasks, and semantic categorization tasks (Wellsby, Siakaluk, Owen, & Pexman, 2011).

Another indicator of off-line embodied cognition is perceptual simulation, which is measured with a sentence-picture verification task. In this task, each picture is preceded by a spoken or written sentence describing an object whose perceptual information (i.e., shape or orientation) matched or did not match the depicted object in the picture. For example, in the match condition, a picture of a whole watermelon matches the shape of a watermelon in the sentence, “Keith saw the watermelon in the garden” while a picture of pieces of watermelon matches the sentence, “Keith saw the watermelon on the plate.” In the perceptual mismatch condition, the object depicted in the picture is still a watermelon;

however, its shape does not match the shape described in the sentence. Study results have shown that children respond faster to perceptually matched pictures than to mismatched pictures, and this has been labeled the perceptual mismatch effect (Engelen et al., 2011). Taken together, studies on the BOI effect and perceptual mismatch effect provide evidence that off-line embodied information is utilized in semantic processing (Engelen et al., 2011; Wellsby & Pexman, 2014).

However, the relationship between off-line embodied cognition and age is inconsistent when using different indicators (i.e., the BOI effect and the perceptual mismatch effect). To illustrate, in one study with English-speaking children (aged 6 to 9 years) as participants (Wellsby & Pexman, 2014), a developmental difference in the BOI effect was found. In this study, high and low BOI words were matched with the initial phoneme, word length, age of acquisition, subject frequency, print frequency, rated imageability and spelling-sound consistency. The results showed that only children who were 8 years or older showed a significant BOI effect, which was explained by the fact that children under 8 years of age did not have enough embodied experience to assist them in understanding and recognizing the words. This finding suggests that once sufficient life experience has been accumulated through interacting with objects, BOI effects emerge in word naming. In other words, young children (under 8 years old) have less life experience interacting with and gaining embodied knowledge from objects, which is important for lexical processing at the single word level (Engelen et al., 2011). In contrast, older children and adults have richer semantic representations for high BOI words due to previous bodily experience. This experience generates more semantic activation and provides stronger feedback in word processing. That is, the importance of off-line embodied cognition increases with age. In contrast, the findings from Engelen et al. (2011) indicated that the importance of perceptual simulation did not increase with age. That is, the embodied experience of younger children was enough for processing reading content and simulating the corresponding images, and the richer experience of older children had no extra effect. A possible reason for these inconsistent findings is although these two tasks can be used to measure children's off-line embodied cognition, their essences are still different. To illustrate, the BOI effect reflects the influence of off-line embodied cognition on enriching lexical representations, and the perceptual mismatch effect reflects the automatic reactivation of former concept-related embodied information. Analyzing the performance of the same participants in these two tasks can help us determine whether the developmental issue of the impact of off-line embodied cognition on children's language comprehension would be different with tasks.

The results regarding the association between off-line embodied cognition and literacy performance have also been inconsistent in studies in which the BOI effect and the perceptual mismatch effect were examined. To illustrate, in a study on the BOI effect using correlational analyses, the results showed that children's reading performance (letter identification, word comprehension, and passage comprehension skills) were all positively correlated with the BOI effect (Wellsby & Pexman, 2014). Further multiple regression analysis indicated that neither reading ability nor age predicted the BOI effect. Interestingly, after combining reading ability with age as a single indicator, the BOI effect was significantly predicted. However, in Engelen et al.'s (2011) study, there was no difference between less skilled (n=20, mean age = 8.4 years, range = 7.6-9.4) and skilled readers (n=58, mean age = 9.4 years, range = 7.5-11.0) in terms of the perceptual simulation effect. It should be noted that the influence of age was not taken into account in Engelen et al.'s (2011) study. That is, the possible relationship between off-line embodied cognition and children's reading might be counteracted by age. Typically, children's reading ability develops with age whereas off-line embodied cognition develops with the accumulation of embodied experience (Antonucci & Alt, 2011). Wellsby and Pexman's (2014) findings implied a possible positive relationship between embodied cognition and literacy performance. However, Engelen et al.'s (2011) results suggested the possibility that as age increases, the positive relationship between embodied cognition and literacy performance declines. To explore this possibility, the current study controlled the influence of age and then investigated the relationships between the BOI effect and literacy performance as well as between the perceptual mismatch effect and literacy performance.

To summarize, to explore the relationship between off-line embodied cognition (i.e., perceptual simulation) and literacy performance, we expanded on studies on the BOI effect and the perceptual mismatch effect (i.e., Engelen et al., 2011; Wellsby & Pexman, 2014) to some extent. First, we extended the research on perceptual simulation in Chinese, which has not been well investigated in the past. We utilized a lexical decision task (Wellsby & Pexman, 2014) and a picture-sentence verification task (Engelen et al., 2011) to measure the BOI effect and the perceptual mismatch effect, respectively, in Chinese children. In addition, regarding the relationship between age and off-line embodied cognition, the previous studies on both the BOI effect and the perceptual mismatch effect did not compare the results for children with those for adults. Comparing the results for children and adults can provide a clearer understanding of the development of off-line embodied cognition, for example, whether older children (i.e., fourth-grade students) have developed a similar pattern of the BOI effect and/or the perceptual mismatch effect as adults (i.e., who have well-developed off-line embodied cognition). Thus, in the present study, in addition to children of different ages (i.e., second- and fourth-grade students), we included a group of adults. Embodied experience is expected to accumulate with age if perceptual simulation has a positive correlation with age, as predicted by Wellsby and Pexman's (2014) study. Thus, we presumed that adults would have the largest BOI effect and perceptual mismatch effect while older children would have a larger BOI effect and perceptual mismatch effect than younger children.

Finally, we investigated the relationship between off-line embodied cognition and children's literacy performance with age as one of the control variables. The results for the BOI effect and perceptual mismatch effect were adopted as the indexes of off-line embodied cognition to explore how off-line embodied cognition is related to children's literacy performance (i.e., word reading and reading comprehension). In addition, the children were asked to complete tests measuring their literacy performance: Chinese character reading and reading comprehension. According to Wellsby and Pexman's (2014) results, there should be a positive correlation between off-line embodied cognition and children's literacy performance. That is, the larger the effect of off-line embodied cognition (BOI effect and/or perceptual mismatch effect) is, the better the performance on word processing and/or reading comprehension. In addition, we propose that there might be an interaction between age and off-line embodied cognition. Literacy performance involves the ability to integrate embodied cognition and disembodied cognition (Louwerse & Jeuniaux, 2010). As mentioned above, young children have less developed off-line embodied cognition than older children; thus, they have less ability to integrate embodied and disembodied cognition to access comprehensive representation (Antonucci & Alt, 2011). In other words, the association between off-line embodied cognition and literacy performance might be weaker in younger children than in older children. Nonverbal intelligence, RAN, phonological awareness, morphological awareness, and orthographic knowledge were measured as control variables. The details of the control measures are the same as the corresponding tasks of the section on on-line embodied cognition in Chinese character learning.

Summary

Our review of the literature indicates that the effect of embodied cognition on children's literacy performance is not always consistent. The core question is whether on-line and off-line embodied cognition influence younger and older children with different magnitudes. In the present study, we recruited Chinese children of different ages, i.e., second- and fourth-graders, all of whom participated in four tasks related to the association between embodied cognition and word processing and reading comprehension. The four embodied cognition tasks were 1) word learning by handwriting (to assess the relationship between on-line embodied cognition and Chinese character learning); 2) passage learning following the manipulation approach (to assess the relationship between on-line embodied cognition and reading comprehension); 3) lexical decision testing for the BOI effect; and 4) sentence-picture verification to assess perceptual simulation. The correlations of the BOI effect and perceptual simulation with word reading and reading comprehension were examined to investigate the relationship between off-line embodied cognition and Chinese children's literacy performance.

Second- and fourth-grade Chinese children were recruited because the lexical knowledge of the fourth-graders was fairly well developed but did not yet reach the ceiling while the second-graders were beginning to acquire literacy. The inclusion of children of both ages helped us better understand the development of embodied cognition and the role of age in the relationship between embodied cognition and literacy performance. In addition, to study the development of embodied cognition (off-line), adults, who are presumed to have well-developed embodied cognition, were also recruited.

Both the word/character and passage learning tasks had three phases: in the first phase (pretest), the children participated in a test measuring their performance on word reading or reading comprehension. In the second phase, the children were measured based on factors that may influence the learning effect: age, nonverbal intelligence, RAN, working memory, Chinese character reading, phonological awareness, morphological awareness, orthographic knowledge, writing, and visual-spatial processing (the last three control variables were included only in Study 1). The children were randomly assigned to different groups and received the corresponding training. Finally, in the posttest phase, all the children were asked to again complete relevant tests measuring word reading or reading comprehension. The magnitude of improvement observed for each training condition was used to analyze the effects of on-line embodied cognition. We assumed that training based on on-line embodied cognition would improve children's word reading and reading comprehension. Meanwhile, based on the literature (Glenberg & Robertson, 1999; Karlsdottir & Stefansson, 2002; Marley & Szabo, 2010), we assumed that second-grade students would benefit more from on-line embodied information than fourth-grade students.

The lexical decision task and sentence-picture verification task focused on the effect of off-line embodied cognition. Adults were recruited for these tasks in addition to the younger and older children. These two tasks investigated whether previous embodied experience is involved in word and sentence processing and whether there is an age difference in the effect of embodied experience. We assumed that due to different accumulations of embodied experience, adults would exhibit the largest effect of perceptual simulation (i.e., the BOI effect and perceptual mismatch effect) while older children would show a larger effect from perceptual simulation than younger children.

Next, we investigated the relationship between off-line embodied cognition and children's literacy performance. According to the results for the children on the two off-line embodied cognition tasks, we adopted two indexes of children's off-line embodied cognition, specifically, the BOI effect and the perceptual mismatch effect. The children were asked to complete tests measuring their literacy performance: Chinese character reading and reading comprehension. According to Wellsby and Pexman's (2014) results, there should be a positive correlation between off-line embodied cognition and children's literacy performance. That is, the larger the effect of off-line embodied cognition (BOI effect and/or perceptual mismatch effect), the better the performance on word processing and/or reading comprehension. Nonverbal intelligence (Raven's Standard Progressive Matrices), RAN (rapid naming of digits), working memory (repeat number sequences backward), morphological awareness (compounding production task), phonological awareness (phonological awareness task), and orthographic knowledge (Chinese character decision task) were measured as control variables.

Chapter 2: Study 1 Chinese character learning by handwriting

(Tap the relationship between on-line embodied cognition and word/character learning)

Study 1 explored the impact of on-line embodied cognition (i.e., handwriting) in Chinese character learning and whether this impact would differ with age. From the perspective of sensory-motor components, three training conditions were designed to explore the specific roles of visual, motor, and haptic modalities in the relationship between handwriting and Chinese character learning.

Method

Participants

In total, parental permission to participate in the experiment was obtained from 144 second-grade students (73 boys and 71 girls) and 150 fourth-grade students (82 boys and 68 girls). The children were recruited from a middle socioeconomic status public school in Zhejiang province, Mainland China. The mean age of the second-graders was 7 years and 9 months (SD = .37 months), and the mean age of the fourth-graders was 9 years and 9 months (SD = .36 months). All students were native speakers of Chinese (i.e., Putonghua) and had no physical or mental problems according to their teachers and parents.

Procedure

All children completed a test for control measures two weeks before the training session. The control measures included nonverbal intelligence, RAN, working memory, copying, and visual processing. In addition, abilities related to reading comprehension were also measured, including

Chinese character reading ability, morphological awareness, phonological awareness, and orthographical awareness. All these measures were conducted by trained experimenters individually and were completed in 1 hour. Each child received a set of stationery as incitement after they complete the whole study.

Measures

Control measures.

Raven's Standard Progressive Matrices. Raven's Standard Progressive Matrices (Raven, 1996) is a nonverbal multiple-choice measure of children's reasoning ability. Sets A, B and C were administered to measure the children's nonverbal reasoning. There were 36 items, and the maximum score was 36. For each test item, the children were asked to identify the missing element that completed a pattern from among six or eight choices. The Cronbach's alphas were .85 and .90 for the second- and fourth-graders, respectively.

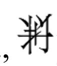
RAN for numbers. The RAN digit task was adapted from a task used in previous studies (e.g., Tong, McBride-Chang, Shu, & Wong, 2009). The participants were required to read aloud single-digit numbers arranged on a single page in a 5 (row) by 5 (column) array as quickly as possible. All five numbers (i.e., 1, 2, 5, 6, 8) were shown in each row in a randomized order. The participants were asked to complete the task twice, and the average completion time was calculated as the score. The Cronbach's alphas were .89 and .83 for the second- and fourth-graders, respectively.

Backward digit recall. The test was drawn from the study by Alloway and Alloway (2010) to measure working memory. In the test, the participants were required to recall a sequence of spoken digits in reverse order. For example, after listening to the digit sequence 3-2-5, the participants were required to give the correct answer: 5-2-3. There were 14 digit sequences in total, and the sequences ranged from two to eight digits. The accuracy of each sequence was recorded, and the maximum score was 14. The Cronbach's alphas were .69 and .77 for the second- and fourth-graders, respectively.

Chinese character reading. A Chinese character reading task (Liu & McBride-Chang, 2010) was used to examine the children's reading ability at the word level. In this task, the participants were required to read 100 characters aloud one-by-one, and testing stopped when the child failed to recognize 15 consecutive characters. The participants were sorted by difficulty. One point was awarded for each correct character; the maximum score for Chinese character reading was 100. The Cronbach's alphas were .94 and .81 for the second- and fourth- graders, respectively.

Phonological awareness. The phonological awareness of the participants was measured with a task consisting of 9 syllable deletions and 22 onset deletion items (McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003). In each syllable deletion item, the participants were asked to remove a syllable from a three-syllable word. For example, when removing "mao4" from "gong1 la1 mao4" the answer was "gong1 la1." In the onset deletion items, the participants were asked to remove the onset of a syllable. For example, "gai4" without "g," gave an answer of "ai4." One point was given for each correct answer, and the maximum score was 31. The Cronbach's alphas were .82 and .80 for the second- and fourth-graders, respectively.

Morphological awareness. The compounding production task was used to test the participants' morphological awareness (Liu et al., 2017). The participants were presented with a scenario and asked to create a novel word to represent it properly. For example, one item in this task was "我们把专门吃铁的怪兽叫做什么? (What should we call a monster that can only eat iron?)" The answer for this item was 吃铁怪 (iron-eating monster). The participants' answers were rated based on a five-point scale (0-4). There was a total of 31 items in this task, and the maximum score was 124. The Cronbach's alphas were .89 and .86 for the second- and fourth-graders, respectively.

Orthographic knowledge. A Chinese character decision task was included to assess the participants' awareness of orthographic patterns. There were four types of stimuli: 45 items with correct radical and legal orthographic rules in Chinese (e.g., ), 15 pseudocharacters with correct radical but illegal orthographic rules (e.g., ), 15 items with incorrect radical but legal orthographic rules (e.g., ), and 15 items with random combination of strokes (e.g., ). One score was recorded if the child judged the pseudocharacter as a character and rejected others as a character. There were a total of 90 items, and the maximum score was 90. The Cronbach's alphas were .82 and .92 for the second- and fourth- graders, respectively.

Copying. A copying task was adopted from a previous study (McBride-Chang et al., 2011) to measure the participants' writing. The participants were asked to copy three types of stimuli from examples: Korean words, Vietnamese diacritics, and Hebrew words. The assessment was administered to evaluate the children's ability to copy unfamiliar script across groups. There were 14 items in total; the accuracy of each item was recorded, and the maximum score was 14. The Cronbach's alphas were .78 and .80 for the second- and fourth- graders, respectively.

Visual-spatial processing. Two visual-spatial tasks were used to measure the participants' visual-spatial processing ability (Gardner et al., 1996). In the visual memory task, the participants were asked to look at an image for 5 seconds and then identify that specific image in a subsequent picture that consisted of 5 images. In the visual differentiation task, the participants were asked to look at a picture that contained 5 images and determine the one that was different from the other four as quickly as possible. There were 16 items in the memory task and 16 items in the differentiation task; the accuracy of each item was recorded, and the maximum score was 32. The Cronbach's alphas were .78 and .85 for the second- and fourth-graders, respectively.

Chinese character learning. There were three sessions in the Chinese character learning task: pretest, training, and posttest. These three sessions were conducted by experimenters in a quiet room in the primary school. The participants were tested individually by a trained experimenter in the three sessions.

Pretest. In the pretest session, 50 Chinese characters with extremely low frequency were measured. Each child was asked to read the characters aloud one-by-one. Based on the results of the pretest, 10 characters were selected as stimuli in the training and posttest sessions. They were compound simplified characters and consisted of two orthographic configurations: top-down and left-right. The average complexity of the characters was 8.6, the minimum was 5, and the maximum was 12. None of the children correctly read out any of these 10 characters in the pretest session, and none of the ten characters had any cues (i.e., phonetic radical) for pronunciation. The pretest was conducted one week before the training session.

Training session. Based on age, nonverbal intelligence, and performance on the control measures related to Chinese character learning and writing (i.e., RAN, working memory, visual-spatial processing, copying, Chinese character reading, phonological awareness, morphological awareness, and orthographic knowledge), the children in each grade were randomly assembled into four groups. A specific training strategy was assigned to each group of children: reading (control), visual processing, air writing, and handwriting. The mean scores and ANOVA results for age, nonverbal intelligence, RAN, working memory, visual-spatial processing, copying, Chinese character reading, morphological awareness, phonological awareness, and orthographic knowledge are summarized in Table 1 and Table 2 for the second-graders and fourth-graders, respectively. In total, there were 34, 36, 34, and 40 second-grade students in the reading, visual processing, air writing, and handwriting groups, respectively, and there were 40, 37, 37, and 36 fourth-grade students in the four conditions, respectively.

