Research Report

Sport expert's motor imagery: Functional imaging of professional motor skills and simple motor skills

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ABSTRACT

Numerous studies provide evidence that motor skill acquisition is associated with dynamic changes in cortical and subcortical regions. Athletes are a professional population who are engaged in extensive motor training for long periods. However, the neural substrates of extreme level motor performance have not been clarified. We used kinesthetic imagery task to induce the mental representation of sport expert's extraordinary performance in view of the shared substrates of executing movement and motor imagery. For the first time, we compared, through functional magnetic resonance imaging (fMRI), the pattern of cerebral activations in 12 professional divers and 12 normal people without extensive training, during imagery of professional skills and imagery of simple motor skills. The sport experts showed significant activation in the parahippocampus during imagery of professional skills relative to the novices, which might reflect the representation adapted to experience-related motor tasks. No significant difference was found between experts and novices when they imagined simple motor skills. These results indicated the experts might utilize their kinesthetic imagery more efficiently than novices, but only for the activity in which they had expertise. The sport experts also demonstrated more focused activation patterns in prefrontal areas in both of imagery tasks, which may be relevant to higher order of motor control during motor imagery. Moreover, this study suggested that the brains of sport experts could be regarded as the ideal subjects to explore the relationship between cerebral plasticity and learning of complex motor skills.

1. Introduction

Motor skill acquisition involves a set of internal process improving movement efficiency such as speed, precision, automaticity, and adaptability. These processes are thought to be complex central nervous system phenomena whereby sensory and motor information is organized and integrated (Lisberger, 1988). More recently, modern brain imaging techniques, such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), have allowed us to identify the neural substrates induced by motor skill learning in normal, healthy humans and to explore the functional dynamic changes that occur over the entire course of the acquisition process (Doyon et al., 2002; Karni, 1996). Across these studies,

two main approaches of neural substrates of human motor skill acquisition can be distinguished.

One approach is to adopt longitudinal studies that highlight the dynamic changes in cortical and subcortical regions during different phases of motor skill learning. Researchers used motor sequence learning paradigms including execution of the fingers, hands, arms or feet (Doyon et al., 1997; Van Mier, 2000), in view of good controllability of these types of movements in the scanner. In human studies of motor sequence learning, it was proved that functional changes could be seen in cortical regions (Floyer-Lea and Matthews, 2005a; Grafton et al., 1995; Hazeltine et al., 1997; Lafleur et al., 2002). The primary motor cortex (M1) (for reviews, see Sanes and Donoghue, 2000; Ungerleider et al., 2002), premotor areas (PMA) (Gerardin et al., 2000; Luft et al., 1998) and supplementary motor area (SMA) (Verwey et al., 2002) were commonly reported to be the dynamic substrates that participated in motor learning. Subcortical regions (cerebellum and basal ganglia) (Doyon et al., 1997; Doyon and Ungerleider, 2002; Floyer-Lea and Matthews, 2005b; Seitz and Roland, 1992) also showed functional plasticity associated with the improvement of performance.

The other approach is to recruit a professional population with a certain expertise, as subjects, for example musicians playing a keyboard or violin or a typist, to investigate the effect of motor experience on the motor function of the brain. They were chosen for their extraordinary use in hand or finger skills during performance. In learning to perform a piece of music on an instrument, one has to coordinate the required hand and finger movement sequences within a strictly defined temporal structure, encode, restore and retrieve the motor information during performance, and also receive kinesthetic feedback in their earlier learning phase. Given the above characteristics of musical training, the researchers assume such long-term motor practice contributes to the difference between musician's functional brain and the healthy, normal people's brain. Functional studies investigating the performance of sequential finger movements reported that a professional pianist performing unimanual complex motor tasks demonstrated decreased activation in the motor cortex including the SMA, PMA, and the ipsilateral primary motor cortex (Im1) (Hund-Georgiadis and von Cramon, 1999; Krings et al., 2000). A comparison of professional and amateur violinists revealed that a higher economy of motor areas frees resources for increased connectivity between the finger sequences and auditory as well as somatosensory loops for professionals (Lotze et al., 2003). The reduced activity in motor cortex implying an economy of effort was confirmed by a study on a pianist which showed reduced recruitment of motor association areas during bimanual coordination relative to the controls (Haslinger et al., 2004). On the other hand, practice-related expansions in cortical representations are also observed. For instance, the research revealed that musicians had enlarged cortical finger representations (Elbert et al., 1995).

These brain imaging studies on motor skills undoubtedly provide better understanding in human brain changes associated with motor practice. However, these studies only examine the confined simple distal limb but not the complex, whole-body movement, which is vital for humans. Such complexity is observed in professional athletes (also called sport experts) who have acquired above average physical skills (strength, agility, and endurance) and extraordinary motor ability. Specifically, in order to master a specific movement with high quality, one has to recruit the required muscles and joints and to suppress corresponding muscles. Sports experts have well-developed motor control ability and an extreme level of movement coordination. Given the length and intensity of motor skill practice, sport experts are ideal subjects for the investigation of motor skills acquisition in addition to dancers and musicians. We are interested in the neural correlates of their extraordinary performance based on extreme level movements.

