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Mental Practice:

Rehearsal Strategies and Sensorimotor Outcomes

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Abstract

Mental practice (MP) is the cognitive rehearsal of a task in the absence of overt physical movements. It has been shown that MP allows performance improvements in various tasks, but little is known about the effectiveness of different strategies of MP and about the exact sensorimotor mechanisms that underlie this improvement. Several strategies of MP are here investigated in relation to the practice outcome. In particular, in the context of music performance, it is shown that pitch imagery is strongly associated with better performance, regardless of the specific nature of the musical task. Conversely, structural/formal analysis appears to be important for music memorization, and motor imagery for fine motor control. In terms of sensorimotor outcomes of the practice, it is shown that MP results in improvements of movement velocity, movement anticipation and coarticulation. Additional experiments from force-field learning paradigm show that MP can also result in changes of somatosensory perception. Results are discussed in the context of the simulation theories of motor control.

1. Introduction

This thesis elaborates and presents original experimental data about mental practice. To introduce the reader to this topic, I will start by asking and answering four questions that are useful to frame the present contribution:

- i) What is mental practice?
- ii) Why is it important for cognitive neuroscience?
- iii) What practical application does it have?
- iv) What is the novel contribution provided here?

- *What is mental practice?*

Mental practice (MP) is the “cognitive rehearsal of a task in the absence of overt physical movements” (Driskell et al., 1994, pp. 481). This is possible through the use of mental imagery, that is motor imagery, visual imagery and auditory imagery, or through the observation of the movements of others.

- *Why is mental practice important for cognitive neuroscience?*

MP builds on the concept of mental imagery. Mental imagery serves pivotal function such as perception, memory and movement production, with which it shares wide neural circuitries and functional properties. Mental imagery allows to observe the behavioral and neural outcome of these circuitries when they are run in the absence of their factual, external counterpart. MP extends the heuristic potential of mental imagery to the domain of learning, showing what happens when mental imagery is purposefully and repeatedly applied with the aim of improving performance in a task.

- *What practical application does it have?*

MP allows practicing regardless of whether the physical context is compliant or not. For example, it allows repeatedly practicing movements that would otherwise damage the body (e.g., in sports), it allows practicing without the external tools usually required for

the practice (e.g., piano-less, <<silent>> piano practice), it allows practicing when the overt movement cannot be produced (e.g., stroke patients). More in general, the MP approach suggests to shift the focus of attention from the outside to the inside. Whatever one is practicing, this approach can promote process-oriented strategies of practicing, moment-to-moment awareness, focused and sustained attention.

- *What is the novel contribution provided here?*

A considerable amount of research has been devoted to assess how effective MP is, compared to physical practice or no practice. However, at odd with the studies on imagery, an understanding of MP from the perspective of cognitive science is still lacking. This thesis wishes to provide a contribution with this respect, by asking two interrelated questions: first, which strategies more effectively support MP; second, what precisely is modified by MP. The first question pertains to the input information. Previous studies have shown that MP is effective, to a certain extent. However, in terms of characterizing the input information, it can be noticed that several formats of imagery can be fed into the mental rehearsal, but little is known about their role and their relative effectiveness. The second question deals with the output of the MP process: showing improvements in performance is important, but in itself it does not reveal what exactly changes in the behavior of the individual, that makes those improvements possible.

The first question is tackled by the first and the second study present here. Music performance is employed as a model of skilled behavior, and several mental strategies are confronted to the practice outcome. It is shown that, in the case of a musical context, auditory imagery plays a central role, while the importance of motor imagery and of structural/formal analysis depends on the motor *vs.* cognitive emphasis of the specific task. The second question drives the second and the third study reported in this thesis. These two investigations expand the present knowledge about how MP influences behavior showing that it results in motor anticipation, coarticulation and in changes in somatosensory perception.

This introduction will review the literature pertinent to the content of these studies. Topics such as the applications of MP in sport psychology or stroke rehabilitation, that are not directly related to the experimental content of this thesis, will not be covered (for

a recent review on MP in sport psychology, see Cumming and Ramsey, 2009; for stroke rehabilitation, see Zimmermann-Schlatter et al., 2008).

1.1 A direct taste

I would like the reader to begin by directly experiencing what MP is about. If you'd like to abide my suggestion, you can ask somebody close to you to read slowly the following list of instructions, while you follow them closely. This will take only a few minutes.

Let your hands rest on the table, palms up, the fingers open.

Take a deep breath, and fully relax all the muscles in your body.

Let your mind become quiet and still.

Now look attentively at your right hand.

Imagine that a light dumb-bell, one of those we use for training biceps at the gym, is resting in your right palm. Visualize it in your hand, as if it was really there.

See its color, its size, and its precise shape.

Feel how it weights, and feel how it sinks in the softness of your palm.

Pay attention to the quality of the touch on your skin, depending of the material you are imagining.

Feel the difference whether it is made of metal, or of soft porous plastic, or of wood. You might notice a particular temperature, and a particular reaction of the various layers in your hand tissues.

Perhaps you might feel a gentle current moving into you fingers, as is they were eager to satisfy the affordance of this object, to grasp and to hold it in the fist.

If so, feel free to give in to this impulse, and imagine to close your hand on the dumb-bell.

Just make sure that your hand remains relaxed, and you don't really move the fingers.

While imagining holding this imaginary weight, let's start some exercise.

Feel yourself lifting the weight.

Carefully follow within your limb the pattern of imaginary muscular contraction.

Perhaps you will first feel activation in the right bicep, and the delicate release in the triceps that together allow your arm to exert the exact amount of force necessary to accomplish this lifting.

You might feel this force progressively propagating from the arm to the forearm, causing the elbow to bend and the skin inside the elbow to become slightly compressed.

Feel, as the full force displays through your entire arm, your wrist bending under the weight of the dumb-bell, and the additional rush of force moving into your arm to compensate for this.

Complete the lifting, and reach the peak of your effort.

Feel the beat of your heart, and pass through the status of the muscles of your neck and shoulders. Notice how is your breath in this moment.

And now, gently, release the arm, release the effort.

While you do this, bring your attention to the new, and entirely different, pattern of muscular activation that is supporting your controlled downward movement.

Completely relax your hand on the table.

Take a breath, and repeat the same move.

As a next step, you can now do the same exercise imagining a heavier weight.

Be aware of the difference between the two, the lighter and the heavier weight, and how they call for different responses from your arm.

Always remember to keep you arm relaxed and still on the table.

This short exercise has shown how a mental exercise can be constructed and how different formats of imagery contribute to the MP process. In the following paragraphs, the literature about these imagery modalities will be briefly reviewed, followed by a concise presentation of the findings on MP.

1.2 Visual imagery

Visual imagery can be defined as a set of representations that gives rise to the experience of perceiving a stimulus in the absence of appropriate sensory input (Kosslyn, 2005). The internal events that produce this experience rely on mnemonic information.

The visual domain of imagery has been historically the first and the most extensively studied, and nowadays it remains one of the better understood. Given this, even if the experimental part of this thesis will only occasionally touch on visual imagery, I will review some findings of interest for the concept of MP and imagery in general.

1.2.1 Visual perception and visual imagery

One of the main research focus on this topic has been whether, and to what extent, visual imagery and visual perception share functional properties and neuroanatomical substrates.

First crucial observations were reports of brain activation in primary and secondary visual areas (BA 17, 18) when subjects were requested to form a high-resolution mental image (Kosslyn et al., 1993; Kosslyn and Thompson, 2003; LeBihan et al., 1993). Such activations seem also to reflect the topographical mapping observed for visual images, in that larger images activate relatively more anterior areas than smaller images (Kosslyn et al., 1993). Moreover when repetitive transcranial stimulation is applied and disrupts the normal function of area 17, response times in both perceptual and imagery tasks increase, further supporting the involvement of primary visual areas in mental imagery (Kosslyn et al., 1999).

Furthermore, not only early visual areas but also more anterior cortical areas can be activated by imagined stimuli. For example, when subjects imagine previously seen motion stimuli (such as moving dots or rotating gratings), area MT/MST, which is motion sensitive during perception, becomes activated (Goebel et al., 1998). Color perception and imagery also appear to involve partially overlapping cortical regions (Howard et al., 1998), and areas of the brain that are selectively activated during the perception of faces or places are also activated during imagery of these categories of stimuli (O'Craven and Kanwisher, 2000). Areas involved in spatial perception, including a bilateral parieto-occipital network and the para-hippocampal place area, are activated during spatial mental imagery (O'Craven and Kanwisher, 2000), and areas involved in navigation are activated during mental simulation of previously learned routes (Ghaem et al., 1997).

Altogether, this imaging data argue in favor of a considerable overlap in neural mechanisms implicated in imagery and in perception, both at the lower and the higher levels of the visual processing pathway.

This shared-systems view is also supported by neuropsychological evidence. It is known that visual function is organized in the brain in two main streams of processing. One

major visual pathway runs from the occipital lobe down to the inferior temporal lobe (the ventral or 'object properties processing' pathway; Ungerleider and Mishkin, 1982); when damaged, the person cannot easily recognize shape. The other major visual pathway runs from the occipital lobe to the posterior parietal lobe (the dorsal or 'spatial properties processing' pathway); when damaged, the person cannot easily register location. Parallel deficits appear in imagery: damage to the ventral pathway disrupts the ability to visualize shape, whereas damage to the dorsal pathway disrupts the ability to visualize locations (Levine et al., 1985). Indeed, very subtle deficits can occur in imagery that parallel the deficits found in perception. For example, some brain-damaged patients can no longer distinguish colors either perceptually or in imagery (De Vreese, 1991), and others can no longer distinguish faces either perceptually or in imagery (Young et al., 1994). Another interesting parallel is provided by unilateral visual neglect, a disorder caused by lesions of the right parietal lobe in which subjects ignore objects to one side of space (usually the left side). These patients often ignore objects at the same side of space in both perception and mental imagery (e.g., Bisiach & Luzzatti, 1978; Bisiach, Luzzatti, & Perani, 1979).

However, although the deficits in imagery and perception often parallel each other, this is not always the case. For example, Farah showed that some patients have selective problems in generating images, even though they are able to recognize and identify perceptual stimuli (Farah, 1984). In addition, patients who could visualize, but had impaired perception have also been reported (e.g., Behrmann et al., 1992; Jankowiak et al., 1992). In a successive study, Kosslyn and collaborators found that approximately two-thirds of all the brain areas that were activated during perception and during imagery, are activated in both cases (Kosslyn et al., 1997). Presumably, lesions in the areas that are not activated in common produce the dissociations, in which imagery or perception are disrupted independently, whereas lesions in the areas that are activated in both cases produce the more frequently reported parallel deficits in imagery and perception.

1.2.2 A cognitive model of visual imagery

Given the literature revised above, it can be hypothesized that imagery does share some mechanisms with the perceptual processing. Building on this hypothesis, a model of

visual imagery has been proposed by Kosslyn et al. (1994). The model posits seven major components each of which accepts input and transforms it in specific ways to produce the output. Each component, described in detail below, is also assumed to store information.