Table 1

Mean scores (SD) and ANOVA analysis of second graders in each group on age, non-verbal intelligence, RAN, working memory, copying, visual-spatial processing, Chinese character reading, phonological awareness, morphological awareness, and orthographic knowledge

	Second graders						
	Reading (N= 34)	Visual processing (N= 36)	Air writing (N= 34)	Handwriting (N= 40)	df	*F*	*p*
Age	7.87 (.33)	7.76 (.32)	7.89 (.44)	7.81 (.31)	3, 143	.92	.43
Non-verbal intelligence (maximum = 36)	26.73 (4.47)	26.71 (3.82)	27.73 (4.83)	27.13 (3.90)	3, 143	.43	.73
Rapid naming	18.92 (2.51)	17.83 (5.26)	17.09 (3.09)	17.74 (4.07)	3, 143	1.27	.29
Working memory (maximum = 14)	4.49 (1.71)	4.67 (1.56)	4.68 (1.67)	4.78 (1.73)	3, 143	.19	.90
Visual-spatial processing (maximum = 32)	19.48 (4.70)	20.61 (3.83)	20.44 (5.03)	20.93 (4.21)	3, 143	.70	.56
Copying (maximum = 14)	13.06 (1.10)	12.92 (1.00)	13.38 (.50)	13.13 (1.36)	3, 143	1.21	.31

Chinese character reading (maximum = 100)	85.82 (16.86)	81.53 (15.42)	89.44 (15.10)	88.67 (14.42)	3, 143	1.94	.13
Phonological awareness (maximum = 31)	43.71 (6.18)	45.36 (3.99)	44.48 (4.99)	44.55 (5.08)	3, 143	.62	.61
Morphological awareness (maximum = 124)	78.17 (22.00)	84.65 (17.72)	79.57 (22.14)	78.05 (23.36)	3, 143	.76	.52
Orthographic knowledge (maximum = 32)	69.15 (9.31)	71.08 (8.44)	72.32 (8.14)	70.95 (7.72)	3, 143	.83	.48

Table 2

Mean scores (SD) and ANOVA analysis of fourth graders in each group on age, non-verbal intelligence, RAN, working memory, copying, visual spatial processing, Chinese character reading, phonological awareness, morphological awareness, and orthographic knowledge

	Fourth graders						
	Reading (N= 40)	Visual processing (N= 37)	Air writing (N= 37)	Handwriting (N= 36)	df	*F*	*p*
Age	9.80 (.36)	9.95 (.36)	9.82 (.34)	9.74 (.35)	3, 149	2.15	.10
Non-verbal intelligence (maximum = 36)	29.60 (3.45)	27.04 (5.89)	27.48 (6.67)	27.32 (4.62)	3, 149	1.94	.13
Rapid naming	14.17 (3.13)	14.33 (2.94)	14.20 (3.01)	14.06 (2.79)	3, 149	.05	.96
Working memory (maximum = 14)	5.95 (2.76)	5.95 (2.20)	6.45 (2.11)	6.31 (1.72)	3, 149	.54	.65
Visual processing (maximum = 32)	23.76 (3.87)	22.62 (5.31)	23.68 (3.51)	23.35 (4.42)	3, 149	1.15	.33
Copying	13.10 (.67)	12.97 (1.17)	13.24 (.72)	12.75 (1.20)	3, 149	1.72	.17

(maximum = 14)							
Chinese character reading	115.03 (12.27)	110.46 (9.96)	112.39 (13.18)	114.37 (11.55)	3, 149	.54	.66
(maximum = 100)							
Phonological awareness	46.73 (4.19)	45.81 (4.30)	46.40 (4.36)	46.80 (3.17)	3, 149	.46	.71
(maximum = 31)							
Morphological awareness	94.45 (15.62)	88.49 (22.19)	95.46 (14.66)	96.54 (13.24)	3, 149	1.70	.17
(maximum = 124)							
Orthographic knowledge	72.75 (8.00)	88.49 (22.19)	95.46 (14.66)	68.58 (9.24)	3, 149	1.97	.12
(maximum = 32)							

PowerPoint (Microsoft Corporation, 2016) was used to present the characters one-by-one, and each character was presented simultaneously with the corresponding pronunciation three times. The characters in the control condition were presented with images of holistic characters whereas the characters in the other conditions were presented with animations (i.e., graphics interchange format images) of the characters showing the visual stroke presentation order. Examples of characters included in the reading condition and the other three conditions are displayed in Figure 1. Each character was presented for 15 seconds each time, and the duration of the training session was the same for each group (i.e., approximately 8 minutes). Examples of these four conditions are provided in Figure 2.

Figure 1. Examples of the stimuli in the Chinese character learning.

Note. The left one is an example of the holistic characters in the reading condition. The right one is an example of the characters (animation) in the other three conditions. It should be noted that the character animation was presented by stroke order, which was presented by the direction and number of the arrows. However, neither the arrows nor numbers were displayed in the experiment.

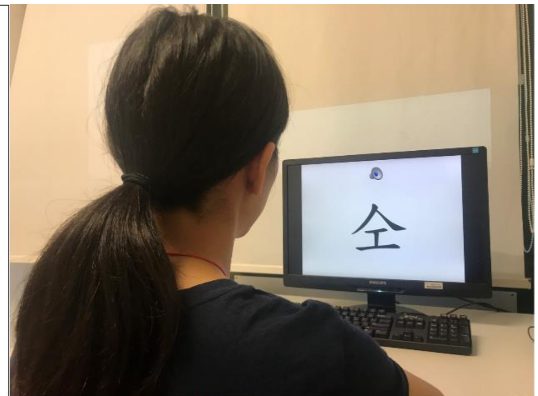
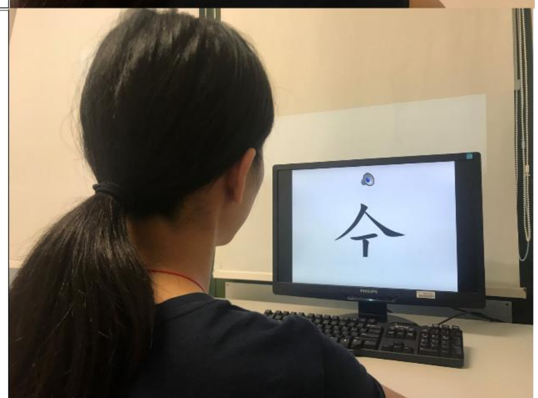
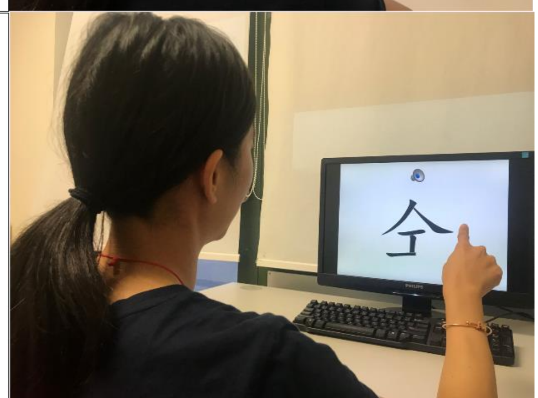
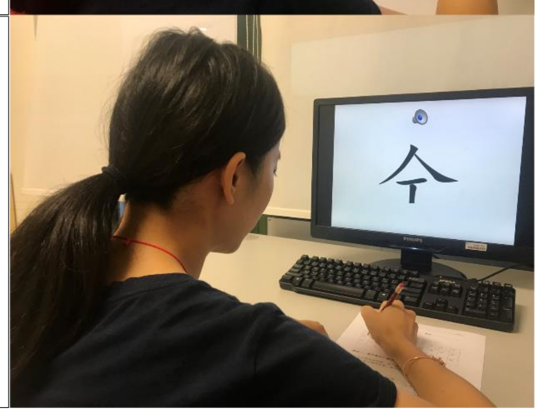
Reading. In the reading (control) condition, images of holistic characters were presented individually. Children were asked to look at the characters and listen to the pronunciation carefully.	
Visual processing. In the visual processing training condition, children were presented with an animation to show them how a given Chinese character is written. Children were asked to look at the animations and listen to the pronunciation carefully.	
Air writing. In the air writing condition, children were presented with an animation to show them how a given Chinese character is written and were asked to follow the animation to write the Chinese character with their index finger in the air and listen to the pronunciation carefully.	
Handwriting. In the handwriting condition, children were presented with an animation to show them how a given Chinese character is written and were asked to follow the animation to write the Chinese character with a pen on paper and listen to the pronunciation carefully.	

Figure 2. Examples of the four conditions in the Chinese character learning.

Reading. In the reading (control) condition, images of holistic characters were presented individually. The children were asked to look at the characters and listen to the pronunciation carefully.

Visual processing. In the visual processing training condition, the children were presented with an animation to show them how a given Chinese character is written. The children were asked to look at the animations and listen to the pronunciation carefully.

Air writing. In the air writing condition, the children were presented with an animation to show them how a given Chinese character is written, and they were asked to follow the animation to write the Chinese character with their index finger in the air and listen to the pronunciation carefully.

Handwriting. In the handwriting condition, the children were presented with an animation showing them how a given Chinese character is written, and they were asked to follow the animation to write the Chinese character with a pen on paper and listen to the pronunciation carefully.

Posttest. After a two-minute distractor (i.e., 60 mathematical addition items), the children were measured one-by-one, and they were asked to read aloud the 10 characters learned in the training session. These 10 characters were presented randomly in this session.

Results

Linear mixed model analysis

The results for each group on the Chinese character learning assessment are summarized in Table 3. A linear mixed model (LMM) was utilized to analyze the results for Chinese character learning. The LMM analysis allowed random factors (i.e., the participants and stimuli factors) to be considered simultaneously with fixed effects of interest such as grade (i.e., second and fourth grade), training group (i.e., reading, visual processing, air writing, and handwriting), item complexity and item order (i.e., the presentation order of the items in the training session). Because all 10 characters had low frequencies and none of the children read them correctly before the training, item frequency was not considered in the current study. A stepwise regression analysis using the LMM method was adopted to answer two questions: 1) Did the training effects differ by training groups? 2) Did the training effects differ by age? The LMM analyses were conducted using the lmer program of the lme4 package in R 3.4.2 (R Core Team, 2017), and the significance of the fixed effects was assessed using the lmerTest package.

Table 3

The mean scores (SD) of Chinese character learning

	Control	Visual processing	Air writing	Handwriting
Second graders	1.44 (1.19)	2.00 (1.71)	3.00 (1.99)	2.95 (1.87)
Fourth graders	2.80 (2.20)	2.89 (2.01)	4.19 (2.38)	4.56 (2.48)

We created an LMM model to investigate the training effects for different groups. The dependent variable was whether the participant read the character correctly. In this model, the random factors included those related to the participants (i.e., individual differences and item complexity and order) and stimuli (individual differences, grade and training group). Grade and training group were entered as fixed categorical factors whereas item complexity and item order were entered as fixed continuous factors. The interaction between grade and training group was also considered. In addition, the continuous factors were centered by a z-score transformation of the raw scores to overcome the problem of collinearity. The results of the primary model are summarized in Table 4. In the model, the reading (control) condition was set as the reference; the other three conditions (i.e., visual processing, air wiring, and handwriting) were compared with the reference. Thus, the model displayed the training effects of visual processing, air wiring, and handwriting compared with the control condition. To display the results more clearly, the training effects of the three conditions are presented as TVP (i.e., the difference between the visual processing and control conditions), TAW (i.e., the difference between the air writing and control conditions), and TH (i.e., the difference between the handwriting and control conditions).

Table 4

Linear mixed model estimates of fixed effects for training results of all participants

	Variables	Beta	SE	*t*	*p*
Primary model	Grade	.87	.29	2.97	.003
	TVP	.39	.31	1.26	.21
	TAW	1.02	.30	3.36	< .001
	TH	1.02	.29	3.47	< .001
	Item complexity	.33	.61	.55	.59
	Item order	-.24	.21	-1.12	.26
	Grade × TVP	-.32	.41	-.78	.44
	Grade × TAW	-.26	.40	-.63	.53
	Grade × TH	-.05	.40	-.13	.90

Note. TVP = training effect of visual processing; TAW = training effect of air writing; TH = training effect of handwriting.

The results of the LMM model showed that the main effect of grade was significant; the children in grade 4 showed greater improvement than the children in grade 2 (mean difference = 1.26, $p = .003$). The effects of TAW and TH were significant. In detail, the children in the air writing (mean difference = 1.47, $p < .001$) and handwriting (mean difference = 1.64, $p < .001$) conditions learned more characters than those in the control condition. However, there was no significant difference between the children in the visual processing and control groups (mean difference = .33, $p = .21$). The main effects of item complexity and item order were nonsignificant ($ps > .05$). The interactions between grade and TVP, between grade and TAW, and between grade and TH were nonsignificant. The results for each group in the second and fourth grades are displayed in Figure 3.

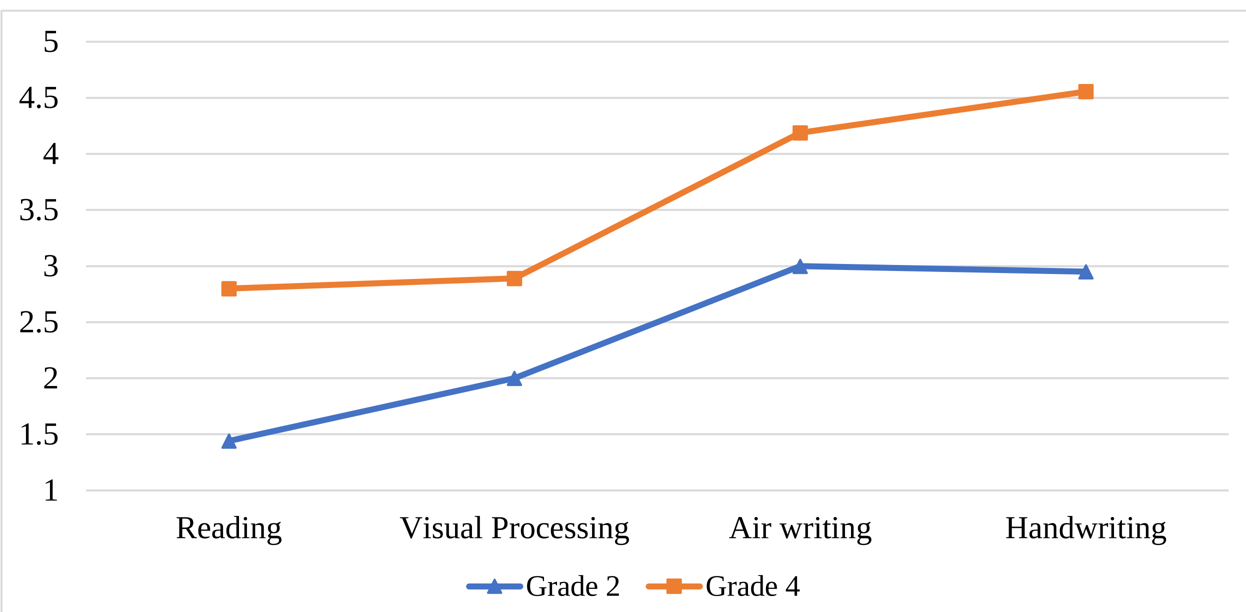


Figure 3. The results of Chinese character learning.

We conducted further post hoc analysis to compare the effects of three training conditions (i.e., TVP, TAW, and TH). The difference between the training effects of air writing and visual processing (Beta = .69, SE = .25, p = .045) and the difference between handwriting and visual processing were significant (Beta = .93, SE = .41, p = .02). The children in both the air writing condition and the handwriting condition exhibited a larger training effect than those in the visual processing condition. However, there was no significant difference between the handwriting and air writing groups (Beta = .29, SE = .38, p = .45).

Discussion

Study 1 addressed two research questions: 1) Do strategies with different degrees of on-line embodied information lead to different effects in Chinese character learning? and 2) Is there an age difference in the role of on-line embodied cognition in Chinese character learning? In line with the view of embodied cognition (Barsalou, 1999), we found that the children who used the air writing and handwriting strategies had better performance than the children in the control group (i.e., reading) and the visual processing group. However, unlike a previous study (Berninger et al., 1997), the children in the visual processing group did not gain more benefits than those in the control group. More importantly, the results of Study 1 illustrated that the children in the air writing and handwriting groups exhibited similar levels of improvement. However, Study 1 also found that there was no age difference in the relationship between on-line embodied cognition and Chinese character learning.

The roles of the on-line embodied components of handwriting in Chinese children's character recognition

Overall, consistent with the view of embodied cognition (Barsalou, 2008), the children who used strategies involving relatively more on-line embodied components (i.e., air writing and handwriting) performed better in Chinese character recognition than the children using strategies that involved fewer on-line embodied components (i.e., reading and visual processing). The findings suggest that the sensory-motor components of handwriting contribute to the improvement of reading performance in Chinese children.

However, inconsistent with our assumption, the visual processing condition, i.e., displaying characters with their stroke order information, did not provide additional benefits compared to the control condition, which displayed the overall shape. One possible reason for this result is that the focus of this study was on the link between orthography and pronunciation, which is relatively opaque in Chinese (Siok & Fletcher, 2001). Consistent with the present study, the previous studies in Chinese as a foreign language learners (i.e., adults) found that handwriting, either with or without stroke order, did not lead to significant improvement in the orthography-phonology link (Guan et al., 2011; Hsiung, Chang, Chen, & Sung, 2017).

However, in line with our assumption, both the air writing and handwriting conditions resulted in greater enhancements than the reading condition. Consistent with the previous studies (Bara & Gentaz, 2011; Maeland, 1992; McBride-Chang et al., 2011; Tseng & Murray, 1994; Vinter & Chartrel, 2010;

Wei & Amundson, 1994), the advantages of air writing and handwriting (compared with reading) highlight the important role of visual-motor integration and visual-motor-haptic integration of handwriting, respectively, in enhancing reading in Chinese children. To illustrate, although compared with reading holistic characters, the stroke order animation in the visual processing condition did not elicit a facilitative effect, additional improvement occurred once it was combined with motor processing and integrated with motor and haptic processing. These results demonstrate that the passive viewing of stroke order was not sufficient to strengthen the orthography-phonology link. However, once the children participated in producing (i.e., either through visual-motor integration or visual-motor-haptic integration) the character by correct stroke order, the connection between orthography and phonology was reinforced, which benefited Chinese character recognition. Together, the findings of the present study support that children cannot acquire the facilitative effect of stroke order based only on information obtained from the visual modality unless they generate the characters via stroke order through writing: air writing or handwriting.

By comparing the training effects of air writing and visual processing conditions, we illustrated the contribution of visual-motor integration. Consistent with a previous study (Tan et al., 2005), the present study showed that motor processing, which involves visual information, makes a unique contribution to improving children's reading performance, i.e., Chinese character recognition. An explanation for this result is that motor processing in air writing provides a motor modality for character processing (Barsalou, 2008). This information integrates with visual information to benefit the formation of the long-term memory of Chinese characters and then facilitates lexical retrieval. Consistent with this view, a functional magnetic resonance imaging study of Chinese character learning in English-speaking adults found involvement of the bilateral sensory-motor cortex in handwriting trained characters in the lexical decision task (Cao et al., 2013). Together, the visual-motor integrated processing of handwriting contributes to high-quality representations (Perfetti, 2007). Even in the case of Chinese, in which a character does not have a strong association with its pronunciation (Guan et al., 2011), motor processing can facilitate children's reading.

By comparing the training effects of handwriting and visual processing groups, we illuminated the unique contribution of the motor-haptic integration of handwriting to reading. In line with the study by Bara and Gentaz (2011) in French, the present study extended the crucial role of motor-haptic integration in benefiting Chinese children's reading ability. The findings in Bara and Gentaz (2011) implied that haptic exploration integrated with visual-motor skills contributes to a more complete perception of Chinese characters.

However, the similar training effects of the handwriting and air writing conditions found in the present study suggest that in addition to visual-motor integration, the haptic processing of handwriting per se did not lead to unique reading improvement in Chinese children. Consistent with the findings of the previous studies in Chinese (e.g., Guan et al., 2011; Tan et al., 2005), this study demonstrated a significant contribution of the involvement of visual and motor systems to Chinese character recognition. It has been suggested that visual and motor traces facilitate the memorization and retrieval of Chinese characters. A possible explanation for the similar facilitative effects of air writing is related to the degree of involvement of the motor modality. It should be noted that in the handwriting condition, the children primarily utilized their dominant hand whereas in the air writing condition, the children applied the whole arm from shoulder to fingers. Air writing might involve more processing of the motor modality that is related to the characters than handwriting. There is a possibility that the stronger processing of motor programming in air writing compensates for the effect of haptic processing in handwriting. Hence, despite the numbers of embodied modalities, the results of the current study support that the processing density of the embodied modality (e.g., motor system) is critical for enhancing reading performance (Louwerse, 2011).