However, the investigation into complex, whole-body motor performance by functional imaging has been limited so far by the impossibility of actually performing these movements in standard scanners. Meanwhile, there is now ample evidence to suggest that the performance of a motor task and its imagination share common neural substrates (Gerardin et al., 2000; Jeannerod, 1994). Imagining the motor tasks from a first person perspective is called motor imagery (MI), which is defined as a dynamic state during which a subject simulated an action mentally without any overt body movement (Jeannerod, 1994). Lafleur et al. (2002) have demonstrated that the cerebral plasticity that occurs following physical practice is reflected during MI. This relationship is regarded as "functional equivalence" (Holmes and Collins, 2001). Accordingly, brain imaging studies investigating imagery of finger, hand and foot movements demonstrated activation of the SMA, the PMC, and the cerebellum but also the cM1 (Lacourse et al., 2005; Luft et al., 1998; Porro et al., 1996). These functional imaging studies utilizing motor imagery as experimental tasks may provide a feasible way to explore the sport expert's brain. Ross et al. (2003) and Fourkas et al. (2008) demonstrated areas of activation in athletes' brains in complex motor imagery by using functional MR imaging and transcranial magnetic stimulation, respectively.

In our study, kinesthetic imagery tasks are used to tackle the problem of executing whole-body movements in the scanner. Two types of imagery tasks are utilized. One is to image professional movement — diving, and the other is to image simple gymnastics, involving walking, jumping, arm swinging, kicking, etc. These gymnastic movements could be accomplished by all normal, healthy people without extensive training. In addition, professional divers were selected as the subjects due to their having practiced diving movements from their earlier childhood, based on the great training intensity required. In order to examine expert's predominance in representing general movement, a novice group with no training experience was also used in the study. The aim of the present fMRI study on sport experts and novices during imagining of professional movements or simple motor gymnastics is twofold: (1) whether there would be manifestations of experience-related neural activity with reference to professional motor skills for the sport experts. In view of the characteristics of diving movements, we hypothesize that greater brain activation relevant to space-orientation processing would be found during diving imagery; (2) whether there would be manifestations of economy of efficiency in imaging simple gymnastic movements for the sport experts relative to the novices.

Group	Contrast	Lobe	Anatomical region	BA	Side	Local maxima coordinates (x, y, z)			Cluster size (voxels)	Max z
Expert	DO-R	Occipital	Lingual gyrus	18	R	12	−76	0	124,353	6.42
	GO-R	Occipital	Lingual gyrus	18	R	20	−72	−3	105,944	6.74
		Frontal	Superior frontal gyrus	10	L	−18	70	0	2987	4.23
	DI-R	Frontal	Sub-gyral	6	L	−26	−1	55	7459	4.63
		Temporal	Inferior temporal gyrus	37	R	48	−38	−18	1630	4.45
		Frontal	Superior frontal gyrus	10	L	−18	70	−2	840	4.17
	GI-R	Frontal	Sub-gyral	6	L	−28	−3	55	6469	4.68
		Parietal	Postcentral gyrus	7	R	24	−53	69	2186	4.29
		Parietal	Inferior parietal lobule	40	L	−48	−36	50	2161	4.82
		Frontal	Superior frontal gyrus	10	L	−16	70	0	938	3.76
Novice	DO-R	Occipital	Cuneus	18	L	−6	−89	10	101,809	6.24
	GO-R	Occipital	Lingual gyrus	18	R	6	−68	2	98,429	6.1
		Frontal	Middle frontal gyrus	10	L	−48	54	−6	898	4.01
	DI-R	Frontal	Middle frontal gyrus	6	L	−14	−7	59	3616	5.28
		Parietal	Inferior parietal gyrus	40	L	−40	−31	35	1527	4.29
		Sub-lobar	Putamen		L	−24	−9	15	1382	3.94
		Temporal	Inferior temporal gyrus	20	L	−42	−17	−26	771	3.66
	GI-R	Frontal	Superior frontal gyrus	6	L	−10	−5	63	5195	5.29
		Temporal	Superior temporal gyrus	22	L	−55	−31	9	1696	4.26
		Sub-lobar	Putamen		L	−24	−7	10	1684	4.84
		Cerebellum	Culmen		R	28	−50	−26	1566	4.35
		Temporal	Fusiform gyrus	20	L	−50	−34	−22	1073	4.10

Table 1 – Activated region, coordinates, volumes and Z-scores of peak voxels of local maxima during diving imagery and gymnastic imagery condition in expert group and novice group (effects after cluster correction at $p < 0.01$ and $Z > 2.3$).

Note. MNI coordinates; Labels: DO — diving observation; GO — gymnastic observation; DI — diving imagery; GI — gymnastic imagery; BA — Brodmann's area; R — baseline; Side L — left hemisphere; Side R — right hemisphere.