- *Visual buffer and attention window*

Introspectively, one of the most striking effects of imagery is the sensation that objects are extended in space. According to the model, this happens because images occur in a structure with the properties of a visual buffer, which corresponds to a set of retinotopically mapped areas located in the occipital lobe (e.g., in area 17, posterior-to-anterior organization of the information received from foveal-to-paravofeal regions of the retina, Fox et al., 1986). The visual mental image then is a pattern of activation in the visual buffer built starting from stored information, instead of direct bottom-up perception. The intrinsic topographical organization of the visual buffer would be responsible for its ability to depict shapes. The term “depict” implies that each part of the representation corresponds to a part of the object such that the distances among object parts are reflected (albeit not perfectly) by the distances among the representation of the parts (Kosslyn, 1980). At each location in the topographically organized buffer a set of “symbolic” codes that indicate information such as the color and the luminance at that specific point are found. Thus, in addition to the “picture like” depictive aspect of the representation, the visual buffer specifies information interpretable as non-spatial properties associated with each location. Finally, the visual buffer is not a passive screen, but rather serves to organize input in various ways, such as separating the figure from the ground.

There is far more information in the visual buffer than can be processed in detail. Thus, an “attention window” operates within this structure, selecting a region of the buffer and sending the pattern of activation in it to other areas for further processing (cf. Brefczynski & DeYoe, 1999). The attention window can be covertly shifted, and allows one to scan over entire images in the visual buffer without moving one’s eyes.

- *Processing of object properties*

The information about object properties such as shape, color and texture, runs from the occipital lobe ventrally to the inferior temporal lobe. These areas are involved in visual recognition and in storing of visual memories (Ungerleider and Mishkin, 1982). During the process of visual recognition, input is compared with stored visual memories, and if a match is found the stimulus is recognized (Haxby et al., 1991). In imagery, according to the model, stored visual representations are activated in order to construct a visual image in the visual buffer. Critically, pathways run back from the temporal lobe areas involved in visual memory to the occipital areas that host the visual buffer (e.g., Van Essen, 1985). These connections allow stored information to be used to reconstruct a visual shape.

- *Processing of spatial properties*

The information about spatial properties, such as location and size, runs from the occipital lobe dorsally to the posterior parietal lobe (Ungerleider and Mishkin, 1982). These mechanisms also play a special role in guiding movements (Goodale and Milner, 1992) and in representing a map of the locations of objects in space (Mesulam, 1990). Processing in these regions plays three roles in imagery: first, such processing can register previously unnoticed aspects of imaged objects (for classic examples of this, observe what you do when trying answering questions such as “in which hand the Statue of Liberty holds the torch?”, Kosslyn, 2002). Second, spatial information can be used to amalgamate two or more parts or objects into a single image of a complex object or scene. Third, one can form “spatial images” by setting up locations and spatial properties of named objects, without needing to represent shape in the image itself (another classic example: if you look at a tiled floor, you can probably “see” shapes, such as letters of the alphabet, even though what you are actually doing is picking out which tiles to pay attention to at the same time, *ibid.*)

- *Associative memory*

The recognition of shape is not sufficient to identify an object. Recognition takes place when visual input matches a stored visual representation in the object-properties-

processing subsystem, resulting in a sense of familiarity. In particular, identification occurs when additional information becomes available such as the name of the object, the categories to which it belongs, the common contexts in which it occurs. Identification takes place when the appropriate representation is activated in associative memory, which cross-indexes various sorts of information. The output from both the object-properties and the spatial-properties processing subsystems converge in associative memory. The information in associative memory is used in imagery to construct images of objects from parts and to define how parts have to be arranged to form an object.

- *Information shunting*

In perception, the information-shunting subsystem registers the most highly activated representation in associative memory. If an object cannot be immediately identified, the most highly activated representation in associative memory is used to guide the examination of potentially relevant aspects of the stimulus. In this case, the corresponding object is treated as a hypothesis about what the stimulus may be. The information-shunting subsystem uses this information in two ways: first, it sends information about location to the mechanisms that shift attention, leading them to focus on the location where a salient part or characteristic is thought to be present; second, the specification of the identity of the part or characteristic is used to prime the corresponding visual representation in the object-properties processing subsystem. This is a sort of anticipatory priming, because one is anticipating seeing a particular shape or characteristic.

In perception, anticipatory priming makes it easier to encode an expected part or characteristic. In imagery, anticipatory priming would be carried to an extreme, forcing a pattern of activation in the visual buffer, which is the representation of the image itself. In other words, one anticipates seeing something so strongly that one actually does see it.

There is evidence that the information-shunting subsystem is implemented in dorsolateral prefrontal cortex (Kosslyn et al., 1995).

- *Attention shifting*

In both perception and imagery, the attention shifting subsystem allows one to focus on a specific part or characteristic. This subsystem relies on a host of areas (Posner and Petersen, 1990), including those that implement voluntary control of attention shifting (e.g., frontal eye fields), disengaging attention from its current location (superior parietal lobes), actually shifting the eyes, head and body, as well as the attention window to a new location (superior colliculus), and engaging attention at a new location (thalamus).

The parallel between imagery and perception in attention shifting mechanisms has been nicely described in experiments showing that similar eye movements are produced when looking and imagining; moreover, blocking eye movements interfere with imagined inspection (Laeng and Teodorescu, 2002).

In perception, once one has shifted attention, a new part or characteristic is encoded, and may be recognized and identified or used to identify the object as a whole. In imagery, the same mechanisms are used to scan over imaged objects and add details: when one has focused on a particular location, a new part or characteristic is added via the priming mechanism. Once the image is formed in the visual buffer, it can be inspected, “zoomed-in” and “zoomed-out”, with the support of the object-properties-processing and spatial-properties-processing mechanisms as they are used during perception, except that the image tends to be less vivid and is very short lived.

- *Image transformation*

Mental images of objects can be modified at will. Parts can be added or deleted, and the image can be expanded, shrunken, stretched, rotated and so on (Shepard and Cooper, 1982). According to Kosslyn’s model, objects can be transformed in two general ways. In the first, subjects anticipate what one would see if someone (or something, e.g., a motor) manipulated the object. This strategy simply involves visual memories of previous events to form the anticipation. On the other hand, in the second strategy the motor system plays a key role. Such image transformations occur when one anticipates what one will see if one manipulates an object in some way. The anticipation modulates the function mapping from the object-properties-processing subsystem to the visual buffer.

As mental rotations represents a traditional bridge-topic between the study of visual imagery and motor imagery, I will now transition to briefly review the literature on motor imagery, which constitutes a central construct for the novel experiments reported in this thesis.

1.3 Motor imagery

Motor imagery can be defined as an active process during which the representation of a specific action is internally reproduced within working memory, without any corresponding motor output (Decety and Grèzes, 1999). The various findings related to motor imagery have been organized within a coherent approach of covert actions under the name of *Simulation Theory* (Jeannerod, 2001).

1.3.1 The simulation theory

The simulation theory states that actions involve a covert stage. This covert stage “is a representation of the future, which includes the goal of the action, the means to reach it, and its consequences on the organism and the external world” (Jeannerod, 2001). Covert and overt stages represent a continuum, such that every overtly executed action implies the existence of a covert stage, whereas a covert action does not necessarily turn out into an overt action. According to the simulation theory, covert actions are in fact actions, except for the fact that they are not executed. The theory therefore predicts a similarity, in functional and neural terms, between the state where an action is simulated and the state of actual execution of that action. Mental states with an active action content would be, for example: intended action, imagined action, prospective action judgments, perceptually based decisions, observation of graspable objects, observation of actions performed by others and actions in dreams (*ibid.*). A wealth of experimental data has provided support to this view, showing that motor images retain many of the properties of the corresponding real actions. Here I will briefly review the main results, focusing on the similarities documented in terms of temporal regularities, programming rules, biomechanical constraints and activation of the autonomous nervous system, of the motor pathways and of cortical and subcortical brain structures.

1.3.2 The representation of temporal regularities

One of the first characterizations of motor imagery was the finding that actual and mental actions similarly span over time. Already in 1962, it was shown that thinking or mentally reciting a series of numbers took approximately the same time as saying them loud (Landauer, 1962). This observation has been consistently replicated since then. In an experiment where subjects had to walk either physically or mentally to prespecified targets, Decety and collaborators found that the subjects took, on average, the same time to achieve the physical and the mental task. In both conditions, the duration was found to increase with the distance covered (Decety, Jeannerod, and Prablanc, 1989; see also Schott and Munzert, 2002). Sirigu and collaborators using a task of reciprocal tapping of two targets separated by a varying distance, also reported a similar temporal scaling of movement duration relative to distance in both the physical and the mental conditions (Sirigu et al., 1996; see also Cerritelli, Maruff, Wilson, and Currie, 2000).

1.3.3 The representation of programming rules

If covert actions resemble real actions, one should expect the rules governing the actual execution to be valid also for the imagined domain. In physical execution, as expressed by the Fitts Law (Fitts, 1954), the duration of an accuracy-demanding task increases with the accuracy demands (e.g., when the target size decreases or the target distance increases). Starting with the early work of Georgopoulos and Massey (1987), a number of works has shown that the same trade-off applies to the imagined domain. For example, Decety and Jeannerod (1996) instructed participants to mentally walk through gates of different widths positioned at different distances. The gates were presented with a virtual reality helmet which prevented the subject from using as reference a known physical environment. Subjects had to indicate the time they started walking mentally and the time they mentally passed through the gate. In accordance with Fitts Law, mental movement times were found to be affected by the difficulty of the task, i.e., they were longer for walking through a narrow gate placed at a farther distance (Decety and Jeannerod, 1996). Interestingly, when the instruction of the task implied the use of visual, instead of motor, imagery, the duration of the imagined motion became a function of path length alone, and it was not influenced anymore by the path width (Stevens, 2005). Furthermore a violation

of Fitt's Law, that occurs in real movements when targets are presented in a structured array (Adam et al., 2006), has been shown to be present also for imagined movements (Radulescu et al., 2010).

1.3.4 The encoding of biomechanical constraints

Several spatiotemporal optimization principles are thought to be represented within the motor system and to operate during execution. Experiments on mental rotation, on decision about feasibility of an action and on grip selection have shown that these principles similarly apply to the imagined domain. Parsons (1994) used a task where the subjects had to compare a test hand (right or left) presented on a picture at different orientations, with a reference hand presented upright. The response time for comparing the two hands was influenced by the biomechanical limitation of the rotation of the hand as a body part, as if the movement was physically executed. Specifically, mental simulation time mimicked movement time for natural efficient movement from a posture midway between each of the hand's joint limits into many other postures. Equal time was required for simulated and real movements into more common postures; shorter but proportional time was required for simulated movement than real movement into less common postures that involved longer trajectories, coordinated activity at more joints, motion near extremes of joint limits, and uncomfortable kinesthetic sensations (Parsons, 1987, 1994). Along the same line, situations have been designed where the subject has to make a prospective judgment about a potential action. For example, Frak and collaborators (2001) asked subjects to determine the feasibility of grasping an object placed at different orientations, some of which afforded an easy grasp and others an awkward one. Again, the response time was a function of the orientation of the object, suggesting that the subjects unknowingly simulated a movement of their hand in an appropriate position before they could give the response. This interpretation is supported by the fact that the time to make this estimate was closely similar to the time taken to physically reach and grasp an object placed at the same orientation (Frak et al., 2001). Finally, merely inspecting graspable objects and tools, or even pictures of them (but not the picture of other object types, like a house or a car) seems to elicit in the observer the covert action of using them. For example, the time taken to determine whether an object

can be grasped by the right or the left hand is influenced by the orientation (right or left) of that object. Response times for either hand and orientation are consistent with the classical compatibility effects (Tucker & Ellis, 1998).