At the same time, although there was no significant difference between the facilitative effects of air writing and handwriting, this does not warrant the conclusion that character-related processing in the haptic modality does not contribute to the facilitating of reading. Writing pressure, which is directly related to haptic feedback during handwriting, has been shown to be unique enough to be a biometric measure of identification (Srimathveeravalli & Thenkurussi, 2005). Thus, it has a unique and important role in influencing one's handwriting. More importantly, with the assistance of haptic processing, writers can produce and acquire the stroke sequence and overall shape of a character, which is important for character recognition (Guan et al., 2011). Thus, the contribution of haptic processing to Chinese character recognition might be elicited through orthography retrieval, which was not a focus of the present study. However, the duration of the training session was not enough to exert the facilitative effect of haptic processing. Typically, in primary school, children must write a new character repeatedly to acquire it. In the present study, the children wrote down each character only three times during a limited time frame. More writing might be needed to generate long-term memory related to the character in the haptic modality.

Furthermore, the nonsignificant contribution of haptic processing in the present study might be related to the participants and the stimuli (i.e., characters). The previous studies in English found that haptic exploration played a role in letter recognition (e.g., Bara, Fredmbach, & Gentaz, 2010; Bara & Gentaz, 2011); however, those studies focused on kindergarten students and letter recognition. The participants in those studies were younger than those in the present study, and the target stimuli were easier (i.e., low visual-spatial complexity) than those in the present study. Hence, it is possible that the impact of haptic processing is significant in younger children (e.g., kindergarten students) and/or for easier stimuli (e.g., characters with low complexity or radicals).

Regarding the developmental issue, the fourth-graders exhibited an overall greater enhancement than the second-graders. This result may be due to the better cognitive abilities of older children. Typically, compared with younger children (i.e., second-graders), older children (i.e., fourth-graders) are better able to focus their attention on a target, and they have better performance in terms of working memory. The advantages of these critical cognitive skills can facilitate learning efficiency (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005).

However, the facilitative effects of different strategies (i.e., visual processing, air writing, and handwriting) did not vary with age. That is, in the group in present study, there was no age difference in terms of the contributions of the visual, motor, and haptic modalities of handwriting to Chinese character recognition. One possible explanation for these results may be that although there was a developmental difference between the students in grades 2 and 4 at both the reading and writing levels (Carlisle, 2000; Karlsdottir & Stefansson, 2002), neither of these differences was large enough to elicit a developmental difference in the contributions of specific sensory-motor components to reading.

Chapter 3: Study 2 Passage learning

(The relationship between on-line embodied cognition and reading comprehension)

Study 2 investigated the role of on-line embodied cognition in the reading comprehension of Chinese second- and fourth-grade students. A typical manipulation strategy, i.e., manipulating related objects according to the text (Glenberg et al., 2004) was adopted as an approach of on-line embodied cognition. There are two critical sensory-motor components of the manipulation, specifically, the visual and motor systems. However, their specific contributions to improving reading comprehension have not been clarified (Glenberg et al., 2007; Marley et al., 2007). Therefore, in addition to a control (rereading) and a participant-performed manipulation condition, an observing-performed manipulation was added to the training groups. The participant-performed manipulation involved both visual and motor modalities whereas the observing-performed manipulation consisted only of the visual modality.

Method

Participants

The children who participated in Study 1 were recruited for Study 2; however, 10 second-graders and 10 fourth-graders did not complete Study 2 because they were absent on the training day. In total, 134 second-grade students (70 boys and 64 girls) and 138 fourth-grade students (75 boys and 63 girls) completed the tasks in Study 2.

Procedure

Each child was asked to complete a series of control measures individually in 1 hour with the instructions of the trained experiment. The control measures included nonverbal intelligence, RAN, and working memory. In addition, abilities related to reading comprehension were measured, including Chinese character reading, phonological awareness, and morphological awareness.

Measures

Raven's Standard Progressive Matrices. Study 2 used the same measurement process that was used in Study 1 for this measure. The Cronbach's alphas were .84 and .91 for the second- and fourth-graders, respectively.

RAN for numbers. The details of this measure were the same as those for the rapid-naming digit task in Study 1. The Cronbach's alphas were .89 and .83 for the second- and fourth-graders, respectively.

Backward digit recall. The details of this measure were the same as those for the repeat number sequences backward task in Study 1. The Cronbach's alphas were .68 and .75 for the second- and fourth-graders, respectively.

Chinese character reading. The details of this measure were the same as those for the Chinese character reading task in Study 1. The Cronbach's alphas were .94 and .81 for the second- and fourth-graders, respectively.

Phonological awareness. The details of this measure were the same as those for the phonological awareness task in Study 1. The Cronbach's alphas were .81 and .80 for the second- and fourth-graders, respectively.

Morphological awareness. The morphological construction test (McBride-Chang et al., 2003) was adapted for this task. The details were the same as those in Study 1. The Cronbach's alphas were .88 and .87 for the second- and fourth-graders, respectively.

Observing- and participant-performed manipulation training. There were three sessions in the present study: pretest, instructional period 1, and instructional period 2. These three sessions were conducted by experimenters in a quiet room in the school. One of two stories was used for the first instructional period, and the other story was used for the second instructional period. The order of the two stories was counterbalanced. These two narrative stories were selected from a Chinese textbook for grade 5 and were modified to ensure that none of the characters was new to the participants as confirmed by their teacher. Both stories were narrative. These two stories had 19 sentences and were composed of 513 and 528 characters, respectively. Each story contained 20 questions with 4 options. The questions were the same in the pre- and posttests and had the same options (but with different orders). The children were asked to choose an answer for each question. One point was awarded for each correct response, and the maximum reading comprehension score for each article was 20. The difference between the pre- and posttests was utilized as an index of the participants' improvement in reading comprehension.

Pretest. All the children were asked to complete two reading comprehension tasks (i.e., passage A and B) in the pretest. Thus, each child had two reading scores for the pretest. The pretest was measured one week before the training session.

Instructional period 1 (Acute enhancement). Based on age, nonverbal intelligence, and performance on the control measures (i.e., RAN, working memory, Chinese character reading, morphological awareness, and phonological awareness) and the pretest (i.e., scores for passages A and B), the children in each grade were randomly assembled into three groups. Each group participated in one of the three training programs: rereading (control), observing-performed manipulation, and participant-performed manipulation. The mean scores and ANOVA values for age, nonverbal intelligence, RAN, working memory, Chinese character reading, morphological awareness, and phonological awareness and scores on the two passages in the pretest are summarized in Table 5. In total, there were 42, 45, and 47 second-grade students in the rereading, observing-performed manipulation, and participant-performed manipulation groups, respectively, and there were 45, 46, 47 fourth-grade students in the three conditions, respectively.

Table 5

The summary of children in each group on age, non-verbal intelligence, RAN, working memory, Chinese character reading, morphological awareness, phonological awareness and scores of two passages in pre-test

	Second graders						Fourth graders					
	Rereading (N = 42)	Observing (N = 45)	Participant (N = 47)	df	*F*	*p*	Rereading (N = 45)	Observing (N = 46)	Participant (N = 47)	df	*F*	*p*
Age	7.87 (.39)	7.80 (.32)	7.80 (.37)	2, 131	.51	.60	9.83 (.39)	9.85 (.36)	9.82 (.33)	2, 135	.09	.91
Non-verbal intelligence (maximum = 36)	27.31 (3.95)	26.58 (3.84)	27.40 (4.00)	2, 131	.59	.56	27. 94 (5.61)	28.64 (4.04)	27.85 (4.87)	2, 135	.03	.98
Rapid naming	17.79 (3.08)	18.24(3.42)	17.76 (4.13)	2, 131	.21	.81	14.60 (2.76)	13.96 (2.99)	13.84 (3.17)	2, 135	.86	.43
Working memory (maximum = 14)	4.69 (1.73)	4.74 (1.64)	4.55 (1.53)	2, 131	.17	.85	6.27 (1.83)	6.20 (2.45)	6.05 (2.00)	2, 135	.13	.88
Chinese character reading	72.76 (10.26)	72.51 (11.93)	69.85 (11.80)	2, 131	.92	.40	87.42 (5.66)	88.67 (4.65)	88.55 (5.37)	2, 135	.79	.46

(maximum =100)												
Phonological awareness (maximum = 31)	44.71 (5.18)	44.56 (4.92)	43.94 (5.45)	2, 131	.28	.75	46.44 (4.15)	46.26 (4.23)	46.21 (3.98)	2, 135	.04	.96
Morphological awareness (maximum = 32)	81.79 (21.77)	81.94 (22.63)	76.17 (19.48)	2, 131	1.09	.34	91.53 (16.98)	96.84 (16.97)	92.37 (19.04)	2, 135	1.30	.28
Pre-test (passage 1) (maximum = 20)	9.88 (2.74)	9.87 (4.60)	9.11 (5.08)	2, 131	.49	.62	9.80 (3.81)	9.37 (6.04)	10.44 (5.42)	2, 135	.51	.60
Pre-test (passage 2) (maximum = 20)	8.84 (2.27)	8.00 (3.75)	8.74 (3.97)	2, 131	.79	.46	10.91 (3.34)	10.46 (5.27)	10.81 (4.74)	2, 135	.13	.88

Note. Observing= Observing-performed manipulation; Participant = Participant-performed manipulation

Each child was asked to read one of the two passages using their assigned strategy; the choice of the passage was counterbalanced. Unlike the previous studies (e.g., Glenberg et al., 2004), no critical sentence was marked in the present study; the children were required to read the whole text using their specific strategy. In the rereading and participant-performed manipulation conditions, the passage was presented sentence-by-sentence at the top of the screen. Each sentence was presented for a limited time (15 seconds). The training for each passage took approximately 5 minutes. In the observing-performed condition, the same passage was presented that was used in the other two conditions except that a corresponding video of the manipulation was presented (below the sentence) simultaneously with the sentence.

The children in all conditions were told the names of the objects in the corresponding playset before the training. None of the children were explicitly told that there would be a reading comprehension test after the training. The reading passage was followed by a 2-minute distractor (i.e., 60 mathematical addition items). Then, the children were asked to complete a reading comprehension task (i.e., related to the passage on which the child trained in instructional period 1). Examples of the rereading condition and the observing- and participant-performed manipulations are provided in Figure 4.

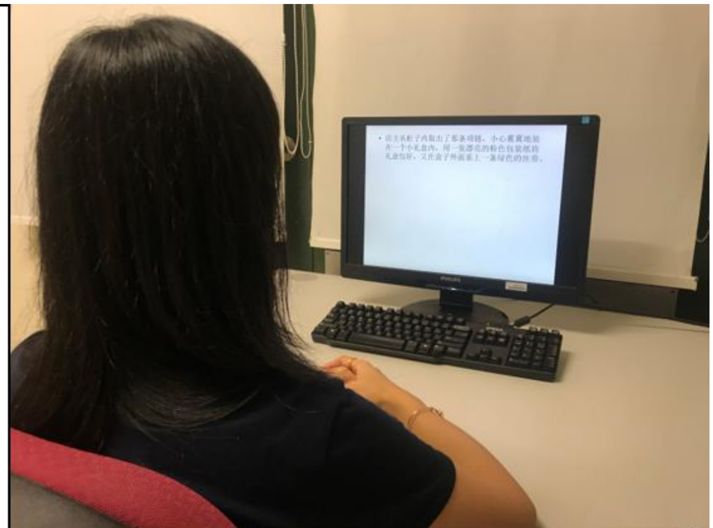
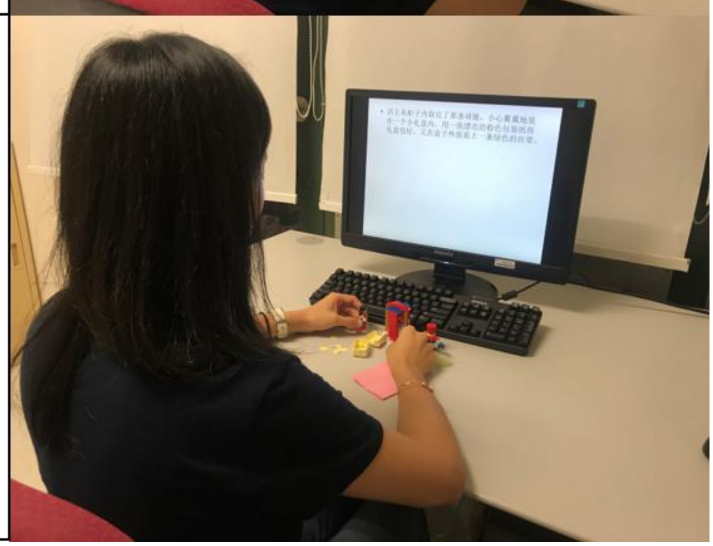
Rereading In the rereading training condition, the children were asked to read the article following the slides, sentence by sentence.	
Observing-performed manipulation Each sentence of the corresponding article was compared with a video of manipulating the relative toys; the children were instructed to observe the video carefully.	
Participant-performed manipulation A play set was provided containing the relative objects that corresponded to the article. In this session, the children were instructed to manipulate the corresponding toys simultaneously with the sentence presented on the slide.	

Figure 4. Examples of reread, observed-, and participant-performed manipulation strategies.

Rereading. In the rereading training condition, the children were asked to read the passages following the slides and sentence-by-sentence.

Observing-performed manipulation. Each sentence of the corresponding passage was compared with a video showing the manipulation of the relevant toys; the children were instructed to observe the video carefully.

Participant-performed manipulation. A playset was provided that contained relevant objects that corresponded to the passage. In this session, the children were instructed to manipulate the corresponding toys as the sentence was presented on the slide.

Instructional period 2 (Strategy maintenance). The children were grouped as they were in period 1. They were asked to read the alternative passage, which was presented by the method used in period 1. The reading passage was followed by the 2-minute distractor (i.e., 60 mathematical addition items) and then a reading comprehension task (i.e., for the passage on which the child trained in instructional period 2).

Rereading. The children were asked to read the passage sentence-by-sentence as they did in the first training session.

Observing-performed manipulation. A playset of objects related to the passage was provided. In this session, the children were instructed to manipulate the corresponding toys simultaneously with the sentences as they were presented on the slide.

Participant-performed manipulation. The instruction for this group was the same as the instruction for the observing-performed manipulation.

The detailed procedures for the pretest, instructional period 1, and instructional period 2 are illustrated in Table 6.

Table 6

The details of pre-test, instructional period 1, and instructional period 2

		Rereading	Observing	Participant
Step 1: Pre-test		Two reading comprehension tasks		
Step 2: Instructional Period 1				
(Acute enhancement)	Introduction	Children were told the name of objects of the corresponding play set (one of two stories, which was counterbalanced) and asked to read the story using their assigned reading strategies.		
	Story passage	Yes	Yes	Yes
	Manipulation video	No	Yes	No
	Physical manipulation	No	No	Yes
Step 3: Two-minute distractor		60 mathematical addition items (session 1)		
Step 4: Reading comprehension task		Children were asked to complete a reading comprehension task for the one for which they were trained in instructional period 1		
Step 5: Instructional Period 2				

(Strategy-maintenance)	Introduction	Children were told the name of objects of the alternative play set and asked to read the story using their assigned reading strategies.		
	Story passage	Yes	Yes	Yes
	Manipulation video	No	No	Yes
	Physical manipulation	No	No	Yes
Step 6: Two-minute distractor		60 mathematical addition items (session 2)		
Step 7: Reading comprehension task		Children were asked to complete a reading comprehension task for the one for which they were trained in instructional period 2		

Note. Observing = Observing-performed manipulation; Participant = Participant-performed manipulation

Results

The differences for each passage were calculated for instructional periods 1 and 2 and utilized as indicators of acute enhancement and strategy maintenance, respectively. A 2 (Grade: second/fourth) × 3 (Training: reading/observation/manipulation) ANOVA was conducted for these two improvement indicators. Both grade and training condition were between-subject factors. The improvements between the two training sessions for the children in each group are summarized in Table 7.

Table 7

The mean (SD) improvement of two instructional periods for children in each group

	Second graders			Fourth graders		
	Rereading (N = 42)	Observing (N = 45)	Participant (N = 47)	Rereading (N = 45)	Observing (N = 46)	Participant (N = 47)
Instructional Period 1	2.19	2.83	3.08	2.20	4.59	6.17
(Acute enhancement)	(2.66)	(3.16)	(3.19)	(2.67)	(3.29)	(4.09)
Instructional Period 2	2.31	2.60	3.17	2.91	4.47	4.95
(Strategy-maintenance)	(1.91)	(3.02)	(2.94)	(2.86)	(4.06)	(4.11)

Note. Observing = Observing-performed manipulation; Participant = Participant-performed manipulation

The analysis of acute enhancement (i.e., instructional period 1) showed that the main effect of grade was significant, $F\ (1, 274) = 17.16$, $p < .001$, $\eta_p^2 = .06$. The fourth-grade students exhibited greater improvement than the second-grade students (mean difference = 1.62). The main effect of the training condition was significant, $F\ (1, 274) = 12.94$, $p < .001$, $\eta_p^2 = .09$. The children in both the observing-performed manipulation (mean difference = 1.51, $p = .002$) and the participant-performed manipulation (mean difference = 2.42, $p < .001$) groups had significantly greater improvements than those in the reading group; the difference between the participant- and observing-performed manipulations was marginally significant (mean difference = .91, $p = .055$).

The interaction between grade and training condition was significant, $F\ (1, 274) = 5.16$, $p = .006$, $\eta_p^2 = .04$ (see Figure 5). Further analysis of the simple main effect of grade revealed that the differences among the three training conditions were not significant for the second-graders (ps > .05). However, for the fourth-graders, the children in both the observing-performed (mean differences = 2.39, $p < .001$) and participant-performed (mean differences = 3.96, $p < .001$) manipulations showed a significantly larger improvement than those in the rereading group. Moreover, the children in the participant-performed manipulation group showed a significantly larger improvement than those in the observing-performed manipulation group (mean difference = 1.58, $p = .02$). However, further analysis on the simple main effect of training revealed that the fourth-graders had a significantly larger improvement than the second-graders in the observing-performed manipulation (mean differences = 1.76, $p = .01$)

and the participant-performed manipulation (mean differences = 3.09, $p < .001$) conditions but not in the rereading condition (mean differences = .01, $p = .99$).

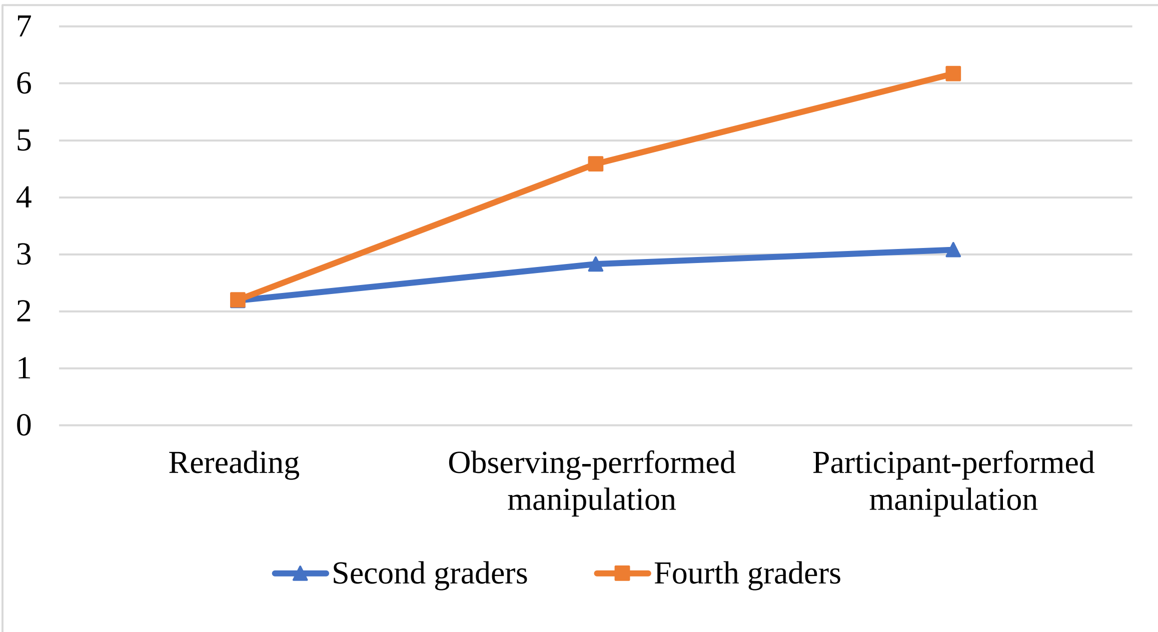


Figure 5. Results of Instruction Period 1 (Acute enhancement).