2. Results

2.1. Brain activation during diving observation (DO), gymnastic imagery (GO), diving imagery (DI) and gymnastic imagery (GI)

Table 1 summarizes the results from one-sample t test for each of the eight experimental conditions. For the expert group, significant activation was observed in bilateral lingual gyrus (BA 18) in DO while bilateral lingual gyrus (BA 18) and bilateral superior frontal gyrus (BA 10) were significantly activated in GO. Moreover, significant activation was observed in the left sub-gyral (BA 6), right inferior temporal gyrus (BA 37) and left superior frontal gyrus (BA 10) in DI while the left sub-gyral (BA 6), right postcentral gyrus (BA 7), left inferior parietal lobule (BA 40) and left superior frontal gyrus (BA 10) were significantly activated in GI. For the novice group, we observed that bilateral cuneus (BA 18) were significantly activated in DO while bilateral lingual gyrus (BA 18) and bilateral middle frontal gyrus (BA 10) showed significantly activated in GO. In addition, left middle frontal gyrus (BA 6), left inferior parietal gyrus (BA 40), putamen and left inferior temporal gyrus (BA 20) were activated significantly in DI while left superior frontal gyrus (BA 6), left superior temporal gyrus (BA 22), left putamen, right culmen of cerebellum and left fusiform gyrus (BA 20) were significantly activated in GI.
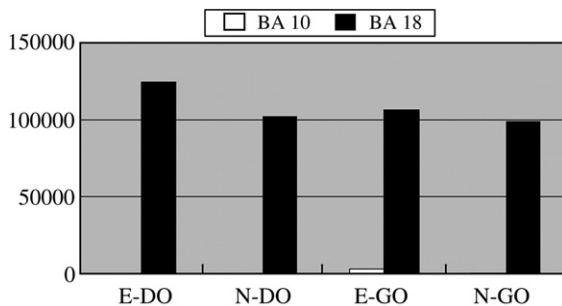

Fig. 1 – Numbers of activated voxels in observation experimental conditions. E-DO: expert-diving observation; E-GO: expert-gymnastic observation; N-DO: novice-diving observation; N-GO: novice-gymnastic observation; BA: Brodmann area.
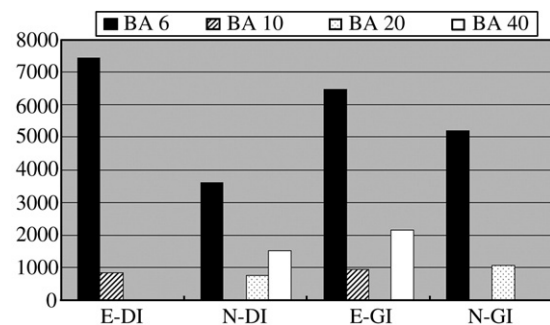

Fig. 2 – Numbers of activated voxels in imaging experimental conditions. E-DI: expert-diving imagery; E-GI: expert-gymnastic imagery; N-DI: novice- diving imagery; N-GI: novice-gymnastic imagery; BA: Brodmann area.

Table 2 – Region, coordinates, volumes and Z-scores of voxels of local maxima of significant differences in four contrasts (effects after cluster correction at $p < 0.01$ and $Z > 2.3$).

Group	Contrast	Lobe	Anatomical region	BA	Side	Local maxima coordinates (x, y, z)			Cluster size (voxels)	Max z
Expert	DO-GO	Occipital	Fusiform gyrus	19	R	28	−55	−6	48686	5.52
		Temporal	Inferior temporal gyrus	20	R	55	−7	−20	1304	4.6
		Temporal	Inferior temporal gyrus	21	L	−57	−11	−16	1156	4.28
	DI-GI	Limbic	Parahippocampus		L	−32	−38	−4	10610	4.41
		Temporal	Fusiform gyrus	20	R	34	−36	−17	2035	3.87
	GI-DI	Parietal	Superior parietal gyrus	7	L	−30	−58	43	2958	4.25
		Parietal	Superior parietal gyrus	7	R	28	−65	59	1843	4.09
		Frontal	Medial frontal gyrus	6	R	12	−1	57	1026	3.82
		Frontal	Middle frontal gyrus	46	L	−46	22	19	739	3.32
		Frontal	Middle frontal gyrus	46	L	51	21	27	682	3.6
		Temporal	Superior temporal gyrus	42	R	63	−32	16	666	3.72
Novice	DO-GO	Occipital	Lingual gyrus	19	L	−18	−70	−8	11523	5.03
	GO-DO	Temporal	Middle temporal gyrus	22	R	48	−40	8	870	4.01
	GI-DI	Occipital	Cuneus	18	R	10	−87	15	817	3.51
		Frontal	Medial frontal gyrus	6	L	−6	−17	54	705	3.63

The results also revealed BA 18 was activated in all observation conditions and BA 10 showed significant activation only in GO condition. As regards the common activated brain areas in imagery condition, we observed that whatever in imaging diving or gymnastics, expert group manifested strong BOLD signals in BA 6 and BA 10 while novice group showed activation in BA 6 and BA 20. Figs. 1 and 2 show the above results.

2.2. Within-group comparisons: DO vs GO and DI vs GI

Statistical contrasts were performed between DO and GO, DI and GI conditions in the expert group and novice group (see Table 2 and Fig. 3 for results). For the experts, activation was significantly greater during diving observation than gymnastic observation in right fusiform gyrus (BA 19) and bilateral inferior temporal gyrus (BA 20 and BA 21) and was also greater during diving imagery than gymnastic imagery in left hippocampus and right fusiform gyrus (BA 20). Moreover, experts revealed more activation in bilateral superior parietal gyrus (BA 7), right medial frontal gyrus (BA 6), right middle frontal gyrus (BA 46) and right superior temporal gyrus (BA 42) during gymnastic imagery than diving imagery.