Notice that these experiments depart from the canonical motor mental imagery in that no conscious image is formed and no explicit strategy is used. Instead, the task request implicitly forces subject to simulating the potential action, and the response time correlates with factors that pertain to the motor execution.

1.3.5 Autonomic nervous system

The results reviewed above suggest a close correspondence between covert and real action. If this is true, one would expect to find in motor imagery physiological correlates similar to those measured during real action.

Early work in the field of physiology of exercise has revealed the existence of a central pattern of vegetative commands during the preparation to an effort: heart and respiration rates show an almost immediate increase at the onset of exercise, or even prior to exercise (Adams et al 1987; Krogh and Lindhart, 1913). As this effect precedes the increase in muscle metabolism, it can only be due to central commands anticipating the metabolic change. During motor imagery of tasks such as running at an increasing speed or pedaling at an increasing rate, several authors found highly consistent changes in heart and respiration rates, which correlated with the mentally represented force (Beyer et al., 1990; Decety et al., 1991; Decety et al., 1993; Wang and Morgan, 1992; Wuyam et al., 1995).

For example, in the studies of Decety and collaborators (1991, 1993), the mean increase in heart rate during mental simulation of running or pedaling at the maximum speed was about 30% above the resting rate, to be compared with a mean increase of about 50% during the corresponding physical effort. Respiration rate also increased during mental simulation, to an even higher rate than during the corresponding physical effort. Notably, these changes happened in the absence of any measurable muscular activity. Autonomic activation during this condition thus pertains to the same phenomenon of central activation as that observed during preparation to action. An additional argument in this direction is provided by an experiment of Gandevia et al. (1993). They observed graded

cardiovascular changes in artificially paralyzed subjects attempting to produce muscular contractions at different intensities. As paralysis was complete, these changes could not be due to residual muscular activity and had to be of a central origin.

The encoding of autonomic variables during motor imagery however is not always correspondent to that of actual movement. Interacting with subjects' explicit expectations, in certain circumstances can be transferred to other, physiologically unrelated, dimensions of the behavior. In an experiment on the duration of mentally walking to targets at different distances (Decety et al., 1989), the authors tested whether mental-walking time remained constant for different levels of effort involved in performing the task. It was found that, in the physical condition, normal subjects loaded with a weight (25 kg) on their shoulders took the same time walking to targets as when they were with no load. Subjects achieved this by spontaneously programming greater muscular force in the loaded task (e.g., Gottlieb et al., 1989). However, when the loaded subjects imagined walking to the targets, the mental time increased by up to 30% with respect to the unloaded condition. Apparently, the participants did not realize that they would simply expend more energy to keep up their previous pace with the heavy load. Thus, imagery showed to reflect subjects' explicit expectations (e.g., that people walk slower with backpacks), which operate jointly with implicit knowledge to govern the imagined scenario (Kosslyn and Moulton, 2009).

1.3.6 Excitability of the motor pathways

Several studies have reported that some degree of background electromyographic activity (EMG) persists in the muscular groups involved in the simulated action (e.g., Gandevia, et al., 1997; Jacobson, 1930; Wehner et al., 1984). When this is the case, EMG activity is limited to those muscles that participate in the simulated action, and tends to be proportional to the amount of imagined effort (Wehner et al., 1984). This finding suggests that during motor imagery, motor commands to muscles are only partially blocked, and that motoneurons are close to firing threshold. However, it has to be noticed that EMG activity during motor imagery has not always been detected (Yue and Cole, 1992).

Spinal reflexes are also modulated during motor-imagery tasks. Bonnet and collaborators (1997) instructed subjects to either press isometrically on a pedal, or mentally simulate the same action with one of two possible levels of strength (weak and strong). The H-reflexes in response to direct electrical stimulation of the popliteal nerve and the T-reflexes in response to a tap on the soleus tendon were measured. Both types of reflexes increased during mental simulation, and this increase correlated with the force of the simulated pressure (see also Gandevia et al., 1997). However, conflicting results have been reported also in this case. For example, Oishi and collaborators (1994) found decreased lower limb H-reflexes in elite athletes, and Hashimoto and Rothwell (1999) found no significant change in upper limb H-reflexes during simulated wrist movements. Finally, Baldissera and collaborators (2001) found changes in upper limb H-reflexes during observation of finger flexion or extension, but, the pattern of activation appeared to be reversed with respect to that observed during imagined action (flexor motoneurons being facilitated during extension and vice versa). What can be concluded from these conflicting results is that motoneuron excitability is affected during action simulation. Different testing conditions (e.g., lower limbs vs. upper limbs, trained athletes vs. normal people) may account for different amplitudes and directions of these changes. To explain these different findings, Jeannerod (2001) proposed the presence of a dual mechanism operating at the spinal level: a sub-threshold preparation to move by the increased corticospinal tract activity, and a parallel suppression of overt movement by inhibitory influences.

The excitability of the corticospinal pathway was also extensively tested in several experiments using transcranial magnetic stimulation (TMS). With this method the amplitude of motor evoked potentials (MEPs) produced in the muscles involved in mental simulation of an action is measured in response to a magnetically induced electrical stimulus applied to the corresponding area of the contralateral motor cortex. Various authors consistently found a specific increase of MEPs in those muscles involved in an imagined task, e.g., in the flexor muscles during imagination of hand closure, whereas no such increase was found in the antagonist extensor muscles (Fadiga et al., 1999; Hashimoto and Rothwell, 1999; Rossini et al., 1999). Facilitation of MEPs is greater when the imagined task involves postures that are compatible with the actual

physical posture of the subject during imagination (Fourkas et al., 2006). Interestingly, for relatively simple motor tasks, both motor and visual imagery have been shown to produce similar corticospinal excitability (Fourkas et al., 2006).

1.3.7 Brain activations during motor imagery

- *Primary motor cortex*

Many studies using functional brain imaging by magnetic resonance (fMRI) reported activation of primary motor cortex during motor imagery (Leonardo et al., 1995; Lotze et al., 1999; Munzert et al., 2008; Nair et al., 2003 Porro et al., 1996; Roth et al., 1996; Sacco et al., 2006). Primary motor cortex activation reported during motor imagery amounts about up to 30% of the level observed during execution, but it has not been found in all subjects (Gerardin et al., 2000, Hanakawa et al., 2003). The activated zone overlaps that activated during execution, with the same voxels involved in the two conditions (e.g., Porro et al., 1996). It has been objected that activation of primary motor cortex during action representation might simply mean incomplete inhibition of action or incomplete relaxation of motor activity during the mental process of imagination. However, this critique has been ruled out by other findings showing primary motor cortical activation during imagined movements in subjects with an amputated or a paralyzed limb. Erslund et al (1996) found an increased metabolic activity in the controlateral primary motor cortex in a subject performing imaginary finger tapping with his amputated right hand. Lotze and collaborators (2001) found in amputees with impressions of phantom limbs that imagination of moving the phantom hand produced an activation of the controlateral motor and somatosensory cortex that was higher than that produced by imagination of hand movements in control subjects.

Some reports suggest that activity in M1 can also be modulated by expertise. For example, Langheim and collaborators (2002) showed that in professional musicians M1 was not active during imagined performance, whereas activity was observed in functional cerebellar, superior parietal, and frontal areas (see also Lotze et al., 2003). Lotze and Halsband (2006) proposed that with increasing experience in a skill, the activation sites related to motor imagery may systematically shift from motor-based representation to

reflect a more abstract, less motor-centered internal representation of the behavior. However, an opposite conclusion was recently drawn by Olsson and collaborators (2008). Studying a group of active high jumpers who performed motor imagery during fMRI scanning, these authors showed that only the group with an extensive high jumping background was able to activate motor regions. By contrast, the novices activated visual and parietal regions. At present it is not clear how such conflicting results can be reconciled.

- *Basal ganglia*

Basal ganglia are found to be activated during imagined actions. There are indications that execution and imagination engage different parts of the striatum (Gerardin et al., 2000). During execution, the putamen, part of a purely sensorimotor corticocortical loop, is activated. During imagination, instead, activation involves the head of the caudate, consistent with the view of this area as part of a more cognitive loop.

- *Cerebellum*

Cerebellar activation has been reported for imagined action (Ryding et al., 1993), as well as in perceptually based motor decisions (Parsons et al., 1995). The involved area include both the medial and the lateral parts of the cerebellum. However, areas in the ipsilateral cerebellar hemisphere that are activated during execution (in the anterior lobe) are much less activated during imagination (Lotze et al., 1999). By contrast, imagined action and action observation activate more posterior areas.

- *Premotor cortex*

Activation of premotor cortex is one of the strongest findings for motor imagery studies. Decety et al. (1994) found a large activation of the dorsal and ventral parts of lateral area 6 during imagined hand movements (see also Stephan et al., 1995; Grafton et al., 1996; Gerardin et al., 2000). This is also true for perceptually based motor decisions (Parsons et al., 1995) and visual presentation of graspable objects (Chao and Martin, 2000). Lateral premotor cortex activation during covert actions overlaps with movement execution for

what concerns dorsal area 6 (Gerardin et al., 2000) and involves an equivalent number of activated pixels whether the action is a covert or an overt one (Roth et al., 1996; Lotze et al., 1999). Activation of ventral area 6 in the inferior frontal gyrus, however, which is quite reliably found in covert actions, is less frequently mentioned during execution (see Binkofski et al., 1999). The same degree of overlap between conditions of covert and overt actions exists for SMA. The general trend is that SMA activation during imagined movements is more rostral than during executed movements (e.g., Stephan et al., 1995; Grafton et al., 1996; Gerardin et al., 2000; Lotze et al., 1999). The function of SMA, which acts as a parser for temporally segmenting the action and anticipating its successive steps, is thus retained during motor imagery.

- *Parietal lobe*

Areas in the inferior parietal lobule and in the intraparietal sulcus are activated during imagined grasping movements (Decety et al., 1994; Grafton et al., 1996), perceptually based decisions and prospective action judgements (Parsons et al., 1995; Johnson, 2000) and visual presentation of graspable objects (Chao and Martin, 2000). During execution, the same parietal areas are also largely involved (Faillenot et al., 1997; Binkofski et al., 1999). The area involved during covert hand actions tends to extend more caudally than during overt actions (Gerardin et al., 2000). Posterior parietal cortex may be the site where action representations are stored and/or generated. Because it integrates abundant visual and somatosensory information, it appears well suited for encoding the technicalities of the action, like transforming object spatial coordinates from a retinocentric framework into an egocentric framework, or processing the constraints related to the objects. These aspects are crucial to many uses of motor imagery.

- *Prefrontal cortex*

Prefrontal activations during motor imagery usually involves the dorsolateral part (areas 9 and 46), the orbitofrontal zone (areas 10 and 11), the cingular gyrus, and a ventral and caudal zone (areas 44–45, see Iacoboni et al., 1999). Dorsolateral prefrontal cortex is also activated during preparation states, when a decision must be taken about which finger to

move or about when to start a movement (Frith et al., 1991). Prefrontal activation, which intervenes during motor preparation before an overt action starts, is far less marked during action execution.

1.4 Auditory imagery

Auditory imagery can be defined as “the introspective persistence of an auditory experience, including one constructed from components drawn from long-term memory, in the absence of direct sensory instigation of that experience” (Intons-Peterson, 1992, p. 46). As auditory imagery is a broad and heterogeneous field of research and this thesis will mainly address auditory imagery in the musical context, I will narrow down the scope of this review to auditory musical imagery (for an exhaustive and up to date review on auditory imagery, see Hubbard, 2010).