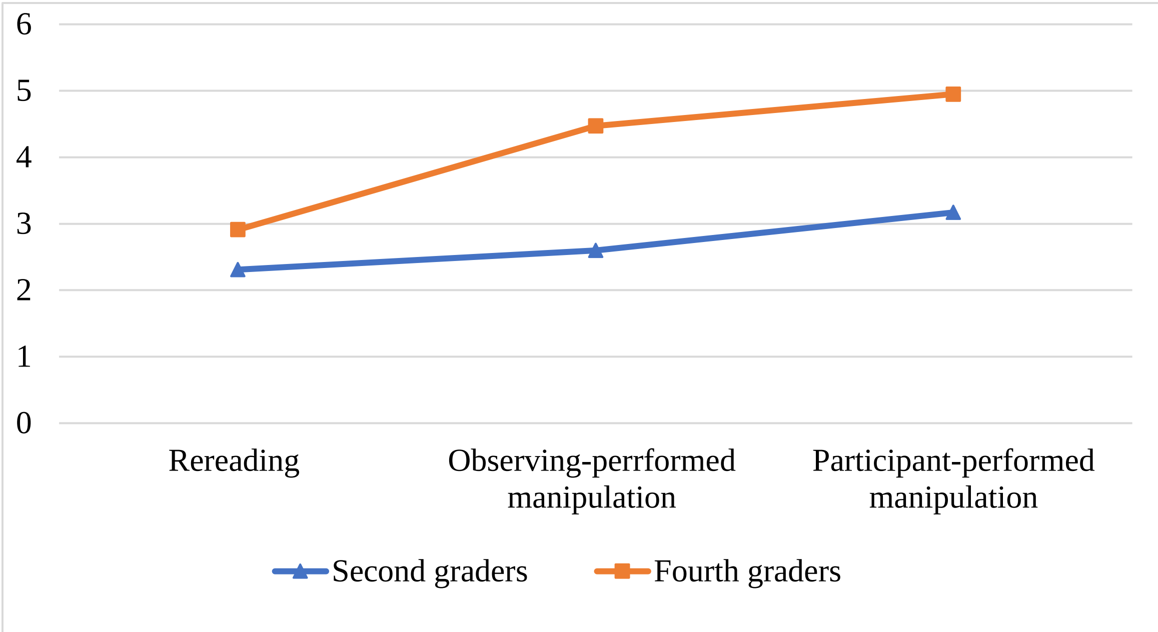


Figure 6. Results of Instruction Period 2 (Strategy maintenance).

The analysis of strategy maintenance (i.e., instructional period 2) showed that the main effect of grade was significant, F (1, 274) = 12.92, $p < .001$, $\eta_p^2 = .05$. The fourth-grade students had a larger improvement than second-grade students (mean difference = 1.42). The main effect of the training condition was significant, F (1, 274) = 4.53, $p = .01$, $\eta_p^2 = .03$. The children in the observing-performed manipulation exhibited a marginally greater facilitative effect than those in the rereading condition (mean differences = .92, $p = .06$). The children in the participant-performed manipulation condition had a significantly greater improvement than those in the rereading condition (mean differences = 1.45, $p = .003$). However, the difference between the observing- and participant-performed manipulations (mean differences = .53, $p = .27$) was nonsignificant, and the interaction between grade and training condition was also nonsignificant, F (1, 274) = 1.05, $p = .35$, $\eta_p^2 = .01$.

The results for strategy maintenance showed that the second- and fourth-grade students had distinctive patterns for the three training conditions (see Figure 6). To determine the specific patterns of the two grades, we split the data by grade and conducted a one-way ANOVA test. The results showed that the main effect of the training condition was not significant in the second-grade children, F (1, 133) = 1.17, p = .31, η_p^2 = .02; however, it was significant in the fourth-grade children, F (1, 133) = 3.75, p = .03, η_p^2 = .05. Further analysis for simple main effects revealed that among the fourth-graders, the children in both the observing-performed (mean differences = 1.56, p = .02) and participant-performed (mean differences = 2.04, p = .003) manipulations showed greater improvement than those in the rereading condition. However, the difference between the observing- and participant-performed manipulations (mean differences = .48, p = .47) was not significant.

Discussion

The present study addressed three questions: (1) Do observing- and participant-performed manipulations elicit different degrees of enhancement for reading comprehension in Chinese children? (2) Do observing- and participant-performed manipulations lead to different effects on strategy maintenance? (3) Are there age-related differences in the ability to benefit from observing- and participant-performed manipulations? It should be noted that as the current study did not investigate other types of passages, the current findings of these questions were specific to the narrative stories. Consistent with the IH (Glenberg et al., 2004), the present study found that both the observing- and participant-performed manipulations had a larger facilitation effect than the rereading condition for both acute enhancement and strategy maintenance in Chinese children. Moreover, the participant-performed manipulation led to a larger improvement than the observing-performed manipulation at the acute enhancement stage; however, there was no difference between these two manipulations at the strategy maintenance stage. However, inconsistent with the previous studies (Marley & Szabo, 2010), the findings of the current study showed that in Chinese speakers, older children (i.e., fourth-graders) benefited more than younger children (i.e., second-graders) from external embodied strategies (i.e., observing- and participant-performed manipulations) in both the enhancement and strategy maintenance of reading comprehension.

The role of the observing- and participant-performed manipulations in the reading comprehension of Chinese children

Overall, the results of the present study demonstrated that, consistent with the view of embodied cognition (Barsalou, 1999), the observing- and participant-performed manipulations provided additional benefits in terms of reading comprehension in Chinese children that were not evident in the rereading condition. Compared with the rereading condition, both of these manipulations included visual representations of objects and motor representations related to how the objects should be moved that were aligned with the sentences in the text. This finding suggests that consistent with studies on gestures (e.g., Dargue & Sweller, 2018; Macoun & Sweller, 2016), children can gain semantically related visual and motor information by observing others' manipulations and actually performing physical manipulation. This sensory-motor information can assist children in simulating the content of stories and constructing a corresponding mental model, which can in turn aid comprehension (Glenberg, Willford, Gibson, Goldberg, & Zhu, 2012).

Furthermore, we extended the findings of Marley et al. (2007) to typical readers. However, in contrast to children with learning disabilities, typical readers benefited more from physical manipulation than from observation. In line with the prediction of the IH (Glenberg et al., 2004), the involvement of readers' bodies and actions in manipulation elicited a unique enhancement of reading comprehension. Consistent with the present study, a study in English-speaking adults found that students who manipulated a virtual anatomical structure (i.e., inner ear) were more likely to draw the structures more successfully than those who observed the structure in a stereoscopic environment (Jang, Vitale, Jyung, & Black, 2017).

According to the view of embodied cognition (Barsalou, 1999), the involvement of the motor system in the participant-performed manipulation provided an additional modality for language processing. This additional modality offers more information for encoding, thereby improving comprehension. Although the findings of studies on observing actions support that the motor system can be activated through observation, it has been found that physically manipulating an object can elicit stronger activity in the motor cortex than passively observing the object being manipulated by a motor (Kosslyn, Thompson, Wraga, & Alpert, 2001). Thus, there is a possibility that participant-performed manipulation may lead to a deeper processing of concepts than observing-performed manipulation, especially for motor representations, which may lead to better comprehension.

In addition to adding a motor modality for information storage and retrieval, another difference between the two types of manipulations was that the connection between readers' perceptual and motor systems was direct in the participant-performed manipulation but not in the observing-performed manipulation. It should be noted that the motor representations of the texts in these two manipulations were provided through different modalities: they were presented through a visual system in the observing-performed condition while they were provided through a motor system in the participant-performed manipulation. That is, the children in the observing-performed manipulation had to acquire the motor information through a visual modality rather than directly from the motor system. Thus, in the participant-performed manipulation, the direct coordination between motion and the visual features of the target objects could make it easier for the children to integrate the visual and motor information than the indirect link involved in the observing-performed manipulation. In other words, physical manipulation was more effective than observation in helping the children to derive the inferences necessary to construct integrated mental models (Moreno & Mayer, 1999; Rubman & Salatas Waters, 2000), resulting in greater reading enhancement.

However, similar to the results for acute enhancement, the findings for strategy maintenance showed that the Chinese children in the observing- and participant-performed manipulations performed better overall than those in the rereading condition. This result demonstrated that after training with specific manipulation strategies (i.e., observing- and participant-performed manipulations), the children acquired knowledge of how to move objects as directed by the sentences and applied this knowledge to new texts. Moreover, our findings showed that the facilitated effects of these two manipulations were no different in the strategy maintenance section. This illustrates that although physical manipulation provided an additional benefit to acute reading enhancement compared with observation, this benefit faded with respect to internalizing the manipulation approaches.

However, the findings of the current study do not indicate that the involvement of the reader's body and actions (i.e., physical manipulation) did not make any extra contribution to manipulation strategy maintenance. It is possible that the specific contribution of physical manipulation was counteracted by other factors in the observing-performed manipulation. To illustrate, it should be noted that in instructional period 1, the observing-performed manipulation might have provided more correct manipulations than the participant-performance manipulation. The manipulation in the observing-performed condition was a standard version guided by the text whereas the manipulation in the participant-performed condition involved individual differences. Without standard guidance, the children may made incorrect, irrelevant, and/or redundant manipulations. Thus, the advantage of physical manipulation may be reduced. In contrast, there were no invalid manipulations in the observing-performed condition. Thus, the children acquired the ability to manipulate effectively, which helped them develop a fundamental manipulation strategy.

Developmental differences between the observing- and participant-performed manipulations in terms of reading comprehension in Chinese children

One of the important findings in the current study was the developmental difference in the role of the observing- and participant-performed manipulations in reading comprehension in this sample of Chinese children. The findings of this study demonstrated that, for the fourth-graders, both the observing- and participant-performed manipulations contributed to reading enhancement from both the acute enhancement and the strategy maintenance aspects. However, for the second-graders, neither of the two manipulations displayed more benefits than rereading. Unlike the study by Marley et al. (2007), in the present study, differences based on age were observed for both acute enhancement and strategy maintenance. More importantly, the older children (i.e., fourth-graders) benefited more from embodied training than did the younger children (i.e., second-graders).

One explanation for the younger children not benefiting from the embodied reading strategies (i.e., observing- and participant-performed manipulations) as much as the older children is that younger children cannot understand linguistic content as efficiently as older children. That is, as a limitation of their reading ability, the younger children may have misunderstood a passage and then made an incorrect manipulation. These incorrect manipulations should interfere with the facilitating effect of the manipulation method on reading comprehension. Another reason may also relate to the integration of external visual and motor information with written language in the construction of a mental model. To achieve successful reading comprehension, children must focus on reading-relevant information. However, for the younger children in the current study, the video used in the observing-performed manipulation, the objects of the participant-performed manipulation, or the manipulation itself may have distracted them such that they could not appropriately integrate these tools with the linguistic symbols. In addition, it should be noted that unlike the previous studies (e.g., Glenberg et al., 2004), no critical sentences were marked in the current study. The children therefore needed to determine the critical information and suppress the irrelevant information themselves. Hence, in the present study, these two manipulation strategies may have provided too much external information, which could have made it more difficult for the younger children to allocate cognition resources (i.e., attention, working memory). Consistent with this assumption, it has been found that moderate external embodied information accompanying reading is better whereas unconstrained physical manipulation can lead to irrelevant and redundant operations, thus making the manipulation suboptimal for learning (Stull, Barrett, & Hegarty, 2013). The findings of the present study imply that Chinese children may be unable to benefit from external embodied information unless they have a relatively well-developed ability to integrate embodied information with linguistic symbols (Wilson & Golonka, 2013).

General discussion of Study 1 and Study 2

From the on-line cognition perspective, the present study found that external on-line sensory-motor information facilitates children's literacy performance (i.e., Chinese character recognition and reading comprehension). More specifically, the findings of Studies 1 and 2 demonstrated that external embodied information, which is related to linguistic stimuli, facilitates children's literacy performance in general. However, the results were inconsistent at the developmental level. Study 1 found that the influences of specific sensory-motor components (i.e., visual, motor, and haptic systems) in handwriting on facilitating

Chinese character learning were similar for the younger and the older children (i.e., second- and fourth-graders); however, Study 2 demonstrated that the older children (i.e., fourth-graders) benefited more from external embodied information for reading comprehension than the younger children (i.e., second-graders). In other words, the older children (i.e., fourth-graders) obtained the benefits of on-line embodied information in both studies. However, the younger children (i.e., second-graders) benefited from on-line embodied information only for Chinese character learning, but not for reading comprehension.

This difference might be because Study 1 focused on form acquisition whereas Study 2 required more semantic processing of text. In Study 1, the embodied modalities were involved in the generation of characters' forms. Thus, the link between embodied cognition and the learning objective was direct. However, in Study 2, the on-line embodied information was associated with semantic processing. The children were supposed to integrate concrete objects and linguistic symbols through their actions, and then they could construct mental models for understanding. Hence, compared with Study 1, Study 2 might have required a more complex integration of external embodied information and linguistic symbols, which is relatively difficult for younger children (i.e., second-graders). Hence, with increasing age, on-line embodied cognition can facilitate children's literacy performance from form processing to semantic processing.

Chapter 4: Study 3 Off-line embodied cognition and literacy performance

Study 3 explored the development of off-line embodied cognition. Two typical tasks, i.e., a sentence-picture verification task (Engelen et al., 2011) and a BOI task (Wellsby et al., 2011), were recruited to measure children's off-line embodied cognition, and their results were compared with those of adults. In addition, the children's two indicators of off-line embodied cognition, i.e., the perceptual mismatch effect and the BOI effect, were utilized to investigate the relationships between off-line embodied cognition and literacy performance.

Method

Participants

The children who participated in Study 1 were recruited for Study 3, except for 4 second-grade students and 1 fourth-grade student who were absent on the testing day. In total, 140 second-grade students (71 boys and 69 girls) and 149 fourth-grade students (78 boys and 71 girls) participated in Study 3. In addition, 30 undergraduate students whose native language was Putonghua were recruited. Each adult was paid in cash (RMB 50/h) after the test.

Procedure

All participants completed the sentence-picture verification task, lexical decision task, and BOI rating. The participants completed the BOI rating last, and the order of the sentence-picture verification and lexical decision tasks was counterbalanced. All participants were asked to complete these three tasks individually with the instruction of trained experiments in 20 minutes. Then, the children individually completed a series of tests in 1 hour on their general literacy ability (i.e., Chinese character reading and reading comprehension) and other control measures.

Measures

Off-line embodied cognition measures.

Sentence-picture verification task. We conducted a sentence-picture verification task adopted from Engelen and colleagues' (2011) study, and the perceptual mismatch effect was used to measure the participants' off-line embodied cognition. We constructed 48 experimental sentence pairs, each of which implied a distinct shape of the same object, for example, "果园里种着西瓜, the watermelon in the garden" and "果盘里放着西瓜, the watermelon on the fruit plate". In the former case, the image was of the whole watermelon whereas, in the latter, the image was of pieces of watermelon. For each experimental sentence pair, we chose one picture of the described object. This picture matched the object's shape implied in one of the sentences but not in the other. All of the pictures were black-and-white and drawn by an undergraduate student majoring in visual arts. In addition, 24 filler items were constructed, all of which featured unrelated pictures.

The trials began with the presentation of a fixation cross at the center of the screen for 250 milliseconds, with a "beep" sound to remind the participant that the test was about to start. After a blank screen that was presented for 1000 milliseconds, a sentence appeared at the center of the screen for 3000 milliseconds. Simultaneously, the subject heard the corresponding audio. Then, after showing another blank screen for 1000 milliseconds, one picture appeared in the center of the screen. After the participant made a judgment, as quickly as possible, about whether the depicted object had been mentioned in the sentence (“F” referred to yes; “J” referred to no), a blank screen was replaced by the next trial after 1000 milliseconds. The participants began with 10 practice trials consisting of 5 related and 5 unrelated pictures. Next, they completed a sequence of 48 trials, of which 24 were experimental. Each participant performed 12 match and 12 mismatch trials, all requiring affirmative responses. In addition, there were 24 trials requiring negative responses. All trials were presented in random order. The participants were encouraged to make judgments as quickly and accurately as possible. The experiment took approximately 15 minutes to complete. The experimental procedure is illustrated in Figure 7.

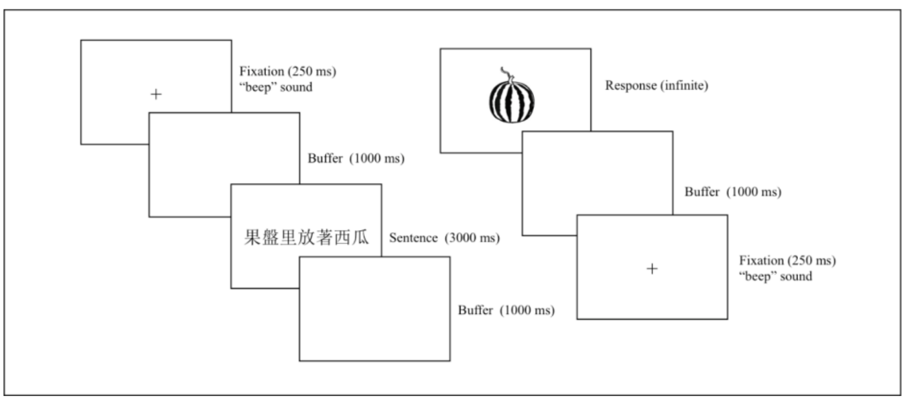


Figure 7. Procedure of sentence-picture verification task.

Lexical decision task. A lexical decision task was utilized to investigate the participants’ off-line embodied cognition (i.e., BOI effect). The task included 60 words and 60 nonwords. All words were selected from a Chinese textbook from Mainland China. The frequency of the words varied from .05 to .16, and the average frequency of the words was .04 (Da, 2004).

In the paradigm, the trials began with the presentation of a fixation cross at the center of the screen for 400 milliseconds, and then a word or pseudoword appeared at the center of the screen for 2000 milliseconds. The participants were asked to judge whether the words made sense. Half of the participants used the “F” key on the keyboard to provide a “yes” response and used the “J” key to provide a “no” response; for the other half of the participants, the response keys were reversed. After a 1000 millisecond blank screen, the next trial began. The participants were encouraged to make judgments as quickly and as accurately as possible. All trials were presented in a random order. The experiment took approximately 10 minutes to complete. The experimental procedure is illustrated in Figure 8.

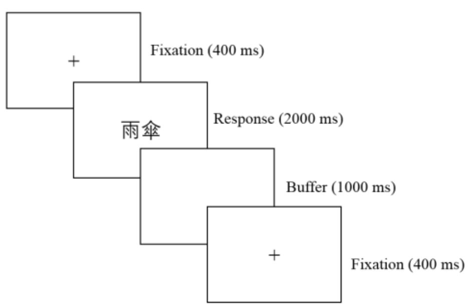


Figure 8. Procedure of lexical decision task.