Statistical contrasts were also performed between DO and GO condition and between DI and GI conditions in the novice group. The results of these contrasts for novice group showed that greater activation was found in left lingual gyrus (BA 19)
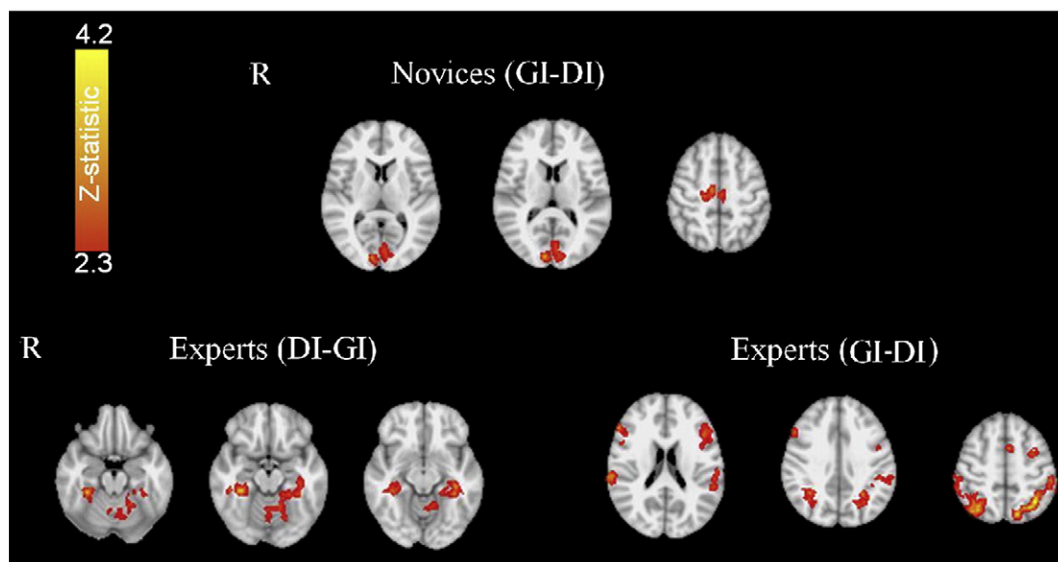

Fig. 3 – Within-group-analysis: significant activation during different imagery conditions. Group mixed effects analyses, Z > 2.3 (p < 0.01 corrected for multiple comparisons using cluster detection). Red areas indicate greater activation during the given imagery. The upper view represents significantly activated areas in gymnastic imagery versus diving imagery conditions for novices. The lower left view represents significantly activated areas in diving imagery versus gymnastic imagery conditions for experts. The lower right view represents significantly activated areas in gymnastic imagery versus diving imagery conditions for experts.
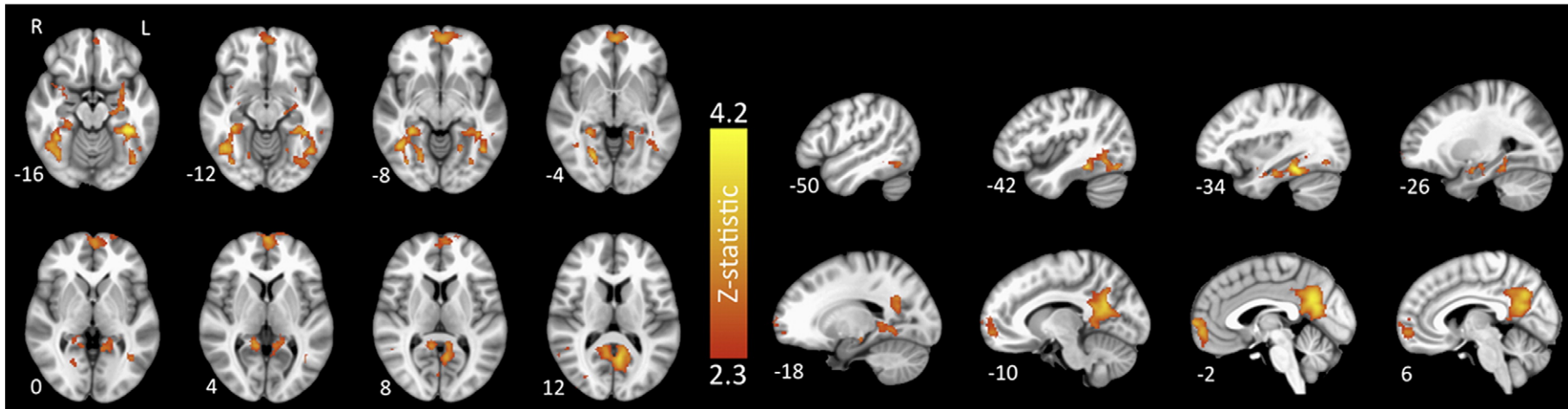
Fig. 4 – Between-group-analysis: fMRI activation maps during diving imagery in the group of sport experts and the novices. Group mixed effects analyses, Z>2.3 (p<0.01 corrected for multiple comparisons using cluster detection). Red areas indicate greater activation during diving imagery. The left slices are represented in axial view and the right slices in sagittal view.

during diving observation than gymnastic observation while right middle temporal gyrus (BA 22) was more activated greatly during gymnastic observation than diving observation. Table 2 also revealed that activation was significantly greater during gymnastic imagery versus diving imagery in clusters located within the right cuneus (BA 18) and left medial frontal gyrus (BA 6).