1.4.1 Musical contour

There is evidence that musical contour information is specified within the auditory image of a melody. For example, Weber and Brown (1986) had participants learn eight note melodies. The participants then drew a sequence of short horizontal lines (moving from left to right) to indicate the pitch height of each note relative to the preceding note while they sang or imaged each melody. The authors found that drawing times and error rates were not influenced by whether participants sang or imaged the melody.

1.4.2 Melody

Several studies on imagery of melodies required subjects to compare whether one pitch of the song, highlighted in various ways, was higher or lower than another pitch of the song. The imagery condition is usually compared with a perceptual condition. Results from this studies have yielded generally converging results, showing that: i) response times increase with increases in the number of intervening beats between the two pitches; ii) participants are generally less accurate in the imagery condition than in the perception condition; iii) the superior temporal gyrus is activated during this task, both for the imagery and for the perceptual conditions (Halpern, 1988; Halpern and Zatorre, 1999;

Zatorre et al., 1996). That the participation of auditory cortex is necessary, and not merely a correlate of the imagery experience, is further suggested by the report of deficits in an auditory imagery task following lesions of the right temporal neocortex (Zatorre and Halpern, 1993). In this study, the performance of patients with a left temporal lobe lesion did not differ from the performance of control participants, but the performance of patients with a right temporal lobe lesion was significantly worse than that of control participants or of patients with a left temporal lobe lesion. The decreased performance of patients with a right temporal lobe lesion occurred in imagery and in perception (*ibid.*). Altogether, these studies demonstrated that the right superior temporal gyrus is involved in comparisons of pitch in imagery and in perception (Halpern, 2003; Yoo et al., 2001). It remains to be determined, however, precisely which subfields of auditory cortex may be involved in which aspects of the imagery phenomenon. In particular, the involvement of core auditory cortical areas in imagery has not yet been clearly shown (Zatorre, 2007).

Other brain areas that have been shown to become active during this task for both the perceptual and imagined conditions are the frontal and parietal lobes, and the supplementary motor area (Zatorre et al., 1996). In this latter case, stronger activations have been reported in imagery than in perception (*ibid.*). The precise role of these activation in the supplementary motor area even when no words (lyrics) were presented remains to be established. However, it is consistent with some form of subvocal rehearsal (e.g., humming the appropriate pitches) or with more general aspect of auditory imagery, such as image generation or preparation, regardless of any potential subvocal contribution to the image. (Halpern et al., 2004).

There is evidence for an automatic nature of auditory imagery. In one study, Kraemer and collaborators (2005) acquired fMRI from participants who listened to excerpts of music, familiar or unfamiliar. Short sections of each musical stimulus were deleted and replaced with silent gaps. Gaps in familiar musical pieces resulted in greater activation in auditory association areas than did gaps in unfamiliar musical pieces. Interestingly, participants reported hearing a continuation of the music in imagery during gaps in familiar pieces but not hearing a continuation of the music in imagery during gaps in unfamiliar pieces. The authors argued that even short gaps were enough to evoke auditory imagery in familiar pieces and, furthermore, that this indicated the automatic nature of auditory imagery.

In another study, auditory imagery was compared with auditory expectations (Janata, 2001). Participants were cued to expect to hear three notes, and to subsequently imagine the following five notes, or cued to expect to hear five notes, and to subsequently imagine the following three notes. In a small percentage of the trials, the cue was invalid (e.g., participants expected to hear five notes but only heard three notes). Imaging a continuation, as well as expectation of a note that was not presented, resulted in emitted potentials highly similar to evoked potentials for perceived notes. The author suggested that similarities of topologies of electroencephalogram during the N100 time window when a continuation was imaged, when a note was expected but not presented, and when a note was perceived are consistent with the hypothesis that auditory imagery, auditory expectation, and auditory perception activate similar brain mechanisms.

1.4.3 Harmony

Evidence exists that harmonic relations are also specified within the auditory image. For example, Hubbard and Stoeckig (1988) presented participants with a cue composed of a single tone or a major chord, and participants were instructed to form an image of what that cue would sound like if it were raised in pitch one semitone (participants were given examples of and practice with feedback in imaging an increase in pitch of one semitone). After participants had an image, they pressed a key, and a probe tone or probe major chord was presented; the participants' task was to compare the pitch(es) in their image with the pitch(es) in the probe. The patterns of response times and accuracy rates as a function of harmonic relatedness of the image and the probe matched patterns for perceived cues and probes reported in the harmonic priming literature (e.g., Bharucha and Stoeckig, 1986). Additionally, images of major chords required more time to generate than did images of single tones, and this was consistent with findings in the visual imagery literature that images of complex objects require more time to generate than images of simple objects (e.g., Kosslyn et al., 1983).

Brain activation during perception or imagery of major or minor chords were investigated by Meyer and collaborators (Meyer et al., 2007). Instructions to generate auditory images of chords resulted in a N1 component in the window of 109–143 ms (cf. Janata, 2001) and a late positive component (LPC) in the window of 400–460 ms. Topology of the

EEG response was consistent with the hypothesis that the N1 in auditory imagery is associated with anterior temporal regions and that the LPC in auditory imagery is associated with activity in the cingulate, cuneus, medial frontal regions, and right auditory association cortex (Zatorre and Halpern, 1993).

1.4.4 Tempo and duration

As reported earlier above (see paragraph 1.4.2.), the time to decide whether one pitch of a song is higher or lower than another pitch of the song increase with increases in the number of intervening beats between the two pitches (Halpern, 1988a). This suggests the auditory image preserved the temporal structure of the melody. Response times also increase the further into the melody the first pitch is located, and this suggests that participants began scanning at the beginning of the melody regardless of the location of the first pitch (*ibid.*). The findings of Halpern (1988a) suggested that auditory images were extended in time, and so Halpern herself (1988b) examined whether tempo was represented in a consistent way. In a perception condition, participants could adjust the tempo on a computer recording, while in an imagery condition, participants were given the title of a familiar melody, instructed to image that melody, and then they had to adjust a metronome to correspond to the tempo in their image. Tempo settings differed across melodies, suggesting that participants differentiated the melodies. Crucially, a significant correlation was found between perceived tempo and imaged tempo for each, suggesting that auditory imagery preserved tempo information.

1.4.5 Notational audiation

Notational audiation refers to the use of auditory imagery to “hear” music that is notated in a visually perceived musical score (e.g., Gordon, 1975). Trained pianists have been shown to be able to judge whether auditory sequences match or not a music notation previously read on paper (Waters et al., 1998). Melodies “audiated” on paper can be stored and sang aloud later, even when an auditory distractor was present during the initial reading (Wöllner et al., 2003). Stronger audiation skills is associated with better memorization during MP (Highben and Palmer, 2004). Brain activity during audiation shows an initial activation of left and right occipital areas, that spreads to the midline

parietal cortex (precuneus) and then to the left temporal auditory association areas and the left and right premotor areas (Schurmann et al., 2002).

The components of notational audiation were investigated by Brodsky and collaborators (Brodsky et al., 2003), who developed the embedded melody task. In this task, a well-known theme is incorporated into visual notation of a larger phrase. This theme is visually indiscernible in the phrase within which it was embedded, but the authors suggested that it might be available to the “mind’s ear” (i.e., to notational audiation) when reading musical notation. Participants silently read notation containing an embedded melody, then heard an auditory presentation of a melody and judged whether that melody was the same as the melody embedded in the previously read notation. While silently reading the notation, different source of interference were provided, such as rhythmic interference (reading while tapping a steady rhythm and listening to a task-irrelevant rhythmic pattern), phonatory interference (reading while wordlessly singing or humming), or auditory interference (reading while listening to a recording of themselves wordlessly singing or humming). On the basis of similarities of speech and vocal music, the authors predicted that recognition of embedded melodies in imagery would be disrupted more by phonatory interference than by rhythmic or auditory interference, and indeed, recognition of embedded melodies in imagery was lowest when phonatory interference was present. Brodsky et al. suggested that notational audiation involves kinaesthetic-like covert phonatory processes. The motor contribution to audiation was further investigated by monitoring the activity level of muscles near the vocal folds during the embedded melody task (Brodsky et al., 2008), as compared to other control tasks (e.g., reading printed text, silent mathematical reasoning). Interestingly, the pattern of subvocal muscle activity was much more dynamic during silent reading of visual notation than during control tasks. In a second study, participants were allowed to make movements on their instrument appropriate to the notated music (e.g., pressing keys on a silent keyboard). Recognition of the embedded melody was still lowest when phonatory interference was present, but addition of movements improved recognition of embedded melodies when rhythmic interference was present. In a third study carried out with professional drummers as participants, recognition of the embedded melody was lowest when phonatory interference was present, and this occurred even though the visual

(drum-kit) notation did not involve pitch or tonality. Summarizing these findings, Brodsky et al. (2008) suggested that both phonatory and motor processing are involved in notational audiation and that phonatory resources in notational audiation are not influenced by instrument or by notational system.

1.5 Action observation

Recent advances in cognitive neuroscience have revealed that observed actions are processed by engaging the observer's circuitries that are responsible for generating the same actions. Observing the actions performed by other individuals can be therefore considered another category of covert action production (Jeannerod, 2001), and observational learning a form of MP. In particular, the mirror neurons system (MNS) has been investigated as a potential neural substrate for this mechanism. Here I will briefly report the original findings of mirror neurons in the monkeys, and the data in support of an analogue system in humans. Here I will not address the implication of these findings in explaining how humans understand the intention of other individuals, as the topic is not directly related to the experimental content of this thesis, but see Zentgraf and collaborators (2011) for a recent review on this matter.

1.5.1 The mirror neuron system in the monkey

A proportion of the neurons in macaque area F5 that discharge during the execution of both hand and mouth goal-directed actions also respond when the monkey observes another monkey or an experimenter performing the same or a similar action (Gallese et al., 1996; Rizzolatti et al., 1996). Macaque area F5 has some homology with the posterior portion of Broca's region and the anterior portion of the PMv in humans (Petrides and Pandya, 1997). These neurons are called mirror neurons because the observed action seems to be "reflected" in the motor representation for the same action of the observer. These neurons were found primarily in posterior premotor cortex of the monkey (subdivision F5c). The congruence between the motor action coded by the neuron and that triggering the same neuron visually can be very strict, in that only the observation of a (virtually) identical action to that coded motorically by the neuron can activate it. These neurons are called "strongly congruent" mirror neurons (Gallese et al., 1996). More

commonly, this congruence is broader, in that the observed and the executed action coded by the neuron match relative to the goal of the action, rather than to the specific movements needed to execute it. These are called “weakly congruent” mirror neurons. For example, the same neuron was found to respond when the observed action was placing an object on the table, whereas the executed action was bringing food to the mouth or grasping the object (di Pellegrino et al., 1992). Whether strong or weak, this visuomotor congruence has prompted the hypothesis that the basic function of mirror neurons consists in understanding actions made by other individuals by a process that matches the visual description of an action with the internal motor representation of the same action in the observer (Rizzolatti et al., 2001; however, see Hickok, 2009 for a different view). In macaques, mirror neurons discharge only when a biological effector (e.g., a hand) interacts with an object; if the action is performed with a tool, the neuron does not discharge, unless a preliminary extended training with the tool is provided (Ferrari, Rozzi, & Fogassi, 2005).