BOI rating. After finishing the sentence-picture verification task and the lexical decision task, all participants were asked to complete a rating task for the 60 words in the lexical decision task. The results of this test were utilized as the BOI index for the corresponding words. The BOI rating procedure was the same as that used for the lexical decision task except that there were no pseudowords and the children were asked to rate on a 1-7 scale how easily they could physically interact with each word's referent; a rating of 1 was extremely easy, and 7 was extremely hard. The experiment took approximately 5 minutes to complete. The experimental procedure is illustrated in Figure 9.

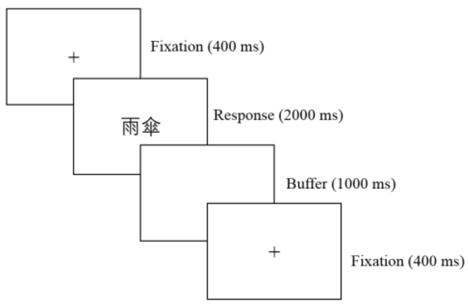


Figure 9. Procedure of BOI rating.

Literacy performance measures.

Chinese character reading. In addition to the 100 characters used in the corresponding task in Study 1, to increase the variance, 50 characters were selected from a Chinese textbook for grade 6. The characters were sorted by difficulty. Testing stopped when the child failed to recognize 15 consecutive characters. Each correct character was measured as one point; the maximum score for Chinese character reading was 150. The Cronbach's alphas were .90 and .82 for the second- and fourth-graders, respectively.

Reading comprehension. A reading comprehension task was adopted from a previous study (Leong, Hau, Tse, and Loh, 2007). The children were asked to read two short passages and answer six multiple-choice questions regarding each passage in 10 minutes. Each correct option was awarded one point; the maximum score for reading comprehension was 12. The Cronbach's alphas were .73 and .78 for the second- and fourth-graders, respectively.

Control measures.

Raven's Standard Progressive Matrices. The details of this measure were the same as those for Raven's Standard Progressive Matrices in Study 1. The Cronbach's alphas were .85 and .90 for the second- and fourth-graders, respectively.

RAN for numbers. The details of this measure were the same as those for the rapid-naming digit task in Study 1. The Cronbach's alphas were .89 and .83 for the second- and fourth-graders, respectively.

Phonological awareness. The details of this measure were the same as those for the phonological awareness task in Study 1. The Cronbach's alphas were .82 and .80 for the second- and fourth-graders, respectively.

Morphological awareness. The morphological construction test (McBride-Chang et al., 2003) was adapted for this task. The details are the same as those in Study 1. The Cronbach's alphas were .89 and .83 for the second- and fourth-graders, respectively.

Orthographic knowledge. The details of this measure were the same as those for the orthographic knowledge task in Study 1. The Cronbach's alphas were .81 and .92 for the second- and fourth-graders, respectively.

Results

Sentence-picture verification task (perceptual mismatch effect)

The response latencies that were three standard deviations above or below a participant's condition mean for "correct" were excluded (1.83%). The percentages of correct responses and average response times for the perceptual matching and mismatching experimental trials in each group are provided in Table 8.

Table 8

Accuracy and response times for children and adults in sentence-picture verification task

	Perceptual matching		Perceptual mismatching	
	ACC	RT	ACC	RT
	M (*SD*)	M (*SD*)	M (*SD*)	M (*SD*)
Grade 2	.83 (.13)	1854.63 (702.44)	.78 (.14)	2003.82 (951.53)
Grade 4	.90 (.13)	1409.15 (474.91)	.80 (.16)	1532.99 (570.25)
Adults	.95 (.08)	562.24 (147.04)	.95 (.10)	653.56 (183.14)

A 2 (Perceptual condition: Match/Mismatch) × 3 (Group: Second-graders/Fourth-graders/Adults) repeated measures ANCOVA was conducted. The perceptual condition was a within-subject factor, and the grade of the participants was a between-subject factor. The results for accuracy showed that the main effects of perceptual simulation (F (1, 316) = 25.77, p < .001, η_p^2 = .08) and group (F (2, 316) = 23.05, p < .001, η_p^2 = .13), and the interaction between them (F (2, 314) = 25.77, p = .001, η_p^2 = .05) were significant. The participants responded with greater accuracy to the perceptual matching stimuli than to the perceptual mismatching stimuli (mean difference = .05). The adults had the highest accuracy whereas the second-graders had the lowest accuracy. Further analysis on the simple main effect showed that the perceptual mismatch effect was significant for the second-grade (t (1,139) = 4.57, $p < .001$, Cohen's $d = .77$) and fourth-grade (t (1,148) = 8.02, $p < .001$, Cohen's $d = 1.36$) students but not for the adults (t (1, 29) = .23, $p = .82$, Cohen's $d = .14$).

The results for response time showed that the main effects of perceptual simulation (F (1, 316) = 10.81, $p = .001$, $\eta_p^2 = .03$) and group (F (2, 316) = 63.03, $p < .001$, $\eta_p^2 = .29$) were significant. The participants responded faster to the perceptual matching stimuli than to the perceptual mismatching stimuli (mean difference = 121.45). The adults had the highest speed whereas the second-graders had the lowest speed. However, the interaction between perceptual condition and group (F (2, 314) = .19, $p = .82$, $\eta_p^2 = .001$) was nonsignificant.

In brief, in the sentence-picture verification task, 1) accuracy and response speed increased with age; 2) a significant perceptual mismatch effect was observed in the children but not in the adults at the accuracy level; and 3) a similar perceptual mismatch effect was observed in the children in both grades and in the adults at the response speed level.

Sentence-picture verification task (perceptual simulation) and literacy performance

To determine the possible relationship between perceptual simulation and children's reading performance, we conducted a correlation analysis. In the correlation analysis, age and nonverbal intelligence were used as control variables. The perceptual mismatch effects of accuracy (PMEacc) (i.e., matching - mismatching) and response time (PMErt) (i.e., mismatching - matching) were treated as indicators of perceptual simulation (embodied cognition). In addition, to consider the perceptual mismatch effect from the simultaneous perspectives of accuracy and latency, we calculated a ratio (PMEratio) (i.e., $\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$) of the perceptual mismatch effect for each child. Thus, there were three indicators for the perceptual mismatch effect: PMEacc, PMErt, and PMEratio. The correlations among all measures for the children in grades 2 and 4 are shown in Tables 9 and 10, respectively.

Table 9

Correlations among all measures of Grade 2

Control variables			1	2	3	4	5	6	7	8	9
Age and Non-verbal IQ	1	PMEacc	-								
	2	PMErt	-.26**	-							
	3	PMEratio	.79***	.08	-						
	4	CCR	-.02	.19*	.13	-					
	5	RC	.06	.20*	.14	.18*	-				
	6	PA	.009	-.03	.05	.32***	.08	-			
	7	MA	.001	.18	.11	.05	.03	.29**	-		
	8	OK	.19*	.05	.27**	.13	.19*	-.15	-.004	-	
	9	RAN	-.02	-.15	-.07	-.31	-.19*	.01	-.02	-.15	-

N = 140

Note. PMEacc = perceptual mismatch effect of accuracy; PMErt = perceptual mismatch effect of response time; PMEratio = perceptual mismatch effect of ratio (i.e., $\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$); CCR = Chinese character reading; RC = reading comprehension; PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming

**p* < .05; ***p* < .01; ****p* < .001

Table 10

Correlations among all measures of Grade 4

Control variables			1	2	3	4	5	6	7	8	9
Age and Non-verbal IQ	1	PMEacc	-								
	2	PMErt	-.08	-							
	3	PMEratio	.71***	.34	-						
	4	CCR	-.16	-.04	-.28**	-					
	5	RC	-.10	-.06	-.17*	.34***	-				
	6	PA	-.12	-.007	-.09	.23**	.12	-			
	7	MA	-.002	.07	-.02	..29***	.18*	.36***	-		
	8	OK	-.11	.11	-.05	.10	.14	-.04	-.04	-	
	9	RAN	.09	-.06	.07	-.30***	-.09	-.22	-.05	-.05	-

N = 149

Note. PMEacc = perceptual mismatch effect of accuracy; PMErt = perceptual mismatch effect of response time; PMEratio = perceptual mismatch effect of ratio (i.e.,$\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$); CCR = Chinese character reading; RC = reading comprehension; PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming

**p* < .05; ***p* < .01; ****p* < .001

The correlation analysis for the second-graders showed that PMEacc was significantly correlated with PMErt ($r = -.26$, $p = .002$), PMEratio ($r = .79$, $p < .001$) and the children's performance in orthographic knowledge ($r = .19$, $p = .03$). PMErt was significantly correlated with the children's performance in Chinese character reading ($r = .19$, $p = .03$) and reading comprehension ($r = .20$, $p = .02$). PMEratio was significantly correlated with the children's performance in orthographic knowledge ($r = .27$, $p = .002$). In addition, the children's performance in Chinese character reading was significantly correlated with their performance in reading comprehension ($r = .18$, $p = .03$) and their performance in phonological awareness ($r = .32$, $p < .001$). The second-graders' performance in reading comprehension was significantly related to their orthographic knowledge ($r = .19$, $p = .03$) and RAN ($r = -.19$, $p = .03$). The correlation between performance in phonological awareness and morphological awareness was significant ($r = .29$, $p = .001$).

The correlation analysis for the fourth-graders showed that the correlation between PMEacc and PMEratio was significant ($r = .71$, $p < .001$). The correlations between PMEratio and the fourth-graders' performance in Chinese character reading ($r = -.28$, $p = .001$) and between PMEratio and the fourth-graders' performance in reading comprehension ($r = -.17$, $p = .045$) were significant. In addition, the fourth-graders' performance in Chinese character reading was significantly correlated with their performance in reading comprehension ($r = .34$, $p < .001$), phonological awareness ($r = .23$, $p = .005$), morphological awareness ($r = .29$, $p < .001$), and RAN ($r = -.29$, $p < .001$). Their performance in morphological awareness was significantly correlated with reading comprehension ($r = .18$, $p = .03$)

and phonological awareness ($r = .36$, $p < .001$).

Multiple regressions were conducted to further explore the associations of perceptual simulation with reading performance (i.e., Chinese character reading and reading comprehension). In all the regression models, age and nonverbal intelligence were entered in the first block, and phonological awareness, morphological awareness, and orthographic knowledge were entered in the second block, RAN was entered in the third block, and the perceptual mismatch effect (i.e., PMEacc, PMErt, and PMEration) was entered in the fourth and final block. Thus, there were six regression models in total, and the details of each model are summarized in Tables 11–16.

Table 11

Hierarchical regressions explaining Chinese character reading (perceptual simulation on accuracy level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	p	R^2	R^2 change	Final beta	p
1	Age	.09	.09	.06	.42	.05	.05	.09	.25
	Non-verbal IQ			.17	.03			.10	.19
2	PA	.21	.12	.35	< .001	.13	.11	.08	.35
	MA			-.06	.44			.25	.003
	OK			.14	.08			.09	.27
3	RAN	.28	.08	-.28	< .001	.18	.06	-.24	.002
4	PMEacc	.25	.002	-.05	.51	.19	.01	-.12	.12

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMEacc = perceptual mismatch effect of accuracy

Table 12

Hierarchical regressions explaining Chinese character reading (perceptual simulation on response time level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.09	.09	.08	.29	.08	.05	.06	.43
	Non-verbal IQ			.15	.06			.10	.21
2	PA	.21	.12	.37	< .001	.16	.11	.09	.28
	MA			-.10	.24			.25	.002
	OK			.13	.09			.11	.17
3	RAN	.28	.08	-.25	.001	.22	.06	-.25	.001
4	PMErt	.31	.03	.17	.03	.22	.007	-.09	.26

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMErt = perceptual mismatch effect of response time

Table 13

Hierarchical regressions explaining Chinese character reading (perceptual simulation on ratio level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.09	.09	.06	.44	.05	.05	.09	.23
	Non-verbal IQ			.17	.03			.09	.26
2	PA	.21	.13	.35	< .001	.16	.11	.07	.37
	MA			-.07	.40			.24	.002
	OK			.11	.15			.09	.25
3	RAN	.28	.08	-.28	< .001	.22	.06	-.24	.002
4	PMEratio	.28	.003	.06	.43	.27	.06	-.24	.001

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMEratio = perceptual mismatch effect of ratio (i.e., $\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$)

Table 14

Hierarchical regressions explaining reading comprehension (perceptual simulation on accuracy level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.04	.69	.14	.13	.09	.24
	Non-verbal IQ			.02	.79			.27	.001
2	PA	.05	.05	.11	.26	.18	.05	.04	.66
	MA			-.001	1.00			.16	.06
	OK			.18	.048			.13	.10
3	RAN	.08	.03	-.16	.62	.18	.003	-.05	.52
4	PMEacc	.08	.00	.02	.83	.19	.004	-.07	.39

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMEacc = perceptual mismatch effect of accuracy

Table 15

Hierarchical regressions explaining reading comprehension (perceptual simulation on response time level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.06	.47	.13	.13	.07	.38
	Non-verbal IQ			-.01	.95			.27	.001
2	PA	.05	.05	.12	.18	.18	.05	.04	.62
	MA			-.04	.68			.16	.05
	OK			.17	.04			.15	.07
3	RAN	.08	.03	-.13	.11	.18	.003	-.06	.45
4	PMErt	.11	.03	.18	.04	.19	.01	-.09	.28

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMErt = perceptual mismatch effect of response time

Table 16

Hierarchical regressions explaining reading comprehension (perceptual simulation on ratio level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.04	.65	.13	.13	.09	.24
	Non-verbal IQ			.02	.79			.27	.001
2	PA	.05	.05	.10	.28	.18	.05	.03	.69
	MA			-.01	.92			.16	.06
	OK			.16	.08			.13	.10
3	RAN	.08	.03	-.16	.07	.18	.003	-.05	.54
4	PMEratio	.09	.01	.08	.35	.20	.02	-.14	.068

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; PMEratio = perceptual mismatch effect of ratio (i.e., $\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$)

Then, to exclude the influence of performance on Chinese character reading on the relationship between off-line embodied cognition and reading comprehension, we added the score for Chinese character reading to the regression models. The results of these three models are summarized in Tables 17, 18, and 19.

Table 17

Hierarchical regressions explaining reading comprehension (perceptual simulation on accuracy level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.03	.74	.13	.13	.06	.38
	Non-verbal IQ			.005	.95			.23	.002
2	PA	.05	.05	.07	.49	.18	.05	.02	.86
	MA			.005	.95			.08	.29
	OK			.16	.07			.10	.17
3	RAN	.08	.03	-.13	.15	.18	.003	.02	.82
4	CCR	.09	.01	.06	.29	.25	.07	.16	.001
5	PMEacc	.09	.00	.02	.79	.25	.001	-.03	.66

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; CCR = Chinese character reading; PMEacc = perceptual mismatch effect of accuracy

Table 18

Hierarchical regressions explaining reading comprehension (perceptual simulation on response time level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.06	.51	.13	.13	.05	.49
	Non-verbal IQ			-.02	.86			.23	.002
2	PA	.05	.05	.10	.33	.18	.05	.02	.84
	MA			-.03	.73			.09	.26
	OK			.16	.06			.11	.13
3	RAN	.08	.03	-.11	.19	.18	.003	.01	.88
4	CCR	.08	.008	.04	.49	.25	.07	.16	.001
5	PMErt	.11	.02	.17	.06	.25	.003	-.06	.42

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; CCR = Chinese character reading; PMErt = perceptual mismatch effect of response time

Table 19

Hierarchical regressions explaining reading comprehension (perceptual simulation on ratio level)

Block and variable		Grade 2				Grade 4			
		R^2	R^2 change	Final beta	*p*	R^2	R^2 change	Final beta	*p*
1	Age	.01	.01	.03	.70	.13	.13	.06	.37
	Non-verbal IQ			.007	.94			.23	.002
2	PA	.05	.05	.07	.50	.18	.05	.01	.86
	MA			-.002	.98			.09	.27
	OK			.14	.11			.11	.16
3	RAN	.08	.03	-.13	.15	.18	.003	.02	.84
4	CCR	.09	.01	.06	.32	.25	.07	.15	.002
5	PMEratio	.09	.005	.08	.39	.25	.005	-.07	.32

Note. PA = phonological awareness; MA = morphological awareness; OK orthographic knowledge; RAN = rapid naming; CCR = Chinese character reading; PMEratio = perceptual mismatch effect of ratio (i.e., $\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$)

Taken together, the results of the original six regression models showed that after controlling for age, nonverbal intelligence, phonological awareness, morphological awareness, orthographic knowledge, and RAN, the perceptual mismatch effect (i.e., perceptual simulation) accounted for unique variance in Chinese character reading for the children in grade 2 (PMErt, 3%, $p = .03$) and grade 4 (PMEratio, 6%, $p = .001$) and in reading comprehension for the children in grade 2 (PMErt, 3%, $p = .04$) and grade 4 (PMEratio, 2%, $p = .068$). However, when Chinese character reading was taken into account, the perceptual mismatch effect accounted for unique variance in reading comprehension only for the children in grade 2 (PMErt, 2%, $p = .06$) and not for those in grade 4. The summarized results of the perceptual mismatch effect in all the regression models are displayed in Table 20.

Table 20

The summarized results of perceptual mismatch effect in all regression models

Dependent variable	Off-line EC index	Grade 2 R^2	Grade 2 R^2 change	Grade 2 Final beta	Grade 2 *p*	Grade 4 R^2	Grade 4 R^2 change	Grade 4 Final beta	Grade 4 *p*
Chinese character reading	PMEacc	.25	.002	-.05	.51	.19	.01	-.12	.12
	PMErt	.31	.03	.17	.03	.22	.007	-.09	.26
	PMEratio	.28	.003	.06	.43	.27	.06	-.24	.001
Reading comprehension	PMEacc	.08	.00	.02	.83	.19	.004	-.07	.39
	PMErt	.11	.03	.18	.04	.19	.01	-.09	.28
	PMEratio	.09	.01	.08	.35	.20	.02	-.14	.068
Reading comprehension (with control of Chinese character reading)	PMEacc	.09	.00	.02	.79	.25	.001	-.03	.66
	PMErt	.11	.02	.17	.06	.25	.003	-.06	.42
	PMEratio	.09	.005	.08	.39	.25	.005	-.07	.32

Note. EC = embodied cognition; PMEacc = perceptual mismatch effect of accuracy; PMErt = perceptual mismatch effect of response time; PMEratio = perceptual mismatch effect of ratio (i.e.,$\frac{\text{Matching}_{\text{Correct\%}} - \text{Matching}_{\text{Incorrect\%}}}{\text{Matching}_{\text{rt}}} - \frac{\text{Mismatching}_{\text{Correct\%}} - \text{Mismatching}_{\text{Incorrect\%}}}{\text{Mismatching}_{\text{rt}}}$)

Lexical decision task (BOI effect)

Three second-graders and five fourth-graders did not complete the lexical decision task due to a disfunction in the program. The results of the BOI rating and lexical decision task are summarized in Table 21 and Table 22, respectively.