2.3. Differences between groups: experts and novices

Brain activation patterns were directly compared between experts and novices in all observation and imagery conditions. Significant differences were found in the left parahippocampal gyrus (BA 36) and left medial frontal gyrus (BA 10) in diving imagery (see Fig. 4). There were no significant differences between the experts and novices in gymnastic imagery. Moreover, the contrast of the cerebral activation in DO and GO conditions between these two groups (experts vs novices) didn't show any significant difference.

3. Discussion

This study aimed to investigate how the high level motor performance in sport experts (cf. novices) might be manifested in fMRI BOLD signals, how imaged performance of professional skills and general skills might differ for experts, and whether differential BOLD signals observed in experts and novice allowed additional insights to changes in neural activity with continued motor training. The present results revealed distinct activation patterns for imagined conditions of simple gross motor skill and professional gross motor skill. Our major findings were as follows: (1) sport experts revealed a special cerebral activity pattern adapted to experience-related motor task, which mainly presented as strong activation in the parahippocampus. Experts utilized their kinesthetic imagery more efficiently than novices but only for the activity in which they had expertise; (2) Prefrontal areas are activated both in diving imagery and gymnastic imagery for sport experts but not for novices; (3) Furthermore, cerebral activation revealed no significant difference between experts and novice when they imagined simple motor skills. That is to say, the experts' ability to image non-professional motor skills does not benefit from the long-term motor training; (4) finally, there was no significant difference between experts and novices in any observation contrasts.

There was greater activation in diving imagery for experts than novices in parahippocampus. Although the exact cause of this activation is still unknown, we suppose it might be relevant to the long-term practice of diving movements on functional change. A number of studies have confirmed the human functional neuroimaging of brain changes associated with practice (Kelly and Garavan, 2005). Lotze et al. (2003) found that music imagery also could induce differential changes in the auditory system and motor system between professionals and amateurs, which provided substantial evidence for the influence of occupation and habits on mental representations of task-related internal simulation. Another study on professional physical practice trained for a relatively long time, such as tennis players, suggests a key role of long-

term experience in modulating sensorimotor body representations during mental simulation of sports (Fourkas et al., 2008). These cerebral changes induced by training are also described in functional imaging researches of gymnastic learners and tango learners (Munzert et al., 2008; Sacco et al., 2006). In an earlier study, Ross et al. (2003) offered a "motor expertise" paradigm, which highlighted the feasibility of defining areas of brain activation during imagery of a complex, coordinated motor task.

The results of between-group contrast in diving imagery and within-group contrast (DI vs GI) for experts also demonstrate that the parahippocampus is strongly activated. Therefore, it is reasonable to infer that the parahippocampus might play a crucial role in diving players' imaging professional movements. This might reflect the motor expert's advantage in cognitive processing specific to experience-related tasks. Specifically, operating one's own body, for instance during a somersault and twist, plays a crucial role for professional diving players in accomplishing diving movements. The perception of spatial information is undoubtedly required in diving imagery. Other studies have described the involvement of the parahippocampus in retrieving spatial information (Ekstrom et al., 2003; Gron et al., 2000). This finding is supported by another study from brain activation of locomotion imagery, which also found parahippocampal involvement (Jahn et al., 2004) in walking imagery. Evidences from neuropsychological and neuroimaging studies suggest the parahippocampus is involved in acquiring spatial information (Aguirre et al., 1996; Barrash et al., 2000; Epstein and Kanwisher, 1998; Habib and Sirigu, 1987; Ross, 1980). Further studies examining the retrieval of remote spatial memories in London (Kumaran and Maguire, 2005; Maguire, 1997; Spiers and Maguire, 2006), Toronto (Rosenbaum et al., 2000), and Liverpool (Mayes et al., 2004), have all reported parahippocampal activations. These findings strongly support a key role of the parahippocampus in spatial navigation, which usually refers to the external environment. Although less evidence is reported that parahippocampus is relevant to spatial perception on oneself, it is possible that the parahippocampus might be crucial to retrieve spatial orientation of self-movement.

Table 1 shows the activated brain areas induced by eight conditions. Further analysis is performed in activated voxels within the same brain regions. It reveals that the superior frontal area is activated both in diving imagery and gymnastic imagery for sport experts while no significant activation is shown by the novices. This difference might be interpreted as better recruitment of the frontal lobe in motor imagery for sport experts. There is much evidence demonstrating that a basic function of the frontal lobe is to control the temporal organization of behavior and cognition (Fuster, 1980; Goldman-Rakic, 1987). The prefrontal cortex plays a major role in higher order aspects of the organization of behavior (Petrides, 1994). Jeannerod (1994) described three levels of computation in motor control. At the coarsest level, a path must be planned. At the next level the inverse kinematics problem must be solved at each point along the path; one must compute the proper joint angles. At the finest level, the inverse dynamics problem must be solved at each point; one must compute the muscle forces needed to move the joints into the proper positions. These levels are not necessarily independent. On

the bases of these points, one would like to suggest that motor imagery is controlled by those parts of the frontal cortex which are specifically involved in carrying out computations of the action programming subsystem which deals with planning at the coarsest level (Decety, 1996). The evidence available shows that the prefrontal cortex plays a fundamental role in this timing (Petrides, 1994). It has been argued that the prefrontal cortex is necessary for regulating behavior demanding strict timing guided by representations or internalized models of reality. We infer that practicing professional movements for a long period may possibly be associated with great control in connecting fragments of movement at the right time. Hence, sport experts seem to reveal a preferential timing activation pattern of motor imagery.