Mirror neurons are present also in the inferior parietal region of the macaque brain (Gallese et al., 2002), especially in the subdivision PFG (Rozzi et al., 2008). Some of these neurons show additional properties, such as a correlation with the motor intentions of the observed actor (Fogassi et al., 2005). Moreover, subdivision PFG and PF of the macaque parietal lobe have strong projection to the PMv, suggesting a functional “mirror” network (Rozzi et al., 2006).

If mirror neurons are responsible for action recognition, then they should also discharge when the whole sequence of the action is not completely seen by the monkey, provided that the goal of the observed action can be clearly inferred. Consistently with this idea, Umiltà and collaborators have shown that mirror neurons discharge not only during the observation of action, but also when the final part of it is hidden (Umiltà et al., 2001).

1.5.2 Mirror systems in humans

Although the existence and the role in humans of neurons with the precise features of macaque’s mirror neurons is a matter of debate (e.g., Lingnau, 2009), a wealth of research have shown that humans are endowed with a versatile systems to mirror internally the actions of others individuals.

Early evidence in this regard came from a study using transcranial magnetic stimulation (Fadiga et al., 1995; see also Gangitano et al., 2001; Strafella and Paus, 2000). Single pulse TMS was delivered to the motor cortex while subjects were observing an experimenter grasping three-dimensional (3D) objects. Stimulation led to an increase in motor evoked potential (MEP) amplitude recorded from precisely those hand muscles normally recruited when the observed action is actually performed by the observer. Control conditions involving both visible actions (i.e., tracing geometrical figures in the air) or objects (i.e., the same 3D objects seen in the actions) did not cause this change. Interestingly, the effects of observation are not limited to the visual domain. Fadiga and collaborators (2002) showed that listening to specific phonemes increases the excitability of the motor pathway to the relevant tongue muscle. Magnetoencephalographic (MEG) data have shown a suppression of 15–25Hz activity during both the execution and observation of goal-directed hand actions (Hari et al., 1998). Replication using electroencephalography (EEG) showed a block of “mu” activity, associated with activation of motor cortex, in the same conditions (Cochin et al., 1999), while using chronically implanted subdural electrodes, a decrease of alpha band absolute power over the primary motor cortex and Broca’s region has been shown during the execution and observation of finger movements (Tremblay et al., 2004). Converging fMRI data have demonstrated a somatotopic pattern of brain activation during observation of actions performed with the mouth, the hand or the foot, with the mouth stimuli activating the most ventral and the foot stimuli the most dorsal section of the premotor cortex (Buccino et al., 2001). Behavioural investigations have also gathered evidence for the existence of processes shared by observation and execution. For example, when subjects are cued to make a finger movement by a symbolic cue or modelled finger movements, they are faster to respond to the modelled action (Brass et al., 2000) and the degree of similarity between the observed and executed movement lead to further advantage. After presentation of a picture of the right hand, subjects were faster to prepare to grasp a bar when the hand orientation of the picture corresponded to that achieved by the hand at the end of the action when actually executed (Craighero et al., 2002). Some forms of action observation also involve central activation of the autonomic system. In an experiment involving observing a scene where an actor performs a running exercise at different

speeds, the respiration rate of the observer was shown to increase while he was watching the actor (Paccalin and Jeannerod, 2000). Furthermore, the respiration rate of the observer correlated with the amount of effort produced by the actor (e.g., the respiration rate is higher during observation of the actor walking at 7 km/h than at 2.5 km/h). These findings underline the similarities between motor imagery and action observation, two situations where physiological mechanisms related to real actions are activated in the absence of motor execution. Indeed, in a recent study, Clark and collaborators (2004) compared MEP amplitude in the same subjects during explicitly imaging, observing, and physically executing the same hand gestures. They found that observation and imagery conditions led to a similar facilitation in MEP amplitude in the relevant hand muscle. In addition, during action observation, a condition of “active” observation (i.e., with the instruction to subsequently imitate) yielded larger MEPs than a purely passive observation. Finally, in the realm of language, subjects are slower to make sensibility judgments about action sentences (e.g., “open the drawer”) if the response requires manual action in the opposite direction (i.e., away from the body) from the action described in the sentence (Glenberg and Kaschak, 2002).

1.6 The ideomotor principle

The research within the context of the ideomotor theory is relevant to the concept of imagery and MP because it shows that action preparation and action anticipation are a form of covert action production. The ideomotor principle states that voluntary behavior is determined by the anticipation of its sensory effects (Greenwald, 1970; Harleß, 1861; Herbart, 1825; Hommel, 2009). In this sense, action preparation and action anticipation represent another category of mental states that fall within the scope of the simulation theory (see paragraph 1.3.1).

The central concept of the ideomotor principle has been nicely shown in experiments on effect-induced action priming and response-effect compatibility (Hommel, 2009). These studies employ a preliminary learning phase, in which the actor is advised about several actions and their specific effects. The strength of these associations increases with every additional successful performance of the action.

An important finding is that once a stable and bidirectional connection is established, the presentation of the response effect activates a representation that becomes associated with the execution of the movement itself, so that execution of the movement is facilitated, or primed (e.g., Elsner and Hommel, 2001). For example, a response is selected more quickly when called by its former effect tone than when triggered by the effect tone associated with an alternative response. These paradigms are therefore called effect-induced action priming. The problem with these priming studies is that they do not directly prove that anticipated action effects ultimately guide action control, because these effects are physically presented, and the effect representations are exogenously activated. This ambiguity however is overcome in the studies that employ a response-effect compatibility paradigm, in which the response effect are not physically presented by the experimenter, but internally anticipated by the participant. For example, Kunde (2001) had subjects perform either soft or forceful presses on a touch-sensitive plate. Each key press produced either a quiet or loud tone. The author found that in blocks of trials in which the to-be-produced tone effect predictably matched manual key press in intensity (e.g., soft press resulting in a quiet tone), response times were much faster than in blocks in which the intensity of the tone effect did not always match the response intensity. This response-effect compatibility effects suggest that anticipatory-effect representations are created and influence response selection, because the effect stimulus was not physically present at the time of movement initiation. In another study, Kunde and collaborators (2004) gave subjects response pre-cues, so that the response could be planned in advance. Clear benefits in reaction times from planning the movement in advance were observed, but the facilitatory effect of anticipating compatible response effects (i.e., tones) was still present, albeit slightly reduced. Finding an influence of anticipated effects even with highly prepared movements is important because it suggests that effect anticipation plays a role not only for the selection but also for the actual initiation of movements. Neuroimaging studies have provided converging evidence, showing that effect anticipation is associated with activation in brain structures related to movement planning like SMA (Elsner et al., 2002). For a more extensive review of the findings and concepts pertaining the ideomotor principle, see Shin and collaborators (2010).

1.7 Mental practice

1.7.1 What is mental practice

A straightforward definition of MP has been provided in a influential review by Driskell and collaborators (1994), as the “cognitive rehearsal of a task in the absence of overt physical movements” (pp. 481). Such apparent simplicity hides in fact a rich variety of practices. Part of this complexity is also due to the fact that MP is an object of study for both applied (e.g., sport psychology) and cognitive sciences (e.g., cognitive neuroscience). As much as the goals of these approaches differ, differences exist in the scope and in the exact meaning of words and definitions. Importantly, recent years are seeing an increasing dialogue and reciprocal understanding between these fields.

To start with, it is important to distinguish the definition pertaining to task rehearsal from the broader term of *mental preparation*. This latter, more general term refers to a variety of techniques that share the goal of enhancing performance, including positive imagery, psyching-up strategies, attention focusing, relaxation, self-efficacy statements, mindfulness meditation and other forms of cognitive or emotional preparation prior to performance (cf. Caudill, Weinberg, & Jackson, 1983; Connolly and Williamon, 2002; Shelton & Mahoney, 1978). As the present thesis is focused on task rehearsal, these techniques will be not reviewed here. However, it is important to clarify that in the applied settings these two sets of strategies are tightly connected and mutually reinforcing (see Chapter 3.2 for a research study that promotes the use of both, at different stages of the experimental procedure).

A typical MP study requires subjects to mentally practice or mentally rehearse performing a task. Common instructions are to sit quietly, not move, and imagine performing the task successfully. Imagery rehearsal is achieved by mean of visual imagery, motor imagery, observation of others individuals or other formats of imagery pertinent to the specific task. The instruction about not moving, which appears is several definition of MP, is in fact not necessary, depending on the context. For example, hinting movements is explicitly recommended in practical guides to MP in sports (Rushall, 1991; also, see Chapter 2 for a research study that allowed finger movements with the aim of understanding the specific role of this strategy in mental rehearsal).

Usually, a control (no-practice) group is included, as well as a group that receives actual physical practice on the task. At a given period following the MP or physical practice treatments, performance is assessed. If the performance of the MP subjects exceeds that of the control subjects, even if it does not necessarily reach the performance obtained in the physical practice subjects, MP is said to have a positive effect on enhancing performance.

1.7.2 General effects of MP

Reviews and meta-analyses report moderately and consistent positive findings supporting the effectiveness of MP (Grouios 1992; Murphy 1990, 1994; Richardson 1967; Suinn 1985, 1997). It is repeatedly found that mentally practicing is more effective than engaging in no practice at all. When compared to the absence of practice, MP yields an effect sizes of 0.48 - 0.68, indicating that employment of MP influences performance positively when compared to no practice at all (Driskell et al. 1994; Druckman 2004; Feltz and Landers 1983; Hinshaw 1991). Sole physical practice is more beneficial than the same time spent engaging in sole MP. It is known that combination of MP and physical practice can achieve effects equal, smaller or even larger than physical practice alone, depending on the task (Murphy 1994; Stebbins, 1978; Suinn 1997).

1.7.3 Determinants of MP effectiveness

MP effects depends on a plethora of factors which will be review in detail below.

- *Type of task*

One meta-analysis (Feltz and Landers 1983) found that the effect of MP on cognitive tasks ($M=1.44$) is significantly larger than the effect on motor ($M=0.43$) or strength ($M=0.20$) tasks. This notion is supported by the suggestion that the higher the level of cognitive involvement of a task, the greater the effect of MP (Hinshaw 1991). In another meta-analysis (Driskell et al. 1994), tasks were examined by the degree to which a task involved more or less cognitive components. The results showed that MP was more

effective the more a task involved cognitive activities. Moreover, it was found that the degree to which components of motor tasks (strength, coordination, and speed) are represented in a task negatively correlates with the effectiveness of MP.

- *Individual factors*

Familiarity with the task is in itself considered an influential parameter for MP (Richardson 1967). The meta-analysis of Driskell and collaborators (1994) concluded that novices generate stronger MP effects for cognitive tasks than for physical tasks. Experienced subjects, instead, seems to benefit equally well for both cognitive and physical tasks. It is argued that beginners at a motor task are at a larger risk of practicing a desired skill incorrectly and thereby potentially worsening their performance instead of improving it (Hinshaw 1991; Murphy 1994; Suinn 1997, 1985). Their ignorance on how to perform the skill leads to the incapacity to practice the “motions” correctly. This supposition may accounts for some findings in which MP did not improve or even worsened performance (Suinn 1997, 1985). It is also found (Guillot and Collet 2005) that the higher the expertise level, the more accurately a movement can be mentally rehearsed in terms of temporal organization of the movement. This indicates that the degree of expertise determines the awareness of the technical complexity of a movement and, thus, the quality of the mental simulation. Consistently, it has been shown that only experts show corticospinal facilitation during imagery of tasks involving the skilled use of a tool (Fourkas et al., 2008). At the same time, it has also been suggested that beginners, who are unfamiliar with a certain skill, could have a higher learning potential and thus a steeper learning curve when it comes to practicing a task with MP (Feltz and Landers 1983).