Table 21

The means (SD)of BOI rating

	BOI value
Grade 2	4.46 (.69)
Grade 4	4.71 (.67)
Adults	4.03 (1.50)

Table 22

Accuracy and response times for children and adults in lexical decision task

	ACC	RT
Grade 2	.80 (.21)	1374.38 (554.38)
Grade 4	.88 (.18)	994.15 (316.14)
Adults	.97 (.04)	553.11 (67.75)

Linear mixed model analysis. An LMM was utilized to compare response preference and response time in the lexical decision task. This approach allowed random factors (i.e., participants and stimuli factors) to be considered simultaneously with fixed effects of interest such as the BOI value (i.e., for each group, that is, for the second- and fourth-graders and the adults, their mean score for every word in the BOI rating task was treated as the BOI value for the corresponding stimuli) and participant group (i.e., second- and fourth-graders and adults). A stepwise regression analysis using the LMM method was adopted to answer two questions: a) whether the BOI effect was significant in Chinese; and b) whether there was a difference in the BOI effect among participants of different ages (i.e., second- and fourth-graders and adults). The LMM analyses were conducted by using the lmer program of the lme4 package in R 3.4.2 (R Core Team, 2017), and the significance of the fixed effect was assessed by using the lmerTest package.

BOI effect. We created two primary LMM models for investigating the BOI effect in Chinese: Model 1 focused on the accuracy aspect, and Model 2 focused on the response time aspect. In the primary models, the random factors included those related to the participants (i.e., individual differences and BOI value) and the trials (individual differences in stimuli, participant group). The group was entered as a fixed categorical factor whereas BOI value and the control variables (i.e., item complexity and frequency) were entered as fixed continuous factors. The interaction between BOI value and group was also taken into account. In addition, the continuous factors (i.e., BOI value, item complexity and item frequency) were centered by z-score transformation of raw scores to overcome the problem of collinearity. The results of the primary models are summarized in Table 18. In the primary models for accuracy and response time, the adult group was set as the reference. Thus, in the models, P2vsA referred to the difference between the second-graders and the adults (i.e., second-graders -

adults) while P4vsA referred to the difference between the fourth-graders and the adults (i.e., fourth-graders - adults).

Table 23

Linear mixed model estimates of fixed effects for lexical decision task (BOI effect)

	Variables	Beta	SE	*t*	*p*
Model 1	BOI value	.17	.14	1.23	.22
(Accuracy)	P2vsA	-2.13	.34	-6.23	< .001
	P4vsA	-1.36	.34	-3.98	< .001
	Item complexity	.001	.06	.02	.99
	Item frequency	.17	.06	2.89	.004
	BOI value × P2vsA	-.03	.14	-.23	.82
	BOI value × P4vsA	.01	.14	.05	.96
Model 2	BOI value	-.07	.02	-2.74	.01
(Response time)	P2vsA	-.01	.08	-.12	.91
	P4vsA	-.02	.08	-.21	.83
	Item complexity	.01	.01	1.07	.29
	Item frequency	-.05	.01	-3.93	< .001
	BOI value × P2vsA	.06	.03	2.23	.03
	BOI value × P4vsA	.08	.03	2.96	.003

Note. BOI value = rating of Body-Object Interaction; P2vsA = second graders – adults; P4vsA = fourth graders – adults

The primary model for accuracy showed that the main effects of P2vsA and P4vsA were significant (*p*s < .001). There was a significant difference between the second-graders and the adults and between the fourth-graders and the adults. The adults had greater accuracy than the second-graders (mean difference = .19) and the fourth-graders (mean difference = .09). In addition, the post hoc analysis showed that the fourth-graders had greater accuracy than the second-graders (mean difference = .10, *p* < .001). The main effect of item frequency was significant (*p* = .004); the items with higher frequency had higher accuracy than the items with lower frequency. The main effects of BOI value and item complexity, the interaction between BOI value and P2vsA, and the interaction between BOI value and P4vsA were nonsignificant (*p*s > .05).

The primary model for response time showed that the main effect of BOI value was significant (*p* = .01); the participants utilized less time to provide a correct response to words with a higher BOI value. The main effect of item frequency was significant (*p* < .001); the participants used less time to provide correct responses to words with higher frequency. In addition, the interaction between BOI value and P2vsA (*p* = .03) and the interaction between BOI value and P4vsA were significant (*p* = .003). The effect of BOI value was different between the adults and the second-graders and between the adults and the fourth-graders. That is, the adults were found to have a larger BOI effect than the second-graders and the fourth-graders. The main effects of P2vsA, P4vsA, and item complexity were nonsignificant (*p*s > .05)). In addition, the post hoc analysis showed that the BOI effect was not significantly different between the second- and fourth-graders (Beta = .02, SE = .02, p = .27).

To summarize, in the lexical decision task, the main effect of item frequency, was significant for both accuracy and response time. The higher the frequency of the items, the higher the accuracy and response speed observed. In the accuracy analysis, the adults presented the highest level of accuracy, and the fourth-graders had greater accuracy than the second-graders. In the response time analysis, the BOI effect was significant; items with higher BOI values had higher response speeds. The interaction between BOI value and P2vsA and the interaction between BOI and P4vsA were significant. That is, there was a difference in the BOI effect between the adults and the children in both grades. However, the BOI effect was not different between the children in different grades.

BOI effect and children's literacy performance. To further investigate the BOI effect in children, another two LMM models (i.e., Models 3 and 4) were constructed. These models were similar to Models 1 and 2. In addition to BOI value and grade, the control variables (i.e., children's age, nonverbal intelligence, item complexity and item frequency) were entered as fixed factors. The continuous factors (i.e., BOI value, children's age, nonverbal intelligence, item complexity, and item frequency) were centered by a z-score transformation of the raw scores to overcome the problem of collinearity. The interaction between BOI value and grade was taken into account. The results are summarized in Table 24.

Table 24

Linear mixed model estimates of fixed effects for lexical decision task of children (BOI effect)

	Variables	Beta	SE	*t*	*p*
Model 3	BOI value	.15	.06	2.41	.02
(Accuracy)	Grade	.70	.19	3.63	< .001
	Age	.01	.10	.06	.95
	Non-verbal intelligence	.13	.09	1.44	.15
	Item complexity	-.01	.06	-.09	.93
	Item frequency	.17	.06	2.74	.01
	BOI value × Grade	.04	.05	.81	.42
Model 4	BOI value	-.01	.01	-.80	.42
(Response time)	Grade	-.004	.04	-.10	.92
	Age	-.004	.02	-.19	.85
	Non-verbal intelligence	.003	.02	.16	.88
	Item complexity	.02	.01	1.42	.16
	Item frequency	-.05	.01	-3.78	< .001
	BOI value × Grade	.02	.02	1.26	.21

Note. BOI value = rating of Body-Object Interaction; P2vsA = second graders – adults; P4vsA = fourth graders – adults

The results of Model 3 demonstrated that the main effects of BOI value, grade, and item frequency were significant. That is, the BOI effect was significant. The fourth-graders showed greater accuracy than the second-graders, and the higher the frequency of the items, the greater the accuracy. The main effects of age, nonverbal intelligence, item complexity, and the interaction between BOI value and grade were nonsignificant ($p > .05$). The BOI effect did not show grade-related differences. The results of Model 4 showed that only the main effect of item frequency was significant: the higher the frequency of the items, the faster the response speed.

Then, based on Models 3 and 4, Models 5 and 6 were constructed to investigate the relationship between the BOI effect and Chinese character reading at the accuracy and response time levels, respectively. The score for Chinese character reading and the interactions among BOI value, grade, and score for Chinese character reading were added to Models 3 and 4, respectively. The results are summarized in Table 25.

Table 25

Linear mixed model estimates of fixed effects for the relationship between lexical decision task (BOI effect) and Chinese character reading

	Variables	Beta	SE	*t*	*p*
Model 5	BOI value	.18	.14	2.89	<.001
(Accuracy)	Grade	.64	.18	3.51	<.001
	Chinese character reading	.39	.07	5.26	<.001
	Age	.001	.09	.02	.99
	Non-verbal intelligence	.03	.09	.33	.74
	Item complexity	-.01	.06	-.09	.93
	Item frequency	.17	.06	2.68	.01
	BOI value × Grade	.02	.05	.38	.71
	BOI value × Chinese character reading	.03	.02	1.49	.14
	Grade × Chinese character reading	-.29	.10	-2.80	.01
	BOI value × Grade × Chinese character reading	-.02	.03	-.65	.52
Model 6	BOI value	-.02	.01	-1.80	.07
(Response	Grade	-.01	.04	-.15	.88
time)	Chinese character reading	-.06	.01	-4.25	<.001
	Age	-.003	.02	.18	.86
	Non-verbal intelligence	.03	.02	1.51	.13

	Item complexity	.01	.02	.86	.40
	Item frequency	-.05	.01	-3.97	<.001
	BOI value × Grade	.01	.01	.80	.42
	BOI value × Chinese character reading	.0003	.004	.06	.95
	Grade × Chinese character reading	.04	.02	2.13	.03
	BOI value × Grade × Chinese character reading	-.001	.01	-.08	.94

Note. BOI value = rating of Body-Object Interaction

The results of Model 5 showed that the main effects of BOI value ($p < .001$), grade ($p < .001$), Chinese character reading ($p < .001$), and item frequency ($p < .001$) were significant. The BOI effect was significant; that is, words with higher BOI values had higher accuracy than those with lower BOI values. The same result was observed for item frequency; the participants exhibited greater accuracy on words with higher frequency than on words with lower frequency. The fourth-graders exhibited greater accuracy than the second-graders. In addition, the children with better performance for Chinese character reading had higher accuracy than those with lower scores for Chinese character reading. The main effects of age, nonverbal intelligence, and item complexity were nonsignificant (*p*s > .05).

The interaction between grade and Chinese character reading was significant ($p = .01$). The influence of Chinese character reading on accuracy (i.e., children with higher scores for Chinese character reading had higher accuracy on the lexical decision task) was smaller in the fourth-graders than in the second-graders; the impact of grade on accuracy (i.e., fourth-graders had higher accuracy than second-graders) was smaller in the children with better performance in Chinese character reading than in those with worse performance in Chinese character reading. However, the interactions between BOI value and grade, between BOI value and Chinese character reading, and among BOI value, age, and Chinese character reading were nonsignificant (*p*s > .05).

The results of Model 6 showed that the main effect of BOI value was marginally significant (*p*

= .07); the children responded faster to words with higher BOI values than to those with lower BOI values. The main effects of Chinese character reading ($p = .04$) and item frequency ($p < .001$) were significant. The children with higher scores for Chinese character reading showed a faster response speed than those with lower scores. The higher the frequency of the words, the faster the correct response was given. The main effects of grade, age, nonverbal intelligence, and item complexity were nonsignificant (*p*s > .05). The interaction between grade and Chinese character reading was significant ($p = .03$), and the fourth-graders were less affected by the effect of Chinese character reading than the second-graders. However, the interactions between BOI value and grade, between BOI value and Chinese character reading, and among BOI value, age, and Chinese character reading were nonsignificant (*p*s > .05).

The models for reading comprehension were exactly the same as those for Chinese character reading except that the score for reading comprehension replaced the score for Chinese character reading. The results of the reading comprehension models (i.e., Model 7 and Model 8) are summarized in Table 26. The results of Model 7 showed that the main effects of BOI value ($p = .01$), grade ($p < .001$), reading comprehension ($p = .002$), and item frequency ($p < .001$)) were significant. The BOI effect was significant for accuracy level: compared with words with a lower BOI value, words with a higher BOI value had higher accuracy. Items with higher frequency also had higher accuracy than items with lower frequency. The children in grade 4 showed greater accuracy than those in grade 2. The children with a better performance in reading comprehension showed greater accuracy than those with worse performance in reading comprehension. The main effects of age, nonverbal intelligence, and item complexity were nonsignificant ($ps > .05$). In addition, the interaction among BOI value, grade, and reading comprehension was significant ($p = .03$). The interactions between BOI value and grade, between BOI value and reading comprehension, and between grade and reading comprehension were nonsignificant ($ps > .05$).

The results of Model 8 showed that the main effect of BOI value was marginally significant ($p = .08$); the higher the BOI value, the faster the response speed. The main effect of item frequency was significant ($p < .001$). The participants responded faster to items with higher frequency than to those with lower frequency. The main effects of grade, reading comprehension, age, nonverbal intelligence, and item complexity were nonsignificant ($ps > .05$). In addition, the interaction between BOI value and reading comprehension was marginally significant ($p = .05$). There was a positive correlation between the BOI effect and reading comprehension. That is, the participants who performed better in reading comprehension elicited a larger BOI effect. However, the interactions between BOI value and grade, between grade and reading comprehension, and among BOI value, grade, and reading comprehension were nonsignificant ($ps > .05$).

Table 26

Linear mixed model estimates of fixed effects for the relationship between lexical decision task (BOI effect) and reading comprehension

	Variables	Beta	SE	*t*	*p*
Model 7	BOI value	.16	.06	2.58	.01
(Accuracy)	Grade	.69	.19	3.69	< .001
	Reading comprehension	.41	.14	3.04	.002
	Age	.02	.09	.22	.83
	Non-verbal intelligence	.04	.09	.38	.70
	Item complexity	-.01	.06	-.11	.91
	Item frequency	.17	.06	2.67	.01
	BOI value × Grade	.05	.05	1.01	.31
	BOI value × Reading comprehension	-.03	.03	-.82	.42
	Grade × Reading comprehension	-.18	.19	-.97	.33
	BOI value × Grade × Reading comprehension	.11	.05	2.11	.03
Model 8	BOI value	-.02	.01	-1.73	.08
(Response	Grade	-.01	.04	-.13	.90
time)	Reading comprehension	-.01	.03	-.25	.79
	Age	.001	.02	.08	.94
	Non-verbal intelligence	.01	.02	.54	.59

Item complexity	.01	.01	.86	.39
Item frequency	-.05	.01	-3.96	<.001
BOI value × Grade	.01	.01	.73	.46
BOI value × Reading comprehension	-.01	.01	-1.93	.05
Grade × Reading comprehension	.01	.04	.24	.81
BOI value × Grade × Reading comprehension	.01	.01	.92	.36

Note. BOI value = rating of Body-Object Interaction

To summarize, the model for the relationship between the BOI effect and Chinese character reading showed that 1) the BOI effect, the main effect of Chinese character reading, and the main effect of item frequency were significant in both the accuracy and response time analyses; 2) the fourth-graders exhibited greater accuracy than the second-graders; and 3) the interaction between grade and performance on Chinese character reading was significant in both the accuracy and response time analyses. The model for the association between the BOI effect and reading comprehension showed that 1) the BOI effect and the main effect of item frequency were significant for both accuracy and response time; 2) the main effects of grade and performance in reading comprehension were significant in the accuracy analysis; 3) there was an interaction among BOI value, grade, and reading comprehension in the accuracy analysis; and 4) there was an interaction between BOI value and reading comprehension in the response time analysis.

Discussion

Study 3 addressed four research questions: 1) Is there a perceptual mismatch effect in the sentence verification task in Chinese readers (i.e., adults and second- and fourth-graders)? 2) Does BOI value influence Chinese speakers' word processing, specifically, is there a BOI effect in the lexical decision task? 3) Is there a relationship between off-line embodied cognition (i.e., perceptual mismatch effect and/or BOI effect) and children's literacy performance (i.e., Chinese character reading and reading comprehension), and what is the strength of the relationship? and 4) Does off-line embodied cognition and its relationship with children's literacy performance differ with age?

In the sentence verification task, overall, both accuracy and response speed increased with age. Consistent with the previous studies (e.g., Engelen et al. 2011; Wang, Mo, Wang, & Wu, 200), we found a significant perceptual mismatch effect at both the accuracy and response time levels. At the accuracy level, only the children (i.e., second- and fourth-graders) displayed the perceptual mismatch effect while the adults did not. At the response time level, no age difference was observed for the perceptual mismatch effect.

For the relationship between the perceptual mismatch effect and children's literacy performance, the results showed that off-line embodied cognition (i.e., the perceptual mismatch effect) can be a significant predictor of children's Chinese character reading and reading comprehension after controlling for age, nonverbal intelligence, RAN, phonological awareness, morphological awareness, and orthographic knowledge. However, opposite correlation patterns were observed for the second- and fourth-graders. That is, there was a positive association between the perceptual mismatch effect and literacy performance for the second-graders in both Chinese character reading and reading comprehension. However, the corresponding correlations for the fourth-graders were negative.

However, the results of the lexical decision task in the present study showed that both participant age and item frequency had a positive correlation with accuracy. In addition, a significant BOI effect (i.e., at the response time level) was observed in the lexical decision task in the present study. The participants responded faster to words with higher BOI values than to those with lower BOI values. A significant interaction between group and BOI value showed that the adults had a larger BOI effect than the children whereas there was no significant difference between the children in the two grade levels.

Regarding the role of the BOI effect in children's Chinese character reading, the analysis of LMM models found a significant BOI effect in both the accuracy and response time analyses: the participants responded more accurately and faster to words with higher BOI values than to those with lower BOI values. In addition, the children's Chinese character reading scores and item frequency had positive correlations with the children's performance on lexical decisions at both the accuracy and response speed levels. The fourth-graders showed higher accuracy than the second-graders in the lexical decision task; however, there was no significant difference between the children in the two grades at the response speed level. The significant interaction between grade and Chinese character reading at both the accuracy and response speed levels resulted in a smaller difference between the fourth-graders and the second-graders with higher Chinese character reading scores on the lexical decision task than between the fourth-graders and the second-graders with lower Chinese character reading scores on the lexical decision task

The LMM models for the role of the BOI effect in reading comprehension showed a significant effect of BOI value and item frequency on accuracy and response time in the lexical decision task. The participants responded more accurately and faster to words with higher BOI values than to those with lower BOI values. Similarly, they responded more accurately and faster to words with higher frequency than to those with lower frequency. The fourth-graders showed greater accuracy than the second-graders. The higher the score was for reading comprehension, the greater the accuracy on the lexical decision task. In the accuracy analysis, the interaction among BOI value, grade, and reading comprehension showed that the BOI effect was modulated by the interaction between grade and reading comprehension score. The significant interaction between BOI value and reading comprehension at the response speed level demonstrated a positive correlation between BOI effect and the children's performance in reading comprehension.

Perceptual simulation in the language comprehension of Chinese speakers

The significant mismatch effect of perceptual simulation in the Chinese adults (at the response time level) and the children (at the accuracy and response time levels) that we found is consistent with the view of embodied cognition (Zwaan, Stanfield, & Yaxley, 2002); specifically, perceptual simulation is involved in language comprehension. In the current study, we found that, overall, the Chinese speakers responded more accurately and faster when the pictures matched the preceding sentence with embodied properties (i.e., shape) than when they were perceptually mismatched. This advantage of the perceptually matched condition illustrated that once reading became effortful, the Chinese speakers could construct perceptual representations of concepts.

In light of these findings, it is important to consider the nature of perceptual simulation, which may be related to the construction of the mental lexicon. As described in the Introduction, when acquiring novel words, children can integrate linguistic symbols with the corresponding perceptual representations to construct and organize their mental lexicon (Smith & Gasser, 2005). The findings in the current study demonstrated that the perceptual experience was reactivated in language comprehension in Chinese speakers. Consistent with the symbol interdependency hypothesis (Louwerse, Hutchinson, Tillman, & Recchia, 2015), these findings suggested that the perceptual properties of corresponding concepts contribute to the production of Chinese characters and words.

From the developmental perspective, both accuracy and response speed increased with age. These results might be related to the participants' decision-making ability in language-based tasks or due to more efficient response execution in older readers (Engelen et al., 2011). Importantly, the interaction between perceptual condition and group (i.e., adults and second- and fourth-grade students) was significant at the accuracy level but not at the response time level. At the response time level, the perceptual mismatch effect was observed in all participants, and there was no age-related difference. The findings at the response time level revealed that the children in grades 2 and 4 had developed an embodied cognition of Chinese (i.e., perceptual simulation) that was similar to that of the adults. However, inconsistent with a previous study in Dutch (Engelen et al., 2011), at the accuracy level, the perceptual mismatch effect was observed in the children.