Moreover, the brain activation induced by all observation tasks is also found in occipital lobe (BA 18) for both experts and novices. Left frontal gyrus (BA 10) showed significant activation only in gymnastic observation for these groups. However, two contrasts between these groups revealed that same observation tasks activated similar brain areas, which indicated that compared to the novices, experts didn't show any difference of cerebral activation benefiting from training when watching the movements.

Imagery in all imagery conditions (E-DI, E-GI, N-DI, and N-GI) induced significant activation in BA 6, at a similar activated level. This demonstrates that these three imagery conditions recruit the premotor areas, which are needed by motor imagery (Lotze and Halsband, 2006). In this study, each participant was required to imagine the movement from the first person perspective without actually moving. Decety (1996) demonstrated that the motor imagery from the first person perspective relied on motor-kinesthetic information processing. Dickstein and Deutsch (2007) described that motor imagery is a complex, cognitive operation that is self-generated using sensory and perceptual processes, enabling the reactivation of specific motor actions within working memory. Numerous studies have reported that the premotor cortex is the predominant area of movement imagery (Decety et al., 1994; Gerardin et al., 2000; Stephan et al., 1995). Moreover, in studies of motor imagery with the focus on externally driven action and internally driven action, premotor neurons are more active during externally guided movement (Mushiake et al., 1991). Our findings obviously confirmed the view that imagery guided by visual clues could induce strong activation in premotor areas. On the other hand, the significant activation of premotor areas demonstrated that the participants executed kinesthetic imagery tasks successfully during all imagery conditions.

As regards the expert group, predominant activation was found in superior frontal gyrus (BA 7) and medial frontal gyrus (BA 6) in gymnastic imagery vs diving imagery, which indicated that the experts mobilize more brain areas related to motor and sensory to guarantee the accomplishment of these gymnastic movements. The point we have to notice is that experts need to activate the prefrontal gyrus (BA 46) governing the executive function. In the study, it is obvious to observe that the cooperation between the control role of the prefrontal gyrus and the motor execution role of premotor areas seems to be so important for experts. However, novices didn't show any recruitment of prefrontal gyrus in same contrast, which indicated that the general people seems to be lacking of the

awareness to control the movements in imaging gymnastic movements.

The limitation of this study is that it was not possible to determine the degree of mental performance while the experiments were running. This limitation is inherent with the technique of imagery that is by definition an internal mental construct. Therefore, an attempt was made to minimize variability by giving strict instructions to each participant. In addition, a subjective survey for monitoring the whole process was completed for each participant immediately after the examination. In our study, given the subjects in our study are teenagers whose functional activation might be influenced by maturation and development, the two groups were entirely matched in age and gender.

In summary, this study has sought to investigate the neural activity manifested during imagery of professional movements and imagery of non-professional movements in sport experts and novices. The findings are consistent with previous studies and support the hypothesis that professionals reveal experience-related neural networks of the brain, which might account for their excellent motor performance (Wei et al., 2009). The problem of which factor (long-term dedicated practice or innate differences) contributes to different pattern of connections needs to be further investigated. Analysis of training status or the addition of amateur athletes into the subject groups might provide a good way to answer this question. Perhaps a longitudinal study on the same athletes group in developing motor skills might be needed to elucidate whether this activation is a kind of reorganization or redistribution. Moreover, the sport experts' activation in the prefrontal areas in both imagery tasks might indicate the representation of expertise that is processed with a top–down pattern. Finally, we suggest that an athlete's brain may provide a new model for examining whether and where functional brain plasticity occurs that is associated with extensive training, because athletes acquire and continuously practice a variety of complex motor skills. In various types of sports, different mental or physical abilities might be demanded, for example, open sports might need more mental strategies in defense or offense, while players engaged in closed sport events might rely much more on proprioceptive sensation and multisensory feedback. Future studies will explore professional athletes' functional plasticity with brain imaging technology.