Not only experience with the performed task might affect the success of MP. Experience with the MP technique itself is considered to have an effect on measures of improved performance as well (Hinshaw 1991; Murphy 1990). In addition to that, personal factors such as gender, intelligence, spatial aptitude, concentration, cognitive flexibility, and vividness of imagery are also likely to play an important role in MP effectiveness (Grouios 1992; Hinshaw 1991; Richardson 1967). However, to my knowledge no systematic investigation has been published on this specific factors.

- *Practice duration*

Feltz and Landers (1983) investigated the role of time on MP and found that practice sessions that lasted less than 1 min or between 15 and 25 min were most effective. This finding was reproduced in Hinshaw's meta-analysis (1991) who found that effect sizes were significantly larger for trials that lasted under 1 min or between 10 and 15 min compared to trials that lasted between 3 and 5 min. When excluding the studies with cognitive tasks, leaving only motor and strength tasks, a more standard linear relation between time and effectiveness of MP has been reported, indicating that the more the practice, the better the performance (Suinn, 1997). However, Driskell and collaborators' meta-analysis (1994) indicated that after reaching an optimum of about 20 minutes, an increasing duration of MP has a decreasing beneficial effect on performance.

Regarding the interval of retention, a significant negative relationship between retention interval and effect of MP has been described, indicating that the longer the time span between pre- and posttest, the weaker the effect of MP (Driskell et al. 1994). This closely resemble what happens for actual practice.

- *Practice instructions*

The most systematic approach to MP in terms of instructions has been developed by Holmes and Collins (2001), in the context of sport psychology. The model, named PETTLEP, posits seven components that should be considered when implementing imagery-based interventions, namely: Physical, Environment, Task, Timing, Learning, Emotion and Perspective. The emphasis of the model is on the "functional equivalence" between imagery and actual movements as it has been described by neurophysiological studies (Jeannerod, 2001). The Physical component of the model is related to the athlete's physical responses in the sporting situation. The authors advise to include all of the senses that would be engaged, and the kinesthetic sensations that would be experienced, during actual performance. This should include unpleasant and stressful physical sensations, if they are an important part of the actual experience. Also, adopting the same posture as one would adopt when performing, holding any implements that would usually

be held, and wearing the correct clothing could enhance the physical nature of the imagery (cf. Mantle, 1994). The individual should imagine performing the relevant skill correctly, and, if unsure of the correct technique, coaching advice should be sought prior to incorporating imagery so as to avoid the possibility of “ingraining” a poor technique.

The Environment component of the model refers to the physical environment in which imagery is performed. To access the same motor representation, the environment when the performance is imagined should be as similar as possible to the actual performing environment. If a similar environment is not possible, photographs of the venue or audiotapes of crowd noise can be used. If imagery scripts are being employed, they should also include descriptions of the athlete’s individual responses to the environment, as opposed to just describing the environmental stimuli (cf. Smith et al., 2001).

Also the imagined Task should be matched as close as possible to the actual task. The task content of the imagery should be specific to the performer, with him or her focusing on the same thoughts, feelings, and actions as during physical performance of the task. A recommendation in this sense is to make use of verbal reports of physiological and behavioral involvement in the scene.

A problematic aspect of Timing is that, in imagery, time is represented as a function of force (Decety et al., 1989). In motor imagery, where external force conditions are not present, athletes will perceive increases in felt force as an increase in movement duration. To overcome these potential duration increases, the authors recommend the interaction with the physical element of the practice during imagery training (e.g., holding the basket-ball while imagining the throw). Besides that, realistic timing is seen as important, especially in sports where the temporal nature of the task matters. For specific instances, however, the authors acknowledge the usefulness of the isolation approach, in which specific frames of the internal image are <<frozen>> in slow motion.

The Learning component of the model refers to the adaptation of imagery content in relation to the stage of learning. As the skill level of the performer moves from being cognitive to autonomous, the motor representation and associated responses will change consequently and therefore the imagery content must be altered in order to reflect this. For example, at first the performer has to think about the movement a great deal, and therefore imagery may focus heavily upon the correct technique with elements such as

limb positioning being central. However, as the skill becomes more automatic, the performer will not have to think so much about technique, and therefore imagery may focus more on the “feel” of the movement rather than on the specific technique and the emotions required for optimal performance.

In terms of Emotions, the athlete should try to experience all of the emotions and arousal associated with the performance. Care should be taken to ensure that the emotions felt during imagery are positive. Negative thoughts should be dealt with by replacing them as far as possible with positive ones. Though the main function of the PETTLEP model is skill enhancement, the focus on positive emotions should also prove beneficial in enhancing self-confidence and motivation.

Finally, the Perspective component refers to the way imagery is viewed. The general suggestion is to perform imagery from an internal perspective. From a functional equivalence perspective, internal visual imagery appears preferable as it more closely approximates the athlete’s view when performing. Accordingly, it is known that this approach elicit greater physiological response, compared to the external perspective (Perry and Morris, 1995; Hale, 1982). The format of imagery should be primarily kinaesthetic, but also internal visual imagery can be helpful depending on the task. Some studies, however, support using an external orientation when imaging certain form-based skills (Hardy and Callow, 1999; White and Hardy, 1995). It may be most beneficial, therefore, for athletes to use a combination of perspectives. More advanced performers will be able to switch from one perspective to another (cf. Smith et al., 1998) and, in doing this, gain advantages from both perspectives, optimizing the imagery experience.

1.7.4 Neural plasticity following MP

While a wealth of research has been conducted to establish the neural basis of mental imagery, only few investigations to my knowledge have compared brain function before and after an extended mental training. In the first of these studies, Pascual-Leone and collaborators (1995) characterized the plastic changes of the human motor system in the acquisition of new fine motor skills. Using TMS, they mapped the cortical motor areas targeting the contralateral long finger flexor and extensor muscles in subjects learning a one-handed, five-finger exercise on the piano. Subjects were randomly assigned to a

physical practice group, to a MP group, or a control group. Subjects in each practice group physically or mentally practiced the five-finger piano exercise independently for 2 hours daily for 5 days. Over the course of 5 days, MP alone led to significant improvement in the performance of the five-finger exercise, even though the improvement was significantly less than that produced by physical practice alone. However, MP and physical practice led to the same increase in the size of the cortical representation for both muscle groups. The authors concluded that MP alone seems sufficient to promote the modulation of neural circuits involved in the early stages of motor skill learning.

Furthermore, Jackson and collaborators (2003) investigated the effects of MP with motor imagery on a sequence motor learning task using PET. Comparing subjects before and after the motor imagery training, these authors found improvements in performance as well as changes in areas of the medial–ventral frontal lobe, especially in the right medial orbitofrontal cortex. Following several days of MP, this area showed increased activation during both the execution and imagination of the sequence after practice. Crucially, a positive correlation was found between the increase in cerebral blood flow within the right medial OFC and the subjects' increase in performance on the task. These changes were similar to those observed after physical practice of the same task (Lafleur et al., 2002). The author interpreted these findings in favour of the potential of MP with MI to improve performance by acting, at least for the early stages of learning, on the preparation and anticipation of movements rather than on execution per se.

Finally, Stefan and collaborators (2005; see also Stefan et al., 2008) investigated changes in corticospinal networks following observation of another individual performing simple repetitive thumb movements. An extended period of observation of thumb movements that were oriented oppositely to the previously determined habitual directional bias increased the probability of TMS-evoked thumb movements to fall within the observed direction. The authors concluded that the mere observation of movements allowed the formation of a lasting specific memory trace that resembled that elicited by physical training.

1.7.5 Mechanisms underlying MP

Various hypotheses have been proposed to explain why MP is effective. They are not mutually exclusive and, in fact, it is very likely that all these mechanisms contribute to MP effectiveness, in proportions that vary depending on the task and on the individual. These mechanisms can be grouped under three main categories: aspecific, psychoneuromuscular, and symbolic.

- *Aspecific hypotheses*

The aspecific hypotheses ascribe the effect of MP to factors not related to the specific content of the practice, but with global aspects of the practice context. In particular the *motivational hypothesis* suggests that due to the attention given to the task (through mentally practicing), an interest in the task is created. This interest manifests itself as an increase in motivation to perform (Grouios 1992; Richardson 1967; Suinn 1997). This motivation could, to some extent, account for increased levels of performance. A variant of this is the *attention-arousal hypothesis*. The attentional–arousal theory asserts that an ideal performance is reliant on optimal levels of physiological arousal and focused attention (Hinshaw 1991). MP, in this light, would then serve as a preparation method to realize optimal performance of a skill (Feltz and Landers 1983). MP elicits feelings of competence and self-belief, thereby focusing attention and getting “psyched up” for performance (Murphy 1990). The low muscle innervations that accompany MP might also set the arousal level and prepare the performer for the action (Grouios 1992). A more drastic version of the aspecific hypothesis considers the effects of MP as a spurious artefact of the experimental design (Corbin, 1967). In experiments that compare the effect of MP with a do-nothing control group, the first group gets “something” that the other group does not. It is hypothesized that “control” groups will have received considerably less attention than groups in either the physical or MP condition. The latter may have seen progress during practice, or otherwise gotten feedback on performance. Even if this is not so, spending time and effort in practicing a skill increases intrinsic motivation. Control groups often are not required to spend as much (if any) time on practicing. A liable consequence could be that control groups are less involved and thus less motivated to perform (Hawthorne effect, see French, 1950).

- *Psychoneuromuscular hypotheses*

These hypotheses states that during MP, and specifically during motor imagery, the circuitry involved in producing a certain movement becomes active, even thought to a lesser degree. Several variants of this concept have been proposed. One possibility is that motor imagery could directly strengthen the appropriate muscles. Several reports have shown that when people imagine performing an action, the pattern of muscles twitch are similar to those observed during actual execution (e.g., Gandevia, et al., 1997; Wehner et al., 1984). However, this mechanism alone is unlikely to fully explain the improvement observed, given that minimal, sub-threshold level of activation that is generated. An alternative, which constitutes the original psychoneuromuscular theory (Carpenter, 1894; Jacobson, 1932; Washburn, 1916), states that the feedback from the stimulated muscles would strengthen the motor program that triggers the muscles. However, it has been shown that MP works even when the relevant muscles are temporarily immobilized, which prevents them from sending pertinent signals back to the brain (Yue et al., 1996). In addition, paralyzed and non-paralyzed individuals show the same changes in brain activity during MP, suggesting that neuromuscular feedback is not vital for MP effects (Cramer et al., 2007). Another variant, also known as the bioinformational hypothesis, states that the central programs that activate muscles may become more efficient through being used more often. Every overt and covert behavior creates a specific and unique pattern of interconnected nodes in the brain (Lang, 1988). Frequent repetition through MP or physical practice will similarly result in a strengthening of the connection between the nodes in this pattern. This idea is supported by studies showing increase in muscle strength following MP in the absence of correlated EMG activity (Yue and Cole, 1992). Moreover, this is in line with the changes in cerebral function described above (e.g., Celnik et al., 2006; Jackson et al., 2003; Pascual-Leone et al., 1995).