This finding demonstrated that in the present sample group, perceptual processing could affect the language comprehension of the Chinese children not only at the response speed level but also at the accuracy level. However, perceptual simulation had no significant influence on the adults' accuracy. These differences demonstrated that for the Chinese children, the perceptual information contained in the sentence influenced not only the processing speed but also the accuracy of comprehending language. This difference between the children and the adults leads to the possibility that although the Chinese children had developed a similar level of perceptual simulation as the adults at the response speed level, their accuracy had not yet developed (Engelen et al., 2011). The lower accuracy of the children in the sentence-picture verification task implied that the perceptual mismatch information may have interfered in the children's ability to provide a correct answer (i.e., the object in the picture was mentioned in the preceding sentence), but not in adults. That is, compared with the adults, the children were more affected by the reactivated perceptual information in language comprehension; the inconsistent perceptual representations between the picture and sentence could thus have impaired their meaning judgments.

BOI effect in Chinese speakers

The results of the lexical decision task demonstrated that accuracy increased with age. Consistent with the previous studies (e.g., Chen, Vaid, & Wu, 2009; Tan et al., 2000), higher frequency facilitated the participants' performance in the lexical decision task at both the accuracy and response speed levels. More importantly, a significant BOI effect was observed at the response speed level; that is, the participants responded faster to words with higher BOI values than to those with lower BOI values. In other words, the embodied information embedded in the concepts facilitated the participants' reading performance. This result may be related to the role of BOI in word acquisition (Bennett, Burnett, Siakaluk, & Pexman, 2011; Glenberg & Gallese, 2012; Tillotson, Siakaluk, & Pexman, 2008). To illustrate, more interactions between readers and corresponding objects for concepts results in more embodied experiences for readers that they can then integrate with related linguistic symbols, which can in turn benefit lexical retrieval (Glenberg et al., 2007; Paivio, 2006; Sadoski & Paivio, 2004).

In addition, we compared the BOI effect for the children and the adults directly rather than analyzing data for the children and the adults separately, as in the study by Wellsby and Pexman (2014). Consistent with the findings of Wellsby and Pexman (2014), the magnitude of the BOI effect in the present study did not show a grade difference. A possible reason for the discrepancy is that in Wellsby and Pexman's (2014) study, the words were grouped into high or low BOI groups, and the BOI effect was a category factor; however, in the present study, the BOI value of each word was taken into account, and the BOI effect was a continuous factor. Compared with the BOI category, the BOI value of each word assisted us in investigating the relationship between BOI value and word processing by including more detail. Therefore, a different development pattern of the BOI effect was revealed in the present study.

Moreover, contrary to Wellsby and Pexman (2014), the current study compared the magnitude of the BOI effect in older children and adults directly. The results showed a developmental difference between the children and the adults in Chinese. The developmental difference demonstrated that with increasing age, adults accumulate more experience interacting with the concrete objects of corresponding concepts, which strengthens the connections between the embodied and semantic representations, resulting in a larger BOI effect than that observed for the children (i.e., grades 2 and 4).

Off-line embodied cognition and literacy performance in Chinese children

In the present study, we utilized two indicators to assess children's off-line embodied cognition: the perceptual mismatch effect and the BOI effect.

Perceptual mismatch effect and literacy performance in Chinese children. First, it should be clarified that the total amounts of variance for the regressions in the present study were not very high. Thus, the findings can only help us to speculate on the possible relationship between off-line embodied cognition and literacy performance. The results of the present study suggested a relationship between the perceptual mismatch effect and Chinese children's literacy performance (i.e., Chinese character reading and reading comprehension). However, in grade 2, perceptual simulation (i.e., perceptual mismatch effect at the respond speed level) was positively related to the children's performance on Chinese character reading and reading comprehension. In contrast, the corresponding correlations in grade 4 were negative. Moreover, the association between perceptual simulation and reading comprehension disappeared once Chinese character reading was taken into account.

The positive link between the magnitudes of perceptual simulation and Chinese character reading scores in the second-graders illuminated a critical role of embodied experience in the process speed of constructing mental representations of lexical (Louwerse et al., 2015). It is possible that the children with more internalized embodied experience (which was presented by a faster process of word-related conceptual information) may have more opportunities to integrate related semantic and embodied information; thus, they may be able to construct higher quality representations. This assumption can be supported by the fact that children always acquire concrete words, which have relatively more embodied referents, earlier than abstract words (Glenberg & Gallese, 2012). Then, these high-quality representations aid Chinese character reading (Perfetti, 2007).

At the same time, a facilitative effect of off-line embodied cognition on reading comprehension was observed in the second-graders. Connecting sensory-motor information to the concurrent reading discourses, i.e., constructing specific embodied models, benefits children's reading comprehension (de Koning, Bos, Wassenburg, & Schoot, 2017; Lakoff & Johnson, 2003; Wilson & Gibbs, 2007). Children with more developed off-line embodied cognition may have more experience integrating embodied and linguistic information to construct mental models for language comprehension, which can benefit their reading (Barsalou, 2008; Glenberg, 2011).

In addition, prior knowledge of a topic or relevant vocabulary can influence the understanding of a text such as inferring the meaning of new words from context (Cain, Oakhill, & Lemmon, 2004; Spilich, Vesonder, Chiesi, & Voss, 1979; Wittrock, Marks, & Doctorow, 1975). However, this benefit of prior knowledge should not be limited to verbal information but should be extended to embodied experience. That is, previous embodied experience, which is related to concurrent reading, can help children infer the meaning of new words and thereby enhance their reading comprehension.

However, the situation was opposite in grade 4. To illustrate, the children with better performance in Chinese character reading had a smaller perceptual mismatch effect. Although there was a negative correlation between reading comprehension and perceptual simulation, it was observed because of the strong positive correlation between the children's Chinese character reading and reading comprehension (Chen, 1992). Additionally, based on the correlational analysis in the present study, the positive relationship between reading comprehension and perceptual stimulation can be confirmed.

According to the symbol interdependency hypothesis, both the linguistic system and the perceptual simulation system are active initially, although the activation of the perceptual simulation systems peaks later (Louwerse et al., 2015). In other words, the perceptual experience is reenacted automatically in conceptual processing (Evans, 2009; Ostarek & Vigliocco, 2017), and there is a subtle possibility that skilled readers did not reactivate the off-line embodied experience in the sentence verification task.

Linguistic symbols can activate related perceptual representations (i.e., shape), and perceptual stimuli (i.e., picture) can activate corresponding semantic representations (e.g., Chasteen, Burdzy, & Pratt, 2010; Estes, Verges, & Barsalou, 2008; Ostarek & Vigliocco, 2017). Thus, there were at least two routes for children to complete the sentence verification task. One involved utilizing perceptual representation, which is reactivated when reading a sentence, to compare with the subsequent picture. Another route was comparing the semantic representation of the concept in the sentence with the semantic representation of the object in the corresponding picture.

The results for the fourth-graders implied that skilled readers might be more flexible in switching between these two routes while less skilled readers relied more heavily on the route of perceptual processing. That is, skilled readers in grade 4 were better at suppressing information once they realized it was inappropriate or irrelevant. Consistent with this possibility, it has been found that poor readers are less competent than their typical counterparts in suppressing distracting information while performing some semantic related tasks for both adults (Gernsbacher & Faust, 1991; Gernsbacher, Varner, & Faust,

1990) and children (Cain, 2006; Carretti, Cornoldi, Beni, & Romano, 2005; Chiappe, Hasher, & Siegel, 2000; De Beni & Palladino, 2000).

Taken together, these findings illustrated that the roles of linguistic knowledge and (off-line) embodied cognition varied across ages (i.e., grades 2 and 4). For younger children, the ability to integrate internalized (off-line) embodied information with verbal stimuli can distinguish children's literacy performance. However, with the development of embodied cognition and reading ability, the ability to suppress inappropriate information, either linguistic or embodied information, becomes a critical factor for distinguishing skilled readers from less skilled readers in older children. Thus, for younger children, in addition to linguistic knowledge, training on how to utilize related nonverbal information for language comprehension is critical for enhancing reading ability; for older children, teaching should focus on how to distinguish and suppress unrelated and/or inappropriate information during reading.

BOI effect and literacy performance in Chinese children. The significant BOI effect at the accuracy and response time level illustrated that embodied information is involved in understanding concepts and facilitates word recognition. Both performance on Chinese character reading and item frequency were positively correlated with response accuracy and speed on the lexical decision task. A significant negative correlation between grade and Chinese character reading at the accuracy level illuminated a compensatory relationship. In other words, a smaller difference was observed for the lexical decision task between the second-graders with better reading skills at the word level and the fourth-graders than between less skilled second-grader readers and the fourth-graders.

There was no significant correlation between the children's BOI effect and Chinese character reading. One explanation for this finding is that the degree of BOI can enrich the meaning aspect of words by increasing related representations through nonverbal modalities (i.e., visual and motor systems) (Wellsby & Pexman, 2014); however, Chinese character reading measures reading ability at the word level and is more concerned with the orthographic-phonology link of words/characters. Thus, the embodied information attached in BOI effect did not present a link with Chinese character reading. At the accuracy level, although a detailed pattern could not be clarified in the present study, a three-factor interaction implied that the interaction between the BOI effect and reading comprehension was modulated by the children's grade, which is in line with the role of age in the development of off-line embodied cognition and reading comprehension.

Furthermore, the results for response time illustrated a positive correlation between the BOI effect and reading comprehension. Unlike the study by Wellsby and Pexman (2014), the present study separated the roles of age and the BOI effect in Chinese children's literacy performance. The findings suggested that the children with better performance in reading comprehension showed a more developed off-line embodied cognition (i.e., a larger BOI effect). This result may due to the fact that the children with a larger BOI effect had more embodied experience and knowledge to construct embodied models for reading stimuli (e.g., words/sentences/passage), which can, in turn, facilitate comprehension.

However, unlike the relationship between the perceptual mismatch effect and reading comprehension, there was no age-related difference in the link between the BOI effect and reading comprehension. One explanation is that compared with the perceptual mismatch effect, the BOI effect reflects another aspect of off-line embodied cognition that may develop earlier than the alternative. The explanation for the BOI effect assumes that the interaction between body and objects provide nonverbal codes for the concept and then enhances the quality of corresponding representations (Siakaluk et al., 2008). That is, the benefit of the interaction between body and objects is always present at the level of words' semantic representation (i.e., meaning of concepts) whereas perpetual simulation is influenced by the context. For both second-graders and fourth-graders, processing the semantic representation of words should be necessary for reading comprehension. Thus, the role of the BOI effect in reading comprehension is similar for children in these two grades.

To summarize, the present study found correlations between different indicators of off-line embodied cognition and Chinese children's literacy performance. The perceptual mismatch effect was a unique predictor of Chinese character reading and reading comprehension. However, there was a developmental difference. The correlations between the perceptual mismatch effect and literacy performance was positive for the second-graders but negative for the fourth-graders. However, the BOI effect had a positive association only with reading comprehension. These findings implied that although the perceptual mismatch effect and the BOI effect are recognized indicators of off-line embodied cognition, they should reflect different perspectives of off-line embodied cognition. Perceptual simulation is not limited to the representations of concepts per se; it involves the processing of sentences: readers must activate related embodied experience based on the context, which is more complex than the embodied cognition reflected in the BOI effect.

The developmental difference in the relationship between perceptual simulation and children's literacy performance illustrated that both embodied and symbolic (i.e., disembodied) systems are involved in language processing; however, with the development of children's reading ability and embodied cognition, children also develop the ability to switch between linguistic and embodied information to comprehend more efficiently. However, BOI value has a positive correlation with word processing speed; nevertheless, it may easily develop to a relatively stable stage. Consistent with this assumption, the previous studies have found that there is a close correlation between BOI value and age of acquisition, which implies that words that tend to be acquired earlier in life have higher BOI values (Bennett et al., 2011; Díez-Álamo, Díez, Alonso, Vargas, & Fernandez, 2018). At the same time, BOI value is related to the semantic processing of words, specifically, the basic unit for further understanding. Thus, the link between the BOI effect and literacy performance (i.e., reading comprehension) does not vary with age.

Chapter 5: General discussion and conclusions

The role of on-line embodied cognition in Chinese children's literacy performance

In the present study, on-line embodied cognition referred to external embodied information related to cognitive tasks (i.e., word reading and reading comprehension), and the study findings demonstrated a facilitating role of on-line embodied cognition in Chinese children's literacy performance. The possible reasons for this facilitative effect of on-line embodied cognition might be related to the generation of conceptual sensory-motor representations and mental models, which are two critical aspects for language comprehension.

First, the findings of the present study support the view that concurrent external (i.e., on-line) embodied information provides a route that connects abstract linguistic symbols to corresponding concrete referents in the world (Barsalou, 1999; Jeannerod, 2001; Hesslow, 2002; Gallese & Lakoff, 2005). To illustrate, the mapping of linguistic symbols to related referents (e.g., objects and actions) can help children acquire conceptual meaning by linking sensory-motor features to related objects/events. These sensory-motor features can enrich conceptual representations and thereby enhance lexical quality. In this processing, each involved modality (i.e., including the embodied and verbal modalities) generates a specific code for the concept, and these are then integrated to generate a comprehensive representation that has a higher quality than that derived from a process using only verbal codes (Sadoski & Paivio, 2004). It has consistently been found that the poorer literacy performance of students with physical deficits (e.g., blind and deaf children) whose intelligence is the same as that of typically developing children (e.g., Kyle, & Harris, 2006; McPhillips, Hepper, & Mulhern, 2000; Wauters, Van Bon, & Tellings, 2006). Compared with students with physical deficits, the advantage of typically developing children in conceptual development is due to a higher degree of involvement and integration of conceptually related embodied information.

However, the ability to integrate objects to construct mental models might be another possible reason for the facilitating role of on-line embodied cognition in literacy performance (Glenberg et al., 2014). In line with the findings of Study 2 in the present work, the IH suggests that mental models can help children map abstract linguistic symbols to their corresponding concrete referents and integrate them with specific relationships. These models provide visible/imaginable scenes of text, which in turn deepen understanding and improve memorization (Glenberg et al., 2014; Glenberg et al., 2011). In our daily life, without explicit instruction as in the studies mentioned above, we also prefer to construct mental models for associated objects. For example, a pen is always presented with paper, an eraser, and a table. They can be connected with each other by a classic human action, specifically, handwriting. In this case, "handwriting" is not merely an action; it is a mental model that consists of each object's physical properties and functions and the interactions among them. There is a possibility that mental models function as a chunk of information that can improve the efficiency of memory (Simon, 1974).

In brief, on-line embodied cognition obtained from information from sensory-motor modalities corresponds to concepts with rich lexical representations. In addition, concurrent embodied information could benefit the integration of objects and the construction of mental models for more accurate comprehension and better memorization.

The role of off-line embodied cognition in Chinese children's literacy performance

Unlike on-line embodied cognition, which focuses on utilizing concurrent external information, off-line embodied cognition focuses on the application of internalized embodied information. The results of Study 3 suggest that sensory-motor information can be reactivated by processing related concepts to facilitate language comprehension (Barsalou, 2008; Louwerse et al., 2015; Zwaan et al., 2004). The involvement of sensory-motor modalities in conceptual acquisition can not only be a channel for acquiring and storing lexical codes but also for retrieving (Sadoski & Paivio, 2004). Thus, the intensity of the links can influence concept processing (Siakaluk et al., 2008; Wellsby & Pexman, 2014),

The findings from Study 3 showed a positive relationship between previous perceptual experience and Chinese character reading in young children (i.e., second-grade students), which implies a role of sensory-motor experience in the construction and organization of a mental lexicon (Smith & Gasser, 2005). To illustrate, actions are the basic means by which children explore and interact with the world. Actions aid children in acquiring sensory-motor information and allow them to develop an initial object categorization system (Gerlach, Law, Gade, & Paulson, 2000; Mounoud, Duscherer, Moy, & Perraudin, 2007; Perraudin & Mounoud, 2009).

However, similar to on-line embodied cognition, off-line embodied cognition is not limited to the concept level but can be extended to the mental model. After construction, mental models can also be embedded in memory, allowing them to be treated as off-line mental models (Halford, 2004). These models can be reactivated to facilitate the processing of similar situations, including verbal and nonverbal issues (Chi, 2000). For example, in Study 3 of the present work, the participants presented a mismatch effect in the sentence-picture verification task. After reading the corresponding sentences, the participants may have predicted a perceptual image of the objects based on their reactivated previous experience. However, the pictures in the mismatched condition were inconsistent with their prediction, which may have hindered their performance.

Taken together, the on-line and off-line perspectives indicate that the involvement of embodied modalities can link sensory-motor features with corresponding linguistic symbols, which can enrich conceptual representations. At the same time, sensory-motor features can aid children in determining relationships between concepts to construct a mental lexicon. These embodied relationships can assist in the integration of concepts to generate mental models for better memory and comprehension. In turn, these internalized sensory-motor features and associations among the concepts and mental models of situations can be reactivated to aid language comprehension without the appearance of corresponding referents (i.e., objects).

From the perspective of development, although the current study recruited only students in 2 grades, a possible developmental tendency of relationships between embodied cognition and literacy performance could be suggested. According to the findings of present study and previous studies (Engelen et al., 2011; Marley & Szabo, 2010; Wilson & Golonka, 2013; Wellsby & Pexman, 2014), both on-line and off-line embodied cognition can facilitate young (e.g., second graders) and older children's (e.g., fourth graders) literacy performance. From the on-line embodied cognition perspective, both young and older children could obtain the benefit in relative easy linguistic tasks (e.g., word/character learning); however, only older children, who have a better ability to integrate embodied and verbal stimuli, could acquire the benefit in complex tasks (e.g., manipulating with reading) (Wilson & Golonka, 2013). From the off-line perspective, the internalized information that is gained through previous concepts relates experience to language and thus can facilitate language comprehension, either for young or old children. Because older children have the more embodied experience, they can gain more benefit from off-line embodied cognition for language comprehension than younger ones (Wellsby & Pexman, 2014). At the same time, children's off-line embodied cognition could be an effective indicator to distinguish children's reading ability. For young children, good readers have more developed embodied cognition (i.e., a larger perceptual mismatch effect) than poor readers; however, the correlation is opposite for older children.

The role of embodied cognition in learning

The nature of embodied cognition is reflected in the interactions among the mind, body, and external world (Barsalou, 2008; Lakoff & Johnson, 1999; Lowswer et al., 2015; Wellsby & Pexman, 2014). Similar to literacy performance, higher level cognitive processes such as learning involve interactions among the mind, body, and external world. Thus, based on the findings of the present study, the role of embodied cognition in learning can be assumed. More specifically, on-line embodied cognition focuses on learning activity that is embedded in a task-relevant external situation; off-line embodied cognition includes any learning activities in which sensory and motor resources are brought to bear on mental tasks whose referents are distant in time and space.

In the case of on-line embodied cognition, the mind can be seen as operating to serve the needs of a body interacting with a real-world situation. On-line embodied cognition assists humans in off-loading cognitive work onto the environment, which can in turn benefit learning efficiency (Wilson, 2002). It has been found that when confronted with tasks involving time pressure or requiring considerable attention and/or working memory, a preferred strategy involves referring to concurrent embodied information to minimize cognitive workload (Ballard, Hayhoe, Pook, & Rao, 1997; Henderson, 2003; O'Regan, & Noë, 2001; Kirsh & Maglio, 1994).