4.   Experimental procedures

4.1.   Participants

In the study, the "expert group" (EG) was defined as professional athletes practicing full-time motor skill with an average daily practice time of at least 5 h. All sports experts are national-level masters (there are A, B, C, and D categories for professional athletes in China to distinguish their competence level, which corresponds to international-level masters, national-level masters, the first-class level and the second-class level, respectively). Athletes ranked in the B category typically compete at a national level and may also compete in regional tournaments. The "novice group" (NG) was defined as healthy participants who are not involved in any extensive

physical training or professional experience. Twelve elite young divers were recruited from the Beijing Diving Team and are diving masters who had experienced continuous diving training since childhood ($M=10.13$ years, SD$=1.78$). The twelve novices were from the Fengtai Middle School and were age and gender matched to the diving group. There were six males and six females in each group. The age of all participants ranged from 13 to 17 years, with a mean age of 14.58 (SD 1.68) years for EG and 14.92 (SD 1.38) years for NG. The difference in mean ages was (95% confidence interval) 0.34 years. All of the participants were right-handed and medically or neurologically stable. No participants had any histories of substance dependence. Informed consent from their parents was obtained, and the study was approved by the Institutional Review Board of Beijing MRI Center for Brain Research and has therefore been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Before scanning, all participants completed volunteers screening forms for the Beijing MRI Center for Brain Research to exclude any subjects who had a history of hearing or vision problems, physical injury, history of seizures, metal implants, and head trauma with loss of consciousness, or pregnancy.

4.2. Subjective measures

We administrated a short questionnaire about the use of mental practice in daily life or sports (Do you use mental image in your daily life, or sports? And if so, when and what type of mental imagery do you use? Do you use visual imagery in your daily life or sports? Do you use imagery from first person perspective in your daily life or sports?) to ascertain if there were differences among participants in their regard to familiarity with this form of mental practice. The reports showed that no one has used imagery from first person perspective as a form of training. Only five of the athletes occasionally experience visual imagery of diving movements before competition. This is not surprising because only the highest level of athletes in China National Teams utilizes the service of sport psychologists. Immediately after the scanning experiment, all participants were asked to accomplish introspective reports of task performance. Participants described their imagery in each condition to assess compliance with instructions. The feedback indicated that athletes and students used their imagery time to comply with the imagery instructions. All participants used a first person perspective and imagined all actions in practice settings.

4.3. Mental practice manipulation

Motor imagery from the first person's perspective (kinesthetic imagery) is quite different from motor imagery from the third person's perspective (visual imagery) and requires the subject to "feel" the movement, i.e., to mentally perceive muscle contractions. If participants don't know what the kinesthetic imagery is, it is impossible for them to perform this mental activity during scanning. Moreover, self-confidence (Abma et al., 2002), skill level (Salmon et al., 1994), sport events (Boyd and Munroe, 2003) and situation (Weinberg et al., 2003) are variable factors that influence the subjective cognition of self-

selected motor images. Therefore an introduction to kinesthetic imagery (e.g. what is kinesthetic imagery and how to perform kinesthetic imagery?) was carried out by a sport psychologist to ensure all the participants grasped the basic skills of kinesthetic imagery as well as understanding kinesthetic imagery. This point was discussed with each subject prior to the imagery and all stated they understood the concept of kinesthetic imagery.

In previous behavioral studies, kinesthetic imagery is reported to be more difficult to perform than visual imagery. So a standardized task familiarization exercise is necessary. With the help of a coach of motor learning, participants executed gymnastic exercises repeatedly until they could perform the overt movements correctly during which the internal "feelings" (muscle contraction, speed and extent of movement) were greatly stressed. Every video clip of diving movements was also played repeatedly so as to make all participants very familiar with the components of the movements. It took about 1 h for each subject to be familiar with the movements.

Finally, all of the participants were trained to use motor imagery in the absence of overt behavior during an extensive training session with the aid of a video. The experimenter showed thirty-two 6-s video clips (16 diving clips and 16 clips of gymnastic exercise movements) with a whole-body view, but without any facial expressions or emotional movements. Every clip was followed by an 18-s black screen for motor imagery. Models in the video clips were female undergraduate students and divers. During this session, the internal "feelings" were also stressed. They were also informed that the movements they imaged during extensive training were the same as those to be used in the scanning.

4.4. Motor imagery task

In this experiment, the independent variables studied were group (expert group or novice group) , observation condition (diving observation scans or gymnastic observation scans) and imagery condition (diving imagery scans or gymnastic imagery scans), yielding eight experimental conditions in a $2\times2\times2$ factorial designs: expert-diving observation (E-DO); expert-diving imagery (E-DI); expert-gymnastic observation (E-GO); expert-gymnastic imagery (E-GI); novice-diving observation (N-DO); novice-diving imagery (N-DI); novice-gymnastic observation (N-GO); novice-gymnastic imagery (N-GI). The dependent variable was brain activation, which was measured with blood oxygen level dependent (BOLD) fMRI.

The stimulus was presented with Motor Imagery Guidance self-programmed by Presentation (http://www.neurobs.com/presentation), an experimental control software system for neuroscience, which also synchronized the presentation of the stimuli with the fMRI scanner. The experiment is composed of an active condition and a rest condition. In the active condition, there are two kinds of task: diving imagery and gymnastic exercise imagery, during both of which participants imagined from the first person perspective. In the rest condition, participants had to feel themselves lying down and relaxing with eyes closed. During scanning sessions, participants worked on a fixed sequence of experimental conditions. First, they observed a video showing diving or gymnastic

exercise movement. They were instructed to observe the video carefully so that they would be able to perform a congruent kinesthetic motor imagery after the observation. Then, they were told to image the observed movement kinesthetically with the audio-recorded voice saying "start" to instruct participants to begin to image and "stop" to instruct them to end the imagery. The audio stimuli were transmitted through earphones.