- *Symbolic learning hypothesis*

A third hypothesis is the cognitive, or symbolic, explanation. The principal idea, as originally proposed by Sackett (1934), is that MP facilitates those skills in which there is

a symbolic control of the movements involved. This is certainly supported by the overall pattern demonstrating MP to be more effective for cognitive tasks in comparison with physical tasks. Along a similar line, research on observational learning suggests that observation facilitates motor learning because it enables an individual to determine the key spatial and/or temporal features of the task, which removes the need to create a cognitive representation of the action pattern through trial and error (Blandin et al. 1994; Buchanan and Dean 2010; Burke et al., 2010; Carroll and Bandura 1982; Pollock and Lee 1992; Schmidt and Lee 2005; Scully and Newell 1985).

In addition, some researchers (Corbin, 1967; Van Lehn, 1989) have argued that with experience, people develop a mental plan of the movements involved. Experts are more likely to have more sophisticated schemata and are better at "chunking" new information (e.g., Posner, 1989). This might explain the overall interaction between task type and experience. Thus, experienced subjects may benefit more from MP on the physical tasks because they have the requisite schematic knowledge to imagine the accurate and precise outcomes associated with the imagined performance. As suggested by Finke (1989), the novices who mentally practiced a physical task may not have sufficient schematic knowledge about successful task performance and may be spending their effort imagining task behaviors that could turn out to be somewhat counterproductive.

The concepts of imagery and MP have been here reviewed. The next chapters of this thesis will present original experimental work that wish to deepen the understanding of how different aspects of imagery contribute to the performance outcome (Chapter 2 and 3), and which sensorimotor aspects of performance are modified by MP (Chapter 3 and 4).

2. Mental practice in music memorization: strategies and outcome

[This study was conducted as a collaboration between the University of Milano-Bicocca (Milano, Italy) and the Institute of Music Physiology and Musicians' Medicine (Hannover, Germany). This chapter is partly based on a paper currently in press in the journal Music Perception].

2.1 Introduction

Mental practice (MP) is generally defined as a technique by which someone with the intent to practice creates a mental representation of a preconceived idea or action in order to enhance performance (van Meer & Theunissen, 2009). The focus of the present study is on performance enhancing rehearsal strategies, which must be distinguished from other techniques of emotional and mental training for performance preparation (e.g., relaxation training, meditation, visualization of prescribed images; see Connolly & Williamon, 2004, for a review).

MP has been investigated as a potentially useful practice technique in different fields, including athletics (Feltz & Landers, 1983), stroke rehabilitation (Zimmermann-Schlatter, Schuster, Puhan, Siekierka, & Steurer, 2008) and music (Cahn, 2008; Theiler & Lippman, 1995). Converging evidence from different fields has shown that MP has a moderate and significant impact on performance, and that the effects of MP are weaker than the effects of physical practice (PP) (Gabrielsson, 1999). The efficacy of MP increases when the task involves cognitive or symbolic skills and when the subject has expertise in the specific task's domain (Driskell, Copper, & Moran, 1994). Moreover, several studies have shown that proper combinations of MP and PP may lead to results that are close to or equal to those obtained in PP alone (Feltz, Landers and Becker, 1988; Kopiez, 1990). Music performance serves as an excellent model for studying MP because it is made up of tasks with complex cognitive elements (to a greater extent than in sport performance). At the same time, for a musician, performance is something that is natural to provide (thus, being ecologically valid) and for a scientist the performance is an output that can be objectively measured. Yet, up to now, few research studies have specifically tested the effectiveness of MP in music performance. In the field of music performance, MP has been used and taught at least since the contribution of the well-known piano teacher Karl Leimer and his most famous pupil Walter Giesecking (Barry & McArthur, 1994; Leimer & Giesecking, 1931; McMillan, 2005). According to Leimer, through the use of MP "...the piece can be perfectly performed and this in a most astonishingly shorter time" (Leimer & Giesecking, 1931). MP techniques for musicians include conducting a formal analysis of the score, listening to a recording of the piece, forming

auditory imagery of the pitches, imagining movement (visually and/or kinaesthetically) and using visual imagery of the score (Klöppel, 1996; Orloff-Tschekorsky, 1996).

Overall, results of empirical studies on musicians show that MP is more effective than no practice and not as effective as PP in terms of both objective measurements (e.g., correctness of notes) and expressive features (Highben & Palmer, 2004; Lim & Lippman, 1991). Still, it has also been shown that MP alone may lead to the same plastic changes in the motor system as those occurring with the acquisition of the skill by repeated PP (Pascual-Leone et al., 1995). MP used along with an auditory model showed better results than MP alone (Lim & Lippman, 1991; Theiler & Lippman, 1995). The combination of MP and PP appeared to be particularly effective in the field of music, as shown by several experiments using different tasks and instrumentalist groups (Cahn, 2008; Coffman, 1990; Kopiez, 1990; Ross, 1985; Theiler & Lippman, 1995). Depending on the task, the use of MP and PP led to performances that were as close to, or even indistinguishable from, those following PP alone (Theiler & Lippman, 1995).

However, all these results come from highly controlled experimental situations that have imposed severe constraints on the practice situation and/or the subjects. First, subjects were always forced to use a specific MP strategy that was chosen by the experimenter independently from task and individual-related features. In fact, MP has been reduced to: a) an analytical pre-study of the score, or listening to a recording of the piece followed by analytical study (Rubin-Rabson, 1937); b) auditory plus kinesthetic imagery (Cahn 2008; Ross, 1985); c) imagery of sounds while pressing silent keys, or imagery of the feeling of the movements while actually hearing the sounds, or auditory plus kinesthetic imagery in the absence of any feedback (Highben & Palmer, 2004); d) visual plus kinesthetic imagery with an auditory model (Coffman, 1990); or e) visual plus auditory plus kinesthetic imagery, with or without an auditory model (Coffman, 1990; Lim & Lippman, 1991; Ross, 1985; Theiler & Lippman, 1995). Second, subjects were often asked to practice in unnatural situations: Depending on the study, subjects had to avoid MP strategies other than the one prescribed (Highben & Palmer, 2004). For example, they had to avoid any overt movement of the hand/fingers (Cahn, 2008; Coffman, 1990; Ross, 1985) or humming (Lim & Lippman, 1991; Ross, 1985). In some studies MP included a recorded version of the piece played at fixed time intervals (Theiler &

Lippman, 1995) or even played continuously for the entire practice time (Coffman, 1990; Highben & Palmer, 2004; Lim & Lippman, 1991). In other studies, participants had a very limited time window (e.g., three minutes) to implement their MP (Cahn, 2008; Coffman, 1990) or had to practice the piece a fixed number of times without stopping or correcting mistakes (Coffman, 1990; Highben & Palmer, 2004; Ross, 1985).

The above mentioned constraints were introduced in order to improve experimental control, and these controlled studies yielded valuable and converging results, indeed. However, these constraints may have significantly altered the MP processes from what they are in a musician's daily life, thereby producing partially ambiguous or biased results. Encouraging or forcing a musician to use a specific MP strategy potentially raises the following problems:

- I. In methodological terms, it is often not clear why the experimenter has a priori decided to select one strategy and not another. Inclusions and exclusions of MP strategies in the previously mentioned studies seem to be partially guided by the author's implicit or explicit assumptions about which strategies constitute the very core of MP. Yet there is no consensus among scientists about the exact nature of these core processes. Furthermore, such a debate would not be particularly relevant for the musician, who appreciates MP as a heterogeneous and flexible tool.
- II. Such experiments do not take into account how much the selected strategy conforms to each subject's preferences, habits, and abilities (individual-related features). For example, both Lim and Lippman (1991) and Highben and Palmer (2004) speculated about the existence of individual MP-related features that could have an important role in the way MP was applied. In fact, many of Lim and Lippman's subjects expressed the desire for more freedom in the application of MP, while Highben and Palmer documented an association between individual performers' musical memory and imagery skills (auditory vs. motor).
- III. Maintaining the same strategy throughout the whole practice process does not allow the subjects to flexibly change their approach in order to optimize the learning process or manage specific elements of the task that might benefit from different MP tactics (task-related features). Comparing the performance of guitarists and vocalists, Theiler and Lippman (1995) concluded that "features of MP regimen

should be adjusted to accommodate particular applications, because different attributes may be optimal for various physical and musical endeavors.”

- IV. The demand of using only one MP strategy to the exclusion of all others appears to be unrealistic for musicians. This can be nicely illustrated by taking the underlying brain mechanisms into account. Several neuroimaging studies have described the tight and automatic coupling between auditory, visual, and motor networks in the brains of musicians (Haslinger et al., 2005) and even of naïve subjects following just 20 minutes of piano training (Bangert & Altenmüller, 2003). It is not likely that all of these tight and long-term developed connections can be effectively interrupted by the subject’s conscious will. Lim and Lippman’s (1991) results underlie this hypothesis, since “all subjects found it almost impossible to separate the kinaesthetic image from the visualization of ‘hands on keyboard’; two of the subjects claimed that musicians automatically listen to music and feel their instrument tactually” (p. 27).

Consequently, the experimental control of a study design that focuses on a specific MP strategy remains doubtful, especially when attempting to identify individual differences in: a) how effectively undesired MP strategies have been switched off; b) the cognitive cost paid for this switching off; c) the practice strategy actually used; and d) preferences, habits, and abilities in the strategy actually applied.

The present study was primarily designed to address these limitations. We therefore designed an “open” MP condition in which the participants were completely free to use any MP strategy they desired without any constraint and within an amount of time close to the one indicated in past research as the most effective for MP (Driskell et al., 1994). We allowed participants, for example, to move fingers and hands without the instrument, since this is a commonly used MP strategy. Furthermore, this strategy is explicitly recommended in practical guides to MP in sports (Rushall, 1991). Thus, a higher degree of ecological validity enables the present investigation to ask questions, such as:

- I. Are certain MP patterns more effective than others?
- II. Is MP more effective when it is freely used than when it is constrained, as in previous studies? Converging evidence has shown that the effectiveness of skill learning can be enhanced if the learner is given some control over the practice

conditions (Chen, Hendrick, & Lidor, 2002; Chiviacowsky & Wulf, 2002; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997).

For the present investigation, a music memorization paradigm was chosen because of its potential implications in both applied and theoretical terms. To begin with, memorization is a major issue for musicians; playing from memory is often a source of anxiety and memorization still tends to be seen as an individual and mysterious process, in which each person has to find his or her own method (Ginsborg, 2002). A deeper and systematic knowledge of the means to improve music memorization abilities could therefore have practical applications in the field.