More daily examples can be observed in spatial tasks. For example, moving around to determine where to put furniture and giving directions for how to get somewhere by first turning one's self and one's listener in the appropriate direction. In fact, concurrent external embodied information could help humans more easily acquire the spatial relations between objects and, more importantly, the spatial relations between objects and our bodies. Then, we can construct an accurate model for the specific situation in a real space. For literacy tasks or other academic tasks (e.g., mathematics), with the assistance of on-line embodied information (i.e., the concurrent external information), children can utilize this information to construct a corresponding model in the environment rather than in their mind. That is, children can off-load the cognitive work to the environment, enabling them to preserve cognitive resources for abstract questions (e.g., inferences), which can benefit learning.

However, in off-line embodied cognition, acquired sensory-motor resources are used to assist in mental representations and the manipulation of things that are not presented as well as purely internal uses of sensory-motor representations in the form of mental simulations (Wilson. 2002). In this case, the body serves the mind. That is, the primary purpose of off-line embodied cognition is to assist humans in understanding and thinking more efficiently. As the findings of Study 3 in the present work demonstrate, internalized perceptual information could be reactivated when facing a similar situation in language processing, which can facilitate reading performance. To extend this finding to learning, off-line embodied cognition could aid humans in making predictions/preparations for situations/problems that have similar internal representations in the mind.

In support of the predictive role of embodied cognition, it has been found that certain types of visual input can activate motor activity. That is, the presence of visual features can prime an associated action, which could serve as efficient preparation for subsequent tasks (e.g., Craighero, Fadiga, Umiltà, & Rizzolatti, 1996; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Murata et al., 1997). Sensory information can elicit actions, and those actions can influence sensory processing. For example, observing a classic action (without the presentation of objects) that is typically presented with specific objects could facilitate the recognition/naming of corresponding objects (Helbig, Steinwender, Graf, & Kiefer, 2010). The reactivated information is not limited to one specific modality but can be extended to related modalities. These reactivated sensory and/or motor systems help us prepare for possible future situations.

In addition to predicting possible situations, another critical function of off-line embodied cognition is to benefit learning by observing others. Internalized embodied cognition can help us understand the goals of others and then learn from others. Cognitive load theory claims that because of the way in which human cognitive architecture is organized, learning by observing and/or imitating what other people do, say, or write is a much more effective and efficient way of acquiring knowledge than trying to devise this knowledge by ourselves (Sweller & Sweller, 2006; Van Merriënboer & Sweller, 2005).

In the present study, although we treated observation as a method of on-line embodied cognition in the observing-performed manipulation condition in Study 2 (acute enhancement stage), observation also includes the activation of previous embodied experience. Only by reactivating previous knowledge about these actions can children understand the information obtained from observation. For example, with related embodied experience, we can understand the reasons underlying others' gestures (Hostetter, & Alibali, 2008; Nishihara, Hsu, Kaehler, & Jangaard, 2017; Wilson, 2002) and facial expressions (Goldman, & de Vignemont, 2009; Niedenthal, Barsalou, Winkielman, Krauth-Gruber, & Ric, 2005; Neal, & Chartrand, 2011). The evidence from neurological studies has also shown that the mirror neuron system, which plays a critical role in understanding the actions of others, is activated in observation (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Rizzolatti & Craighero 2004). This ability to infer others' intentions is crucial for humans in their application of what they have learned through observation to new tasks or contexts (e.g., Detterman & Sternberg, 1993; Van Gog, Paas, & Van Merriënboer, 2004). Hence, similar to the role of on-line embodied cognition in learning, off-line embodied cognition can decrease cognitive workload for learning, at least for some simple problems, enabling people to preserve more cognitive resources to cope with more complex questions. Subsequently, learning efficiency can be improved.

To summarize, it should be noted that although we divided embodied cognition into on-line and off-line aspects to comprehensively investigate the concept, these two aspects are not independent. When processing new on-line embodied information, the experience of interacting with the external world accumulates, and off-line embodied cognition can then be modified accordingly. At the same time, off-line embodied cognition can be activated to facilitate the processing of on-line embodied information. That is, on-line and off-line embodied cognition should be treated as two consecutive stages of embodied cognition that can be applied to enhance the processing efficiency of cognitive tasks. .

Theoretical implications

The present study investigated the role of embodied cognition in the literacy performance of Chinese children from the on-line and off-line perspectives. From the on-line embodied cognition perspective, the role of embodied cognition in reading acquisition was explored while from the off-line embodied cognition perspective, the function of embodied cognition in general reading performance was studied. The present study provides evidence supporting the view of embodied cognition theories with different perspectives. To illustrate, the first two studies focused on how the sensory-motor representations of concepts offer grounding through bodily interactions (e.g., Lakoff & Johnson, 1999; Gibbs, 2005) whereas Study 3 focused on mental simulations of sensory-motor representations (e.g., Barsalou, 2008; Pecher & Zwaan, 2005).

Consistent with the view of dual coding theory (Sadoski & Paivio, 2004), the findings of Study 1 support that bodily interactions and sensory-motor (i.e., nonverbal) codes of concepts are constructed and integrated with verbal codes during word learning. After integrating the codes from sensory-motor systems with verbal codes, the quality of certain lexical representations (i.e., orthographic representations) can be enhanced; subsequently, this process facilitates acquisition and literacy performance. Moreover, the findings of Study 1 extend the view of dual coding theory by specifying the roles of different embodied components. More specifically, in the case of Chinese character learning, compared with watching the whole character, information on stroke order for visual-motor integration makes a unique contribution. Information on stroke order from the visual or haptic modalities cannot promote facilitation. Inconsistent with findings indicating that the learning effect is enhanced by increasing numbers of embodied modalities (e.g., Roy, 2003; Smeets & Bus, 2012), the results of the present study illustrated that not every sensory-motor modality is sufficient to elicit a unique contribution to learning.

Consistent with IH (Glenberg et al., 2004), the results of Study 2 demonstrated that concurrent linguistic text-related sensory-motor information could benefit the construction of mental models and thus aid reading comprehension. By comparing the facilitative effects of direct manipulation (i.e., including the visual and motor systems) and observation (i.e., including the visual system), the present study extends the IH by determining a specific role of the visual system and motor programing in the facilitating role of manipulation in reading. Specifically, children can acquire information for constructing mental models through observation; however, direct manipulation might lead to deeper understanding and thereby generate additional benefits (Glenberg & Kaschak, 2002). The present study also adds the stage of manipulation strategy maintenance to the IH and found that observation is enough for children to learn how to manipulate objects according to texts.

The findings of Study 3 align with the view of the symbol interdependency hypothesis (Louwerse, 2011; Louwerse et al., 2015), which states that both semantic and sensory-motor representations of concepts can be reactivated automatically in language processing. The findings of the present study extended the symbol interdependency hypothesis by demonstrating that the application of reactivated semantic and sensory-motor information can vary based on the age and reading abilities of readers. More specifically, the integration of embodied and symbolic information may help younger children accumulate related representations and improve the quality of their lexicon, which may subsequently benefit their reading comprehension. However, for older children, who have relatively more developed embodied cognition and reading abilities, the ability to integrate embodied and symbolic information might be insufficient to distinguish their literacy performance. The ability to identify and utilize appropriate information from embodied and symbolic information is more critical for older children's literacy performance. Hence, the application of linguistic and embodied systems is dynamic. In addition to the development of reading and embodied cognition, children also develop the ability to determine whether linguistic information or sensory-motor information is more efficient for language comprehension.

Taken together, the findings of the present study and studies on other previous embodied theories (e.g., Glenberg et al., 2014; Louwerse et al., 2015; Sadoski & Paivio, 2004) indicate that the role of embodied cognition in the literacy performance of Chinese children can be treated as two stages: acquisition and application. In the acquisition stage, through interactions between the body and linguistic stimuli, certain representations of words (e.g., orthographic and/or semantic representations) and/or mental models of texts can be generated in actual space rather than in the mind. This explicated generation of representations of words and/or mental models of texts can make them sensible. Moreover, the generation of these representations and models also presents the integration of embodied (nonverbal) and verbal codes, which can deepen understanding and provide variable modalities for information processing and storage, which can in turn benefit the acquisition of words/texts. In addition, the contributions of these embodied components are not equivalent, although the involved sensory-motor modalities are presumed to process stimuli. The contribution of a specific sensory-motor component should be weighted to its situational relevance (Hommel, 2004).

According to the findings of the present study regarding developmental differences (i.e., Study 1 and Study 2), another critical factor that could affect the role of concurrent embodied information in reading acquisition is the quantity of embodied information. Only the appropriate degree of accompanying embodied information can facilitate acquisition, and too much information might hinder children from developing the ability to integrate this embodied information with verbal codes (Wilson & Golonka, 2013). The appropriate magnitude of external embodied information may increase with age.

The acquired embodied information will then be internalized and associated with related verbal codes in the mind. This internalized embodied information can then be used in the application stage. The associations between verbal and embodied codes, as well as the links among embodied codes, can facilitate language processing. Verbal stimuli can prime related embodied information, and vice versa. Both literacy knowledge and related embodied experience are accumulated as age increases, and the associations between verbal and embodied codes increase accordingly. However, not all reactivated embodied information is necessary for certain situations, and irrelevant embodied information might impair performance if it cannot be appropriately suppressed (Hommel, 2015).

Furthermore, the role of embodied cognition in literacy performance can be extended to learning. Concurrent embodied information in the learning environment enables children to engage and participate in the process of meaning making. Sensory-motor information that is congruent with the knowledge being learned can increase children's understanding and learning. During learning, actions are integrations of perceptions and conscious thinking, which could make a unique contribution to changes in learners' behavior. After learning, sensory-motor codes are linked with related codes for the same object/event (Hommel, 2015). When processing certain objects/events, the related links with embodied features can be reactivated for better performance. Through the accumulation of these interactions and integrations, the ability to learn can be transferred to new contexts or areas. Moreover, the role of embodied cognition in learning is dynamic rather than static. That is, established links for objects/events might interact with new embodied inputs and then be modified to enhance learning and performance.

Educational implications

Based on the findings of the current study, we introduce embodied strategies for language acquisition and comprehension. Rather than focusing on linguistic symbols per se, external embodied information that is related to linguistic symbols such as orthographic representations of words/characters and mental models of sentences/passages can be involved in teaching.

Based on the findings of Study 1, a more effective method for teaching writing was introduced, specifically, air writing. The present study found that there was no difference between air writing and handwriting from the perspective of facilitating children's language acquisition. In other words, air writing can help children to acquire characters (i.e., orthography-phonology link) to the level that is the same as handwriting. It should be noted that compared with handwriting, air writing is more economic. To illustrate, it does not require a pen, paper, table, or chair. If the target is to produce high quality representations of characters, rather than to improve handwriting quality, air writing is a better choice for teachers and parents. In addition to Chinese, the facilitating effect of air writing also can be extended to other languages, for example, English, which has a stronger link between orthography-phonology than Chinese (Siok & Fletcher, 2001). The advantage of air writing should be replicated or enlarged in English. For Japanese, consistent with the present findings, it has been found that air writing has a similar effect as that of handwriting for learning Kanji in second language learners of Japanese (Thomas, 2015).

However, the findings of Study 1 can help us develop a more efficient digital input system that is specific to children. To illustrate, the critical role of producing orthography by children in learning has been highlighted in the current study, which may explain the question of why similar sensory-motor components (i.e., visual, motor, and haptic) are involved in handwriting and typewriting; however, there is an advantage of handwriting over the alternative in reading cross languages such as English and Chinese (e.g., James & Atwood, 2009; James & Engelhardt, 2012; Tan et al., 2012). Hence, when designing a digital input system for the facilitating of children's language acquisition, the process of generating the orthography of characters/words should be taken into account.

The results of Study 2 suggest a developmental difference in embodied reading strategies. For younger Chinese children (e.g., second graders), a method to integrate abstract linguistic symbols and external embodied information is critical for them to obtain the benefits of embodied reading strategies. However, for older children (e.g., fourth graders), providing external embodied information with reading (i.e., observing- and participant-performed manipulation) can enhance their reading performance significantly. Furthermore, it should be noted that the strategy for reading comprehension could be varied with different targets. To illustrate, for acute enhancement, physical manipulation is better than observation; however, for strategy maintenance, observation can provide enhancement similar to that brought about by physical manipulation. Compared with participant-performed manipulation, observing-performed manipulation can save more time for teaching and preparation for the objects. With the observation approach, children can watch the same video and be trained by group, even by class; however, with physical manipulation, children must be trained individually, or teachers must prepare several play sets. Thus, if the target is teaching a manipulation strategy, the observation strategy is better. Together, the findings of Study 1 and Study 2 demonstrate the significant effects of the visual and motor systems in language acquisition and comprehension.

At the broader level of learning, the present findings suggest that the interactions among children, knowledge, and the learning environment are significant for learning efficiency. Thus, when designing teaching strategies, offering opportunities for interaction should promote better learning. For example, rather than directly describing the relationships among objects to children, teachers and parents can encourage children to observe and interact with the objects and determine their embodied features. That is, children must make sense of relationships through their own experiences, which can elicit better memory. In brief, an embodied learning environment should consist of task/knowledge-related objects, and higher consistency between the knowledge and the objects is better so that children can make sense of the knowledge by interacting with the objects.

Limitations and future studies

There were some limitations in this study. First, the sample for the present study included only two grades; more grades or a longitudinal design would be beneficial for understanding the developmental pattern of the roles of on-line and off-line embodied cognition in the literacy performance of children. Second, the training programs in the current study (i.e., Studies 1 and 2) were conducted only once. The effects of on-line embodied cognition in literacy performance might vary based on training period and magnitudes, and future studies could change the scope of the training programs to explore whether the roles of concurrent sensory-motor components in literacy performance vary. Third, there was only one type of passage in Study 2, and the impacts of observing- and participant-performed manipulations on reading comprehension in general are still not clear. Future studies could adopt other types of passage to investigate whether the roles of these two manipulations would be different across text types. However, as mentioned above, the children in the physical manipulations of Study 2 may have made some incorrect manipulations. Hence, these incorrect manipulations might weaken the impact of the physical manipulation. A feedback of manipulation can be added after period 1 to help the participants in the physical manipulation condition gain the information of correct manipulations to identify why that the advantage of physical manipulation in the strategy maintenance period disappeared. Fourth, the measures of children's literacy performance in the present study consisted only of Chinese character reading and reading comprehension. Hence, the possible roles of embodied cognition in other literacy and literacy-related abilities were not explored. Future studies could include additional measures such as word reading, reading fluency, phonological awareness, and morphological awareness to investigate whether the effects of on-line and off-line embodied cognition in children's literacy performance varies. In addition, although Study 3 controlled for related reading abilities, to explore the relationship between off-line embodied cognition and children's literacy performance in more detail, there are still other aspects (e.g., vocabulary) that should be taken into account in future studies. Fifth, the results of the current study suggest that both children's embodied cognition and their language knowledge can influence their language acquisition and comprehension. However, the interaction of children's embodied cognition and language knowledge in literacy performance, which can be taken into account in future studies, has not been clarified. Finally, the present study was investigated in Chinese. Future studies could investigate the research questions in different orthographies to deepen the understanding of the relationship between embodied cognition and literacy performance.

Conclusions

The present study explored the roles of on-line and off-line embodied cognition in the literacy performance of Chinese children (i.e., second- and fourth-graders). The present study consisted of three studies. The findings of Study 1 demonstrate that 1) the involvement of specific on-line embodied components (i.e., visual-motor integration, visual-motor-haptic integration, motor programming, and motor-haptic integration of handwriting) facilitates children's Chinese character learning, and the facilitative effects of these components were similar in two grade levels. The findings of Study 2 illustrate that 2) both the visual and motor systems made a unique contribution to improving children's reading comprehension; 3) the involvement of the motor system did not provide an extra benefit at the level of learning a fundamental manipulation strategy, specifically, information from the visual system was enough for the children to develop a fundamental manipulation strategy for reading comprehension; and 4) the older children benefited more than the younger children from on-line embodied training for enhancing reading comprehension. The findings of Study 3 show that 5) the children from the two grades developed similar off-line embodied cognition, which was reactivated in language comprehension; however, their off-line embodied cognition was less developed than that of the adults; 6) off-line embodied cognition (i.e., perceptual simulation) had a positive correlation with literacy performance in the younger children (i.e., second-graders) whereas the link was negative in the older children (i.e., fourth-graders); and 7) there was a positive relationship between the BOI effect and the children's reading comprehension; however, no age difference was observed in this relationship.

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Appendix

The passage 1 and 2 of Study 2.

Passage 1

曹冲是曹操的儿子，他聪明多智，而且很有同情心。

有一天，他父亲一具心爱的马鞍不幸被老鼠咬破了，管仓库的官吏发现后，吓得面无人色。他想去自首，减少一些罪责，但又担心仍不免一死。

这件事被十来岁的曹冲知道了。他想，库吏平时勤勤恳恳，为人老实，马鞍被老鼠咬坏，是一时疏忽，怎能因此而丧命，我得救他。于是他想起办法来，过不多久，他便把库吏叫去，胸有成竹地说："我会设法救你的，两个时辰后你去自首好了。"库吏连连叩头（1）而去。

送走库吏，曹冲走进卧室，用小刀将内衣连戳几个洞，然后装出闷闷不乐的样子，连饭也不吃，曹操便前来【词汇补充 1】。曹冲说："我的衣服被老鼠咬了几个洞。听说衣服被老鼠咬了要倒霉的。"曹操说："老鼠咬坏东西是常有的事，有什么吉祥不吉祥？你不要为这件事苦恼。"曹冲恭敬地说："父亲说得对。"

两个时辰后，库吏来向曹操报告，说库内一具马鞍被老鼠咬坏了，说罢连连叩头（2）谢罪。曹操满脸怒火，本想狠狠惩罚库吏，因为这是件不吉利的事。但见曹冲在一旁，顿时想起刚才【词汇补充 2】儿子的话，于是收起怒容说："我儿子的衣服挂在床边尚且被老鼠咬了，何况马鞍是挂在仓库的柱头上呢。算了，往后留心一点。"

就这样，聪明的小曹冲救了老库吏的性命。

Passage 2

店主站在柜台内，望着门口。一个小女孩走进店门，来到柜台前，出神地盯着柜子里那条蓝宝石项链。她说："这条项链太美啦。我想买下来送给姐姐。您帮我包装得漂亮一点吧！"

"你有多少钱？"店主怀疑地打量着小女孩说。

小女孩从口袋里掏出一块手帕，解开所有的结，然后摊在柜台上，兴奋地说："这些可以吗？"她拿出来的不过几枚硬币而已。她说："今天是姐姐的生日，我想把它当做礼物送给她。自从妈妈去世以后，她就像妈妈一样照顾我们。我相信她一定会喜欢这条项链的，因为项链的颜色像她的眼睛一样漂亮。"

店主从柜子内取出了那条项链，小心翼翼地装在一个小礼盒内，用一张漂亮的粉色包装纸将礼盒包好，又在盒子外面系上一条绿色的丝带。他对小女孩说："拿去吧，路上小心点。"小女孩连蹦带跳地回家了。

就在这一天的工作快要结束的时候，店里来了一位美丽的姑娘，她有一双蓝色的眼睛。她把已经打开的礼品盒放在柜台上，问道："这条项链是从您这儿买的吗？多少钱？"

店主笑了笑说："本店商品的价格是和顾客之间的秘密。"

"我妹妹只有几枚硬币，而您这条珍贵的项链是蓝宝石的，货真价实，她是买不起的。"

店主拿起盒子，将盒子重新包装好，系上丝带，递给了姑娘；"拿走吧！她给出了比任何人都高的价格，她付出了她所拥有的一切！"