The tasks adopted a block design with 30 s of rest alternating with 96 s of the active condition. There were 8 blocks, each of which consisted of 4 trials with the same kinds of movements in the active condition. The active condition of diving movements and gymnastic movements were interleaved between the rest conditions. In each trail, there were 6-s observations and 18-s imagery. Participants had to perform the motor imagery repeatedly with self-paced practice according to the previous observed movement, until they heard the voice saying, "stop". There was no interval between trials in the same active condition.

4.5. Test procedure

Participants were screened prior to the test session to exclude the conditions with disease, injury or drug abuse. All participants provided informed consent by their parents during a screening visit in which the procedure was explained. Upon participants' arrival, some questions on using kinesthetic imagery were also completed, followed by familiarization exercises. Participants were then prepared for testing inside the scanner and allowed one additional 30-s instruction and 96-s practice block to familiarize themselves with performing the task. Eight 96-s epoch, separated by seven 30-s rest periods, consisted of four 24-s trials with the same kinds of movements using the following block paradigm: OBSERVATION–IMAGE–OBSERVATION–IMAGE–OBSERVATION–IMAGE–OBSERVATION–IMAGE. After scanning, participants were assigned to state the subjective feelings of performing the tasks in the scanner.

4.6. fMRI acquisition

The fMRI imaging was performed on a 3.0 T magnetic resonance scanner (Siemens Version, Erlangen, Germany), using the standard radio frequency head coil. The head was fixated with foam pads to minimize head movements during the entire experiments. A high-resolution full-brain 3D T_1-weighted anatomical image (Magnetization Prepared Rapid Acquisition) was acquired in the sagittal orientation for each subject at the beginning of the session. The following parameters were used for the volumetric acquisition: TR (repetition time)=2530 ms, TE (echo time)=3.37 ms, flip angle=7°, slice thickness=1.33 mm, FOV (field of view)=256 mm, 512×512-pixel matrix. The voxel size was 0.5×0.5×1.33 mm.

Functional T_2-weighted images were acquired using echo-planar (EPI) sequences, with a TR of 2000 ms, a TE of 30 ms, 90° flip angle, matrix=64×64, FOV=220 mm, slice thickness=4 mm. The resulting voxel size was 3.4×3.4×4.0 mm. The fMRI acquisition consisted of 513 data volumes. Task stimuli were projected on a screen located at the head end of the scanner table via an LCD projector located outside the scanner room. Participants viewed the screen through a mirror located

on the head coil. Total scanning time, including structural imaging, was an average of 19 min for each subject.

4.7. fMRI data analysis

Functional data sets were analyzed using tools FSL 4.1 (Smith et al., 2004) from the FMRIB Software Library (www.fmrib.ox.ac.uk/fsl). The first 12 EPI images of each session were discarded to allow for T1 stabilization. At the first level (individuals), the following preprocessing was applied: non-brain removal with 0.3 fractional intensity threshold and the voxel size was adjusted from 0.5 mm to 1 mm, slice-timing correction using sinc interpolation, motion correction and spatial smoothing using Gaussian kernel of FWHM 6 mm, high and low pass temporal filtering (Jenkinson and Smith, 2001; Smith, 2002) and Melodic ICA data exploration (We did not analyze the ICA data here, which will be used for our exploration study in the future). Statistical analysis was carried out using the general linear model (GLM), which was convoluted with a hemodynamic response function. For first-level EVS, diving imagery and gymnastic imagery were defined. In view of the difference of observation processing and imagery processing (Munzert et al., 2008), we assayed the brain activations of 8 experimental conditions within one fMRI run, which separated observation task from motor imagery task. Therefore, within each subject, 8 contrasts (DO-R, GO-R, DI-R, GI-R, DO-GO, GO-DO, DI-GI, GI-DI) were taken into consideration in the overall model. Cluster detection, which includes intrinsic correction for multiple comparisons (Poline et al., 1997), was used to adjust the images to a corrected threshold of $p<0.005$. The number of voxels constituting a significant cluster was determined by Gaussian random field theory and depended on the intrinsic smoothness of the data as well as the chosen threshold level (Worsley et al., 1992). The significant level of the clusters was intrinsically corrected for multiple comparisons. Functional neuroimages of each subject were coregistered to corresponding structural images in native space, and structural images were registered to structural Talairach standard images (Talairach and Tournoux, 1988), defined by the Montreal Neurological Institute standard brain supplied with FSL. The same transformation matrices used for structural-to-standard transformations were then used for functional-to-standard space transformations of coregistered functional images.

Group mixed effects analyses were performed (Woolrich et al., 2004). Group mean activation maps were produced for four experimental contrasts. For this analysis, high level EVs were the effects of group (expert vs. novice) forming an unpaired mixed effects analysis performed using FLAME (www.fmrib.ox.ac.uk/fsl; (Woolrich et al., 2004). Z (Gaussianized T/F) statistic images were corrected for multiple comparisons using cluster detection, with clusters determined by Z>2.3 and a corrected cluster significance threshold of $p=0.01$ (Forman et al., 1995; Friston et al., 1994; Worsley et al., 1992). Activation maps were overlaid on the group mean high-resolution images for display purpose.

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