Moreover, Chaffin and collaborators have shown that the main principles described by expert memory theory in classic domains (e.g., chess, see Chase & Simon, 1973; digit strings, see Thompson, Cowan, & Friedman, 1993) rule the behavior of expert musical memorists also, specifically a) the meaningful encoding of novel material; b) the use of a well-learned retrieval structure; and c) extended practice to decrease the time needed for retrieval from long-term memory (Chaffin, Logan, & Begosh, 2009; Ericsson & Kintsch, 1995). Of particular interest is the finding that music performance from memory relies heavily on structural and linguistic memory, in addition to auditory and motor memory. First, expert musicians rely on schematic knowledge already stored in memory to organize information into larger chunks. Second, they use a retrieval scheme to organize the cues that provide access to the chunks of information in long-term memory. Musicians' schematic structures can be identified as familiar patterns such as chords, scales, and arpeggios, while the formal structure of the music conveniently provides a ready made hierarchical organization to serve as a retrieval scheme (Chaffin & Imreh, 2002). These conclusions come from studies in which the piano was always available to the musician; therefore, it would be interesting to see how memorizing strategies are applied and adapted when the physical feedbacks of the real action are not available. For example, movement simulation has been shown to support operations such as letter recall from memory in deaf children (Locke & Locke, 1971) or abacus calculation in expert abacus operators when the abacus was not available (Hatano & Miyake, 1977). Interestingly, this form of "transitional" sensory representation appeared linked with the

degree of expertise, with more advanced subjects being able to avoid it (Hatano & Miyake, 1977).

Based on these considerations, we generated hypotheses about the features and strategies that are more predictive of successful performance. Considering that our subjects had to prepare a memorized performance of a relatively simple piece of music using MP, we hypothesized that: 1) Structural/formal analysis of the piece would be associated with better performance. 2) Pitch imagery would be strongly connected with performance results; in fact, in MP pitch imagery is likely to be a core operation, not a transitional one, acting as a prerequisite for structural analysis or other higher-order operations. Auditory memory-based operations might become less relevant when the piano is available. 3) Motor and visual imagery should play a minor role. It would also be possible to observe differences in the role of motor and visual imagery between subjects with low vs. high motor/visual imagery capabilities. 4) Subjects' listening to the auditory model would be associated with poorer performance. Compared with past studies showing the advantage of auditory model-supported MP vs. MP without this kind of support, in the present study subjects could choose whether to listen to the recording or not. Following the reasoning of Hatano and Miyake (1977), it seems likely that more advanced subjects would not "waste" resources in this transitional operation. 5) For the same reasons, the subjects' moving of fingers should be associated with poorer performance.

2.2 Materials and methods

• Participants

Sixteen right-handed pianists (8 males, 8 females) were recruited on a volunteer basis from the University of Music and Drama, Hannover, Germany. They had a mean age of 26 ± 4 years (range = 18 to 36) and they had at least 15 years of individual piano instruction (mean = 20 ± 4 ; range = 15 to 26). In an initial questionnaire (see Results), all subjects reported being familiar with MP skills and strategies.

- Materials

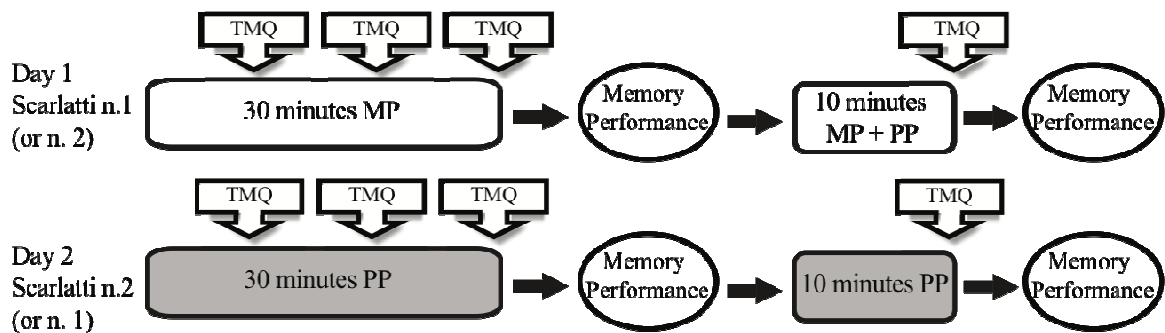
The first half of two Domenico Scarlatti sonatas of comparable length and difficulty were selected (see Appendix for excerpts from the score of the two pieces, Supplementary Figure 1 and Supplementary Figure 2). The pieces were slightly modified to have the highest degree of comparability without altering the original musical context. As a result of these manipulations, the excerpt of the C major sonata (K 72) included a total number of 387 notes, while the excerpt of the A major (K 113) included 385; both pieces included 19 bars, 48 four-semiquaver groups in the right hand, 20 four-semiquaver groups in the left hand (a four-semiquaver group consists of four successive semiquaver notes). In both pieces, eight of these four-semiquaver groups were identically repeated. In the C major sonata excerpt there were 49 octave notes in the left hand and 54 in the A major sonata excerpt. Although there was a high similarity in the general structural form, the two pieces still had several subtle differences; for example, the complexity of the four-semiquaver groups was slightly higher for the A major sonata excerpt. These differences were preserved to avoid interferences between the two pieces, but were leveled due to balanced assignment to the two practice conditions. During performance, as well as during PP, subjects played on a Wersi Digital Piano CT2 (Halsenbach, Germany) using the standard piano timbre. All practice sessions and performances were video documented by a digital video camera from a standardized position that revealed the profile of the pianists.

- Design

Each subject was asked to learn the two pieces, one via MP (see the Appendix for a list of abbreviations) and the other via PP, on two different days (see Figure 2.1 for a brief summary of the design). After the practice session, the piece had to be performed by memory. Because of the focus on the memorization paradigm, we selected two highly comparable music excerpts that had no specific technical difficulties (which would have brought an uncontrolled source of variability between subjects); such pieces would have been too easily sight-read in a non-memory performance task. A certain degree of experimental control was therefore maintained in this component of our design.

The assignment of the two pieces to each condition (MP or PP) was counterbalanced between the subjects so that half of the sample studied the A major sonata excerpt using MP and the C major sonata using PP, and the other half studied the A major sonata using PP and the C major sonata using MP. Half of the sample had the MP trial on the first day; the other half on the second day. The time interval between the two study days was on average 5 days. Subjects were randomly assigned to their respective protocols.

Figure 2.1. Experimental design



MP = Mental Practice. PP = Physical Practice. TMQ = Ten Minute Questionnaire, administered during practice, aimed at describing the mental strategies being used.

• Procedure

Before entering the study, subjects confirmed that they did not know the two musical pieces and filled out a questionnaire assessing their familiarity with MP strategies. This questionnaire was divided into six sections regarding registry information, MP-abilities, MP-habits, MP strategies for music memorization, external resources, and solfège. Apart from registry information, each section contained statements (e.g., “Is mental visualization of the score of a piece useful for you in the memorization of the music?”) that had to be rated on a Likert scale (“1” = “never”/“not at all”/“absolutely not” to “10” = “always”/“perfectly”/“absolutely”).

Subjects using MP on the first day were allowed some time to freely familiarize themselves with the MIDI piano before the start of the experiment. This was done to

avoid unexpected discomfort when playing on an unfamiliar instrument following MP. For both, MP and PP, a metronome indicated a speed of 80 bpm prior to the start of the practice session. Subjects were asked to adjust the tempo of their final performance to this speed. During MP, subjects were seated comfortably in front of a table with the score of the piece to be studied and a pencil. Instructions for the use of MP were as follows: “You can freely use whatever practice method you prefer, except for physically playing a real piano.” A MIDI recording of the piece was also available to the subjects, who were free to listen to it and to pause and resume it as many times as they wished. Subjects were allowed to write on the score as well as to move their fingers.

During PP subjects sat in front of the MIDI piano. Instructions for the use of PP were as follows: “We ask you to focus on physically practicing the piece, ignoring any mental images you have as you practice. Do not to stop to mentally rehearse the music and avoid formal analysis of the piece.” In our view, the definition of PP as a control condition represents a crucial point of methodology. In past research, some studies (Lim & Lippman, 1991; Theiler & Lippman, 1995) required subjects to avoid imagery operations during PP, assuming PP as a “pure” task, complementary to MP. Other studies (Ross, 1985; Coffman, 1990; Cahn, 2008) did not provide any definition of PP, leaving unclear to what extent imagery operations were allowed or not. Only Lim and Lippman (1991) controlled the degree of imagery operations actually implemented during PP, finding that “when given auditory or visual information, or when making actual movements, it was impossible to form an image.” Even if empirically supported, this result is somewhat disputable: The authors reported that in their own study “the sophistication of the subjects appears to have been overestimated” and that a “more sophisticated screening of participants may be necessary, in pursuit of those having highly developed or better practiced imaging skills” (Lim & Lippman, 1991). In the present study, the “pure PP” control task was employed in order to have past research as a clear reference point. To assess how often participants relied on different imagery and mental strategies during MP as well as during PP, we developed a short questionnaire (see below) that was administered from time to time during both MP and PP.

Under both conditions – that is, using MP and PP - subjects had 30 min (Phase 1-3, each phase with a 10-min duration) to study the respective piece; subsequently, they had to

perform the piece on the MIDI piano by memory twice. Following these two performances, subjects had 10 min (Phase 4) to continue studying the same piece. Subjects who had previously studied the piece using MP were now free to combine mental strategies with real piano playing (MP+PP); subjects who had previously studied the piece using physical practice were asked to keep on practicing in the same way, thus avoiding mental rehearsal, imagery, or formal analysis (PP+PP). Finally, the subjects again performed by memory twice. For all conditions, subjects were not forced to memorize the whole piece; while performing, they were free to play as far as they could, but they were explicitly asked to give a performance coherent with the score, thus avoiding improvisation, repetitions, or jumping between different bars of the piece.

- Measurements

During all practice conditions, after each phase (i.e., every 10 min) subjects were asked to fill out a short questionnaire (Ten Minute Questionnaire; TMQ) documenting the mental strategies they may have used. Subjects had to rate on a Likert-scale from “1” (“not at all”) to “5” (“very often”) how often they used the following strategies: mentally hearing the sound of notes, mentally feeling the movement of fingers/hands, mentally visualizing the movements of fingers/hands, mentally visualizing the score, harmonic analysis of the piece, rhythmical analysis of the piece, melodic analysis of the piece.” The TMQ was validated by running a pretest with a sample of 38 professional musicians (the expertise as professional musician always being greater than 4 years). Participants were asked to rate each item of the TMQ questionnaire assessing both clarity and relevance of each question on a 5-point scale (“1” = “very low” to “5” = “very high”). Overall clarity and usefulness of the instrument was investigated as well. A questionnaire similar to TMQ, without the harmonic/rhythmical/melodic questions, was administered after the performance, to reconstruct which mental strategies were used while performing. Following the last performance after Phase 4, a short interview was conducted to reconstruct - this time by free recall - which strategies were used during the 40 min of practice and how thoroughly the piece had been formally analyzed. All participants confirmed that the pieces did not contain any sequence difficult to play and that the main challenge of the task was just to memorize the notes.

At the end of the session, a test for musical auditory imagery was administered. We developed a test based on the task described by Highben and Palmer (2004) to investigate auditory imagery in mental practice research: Participants were shown the score of a single-line melody (9-12 pitches) and simultaneously heard a melody, which was the same as the notated melody or had a difference of one pitch. The stimuli were adjusted by making the one-note difference a change of 1-2 semitones; the total number of changes that moved up or down in pitch were balanced. Twelve of the 16 melodies presented had a one-note difference. The 16 melodies were played via loudspeakers, and subjects were asked to identify any pitch differences between the melodies presented by loudspeaker and the ones presented on the scores. The internal consistency of this test was assessed by computing Cronbach's alpha on the data collected in a pretest with a sample of 20 musicians (the expertise as professional musician always being greater than 4 years).

Individual differences in mental imagery were tested by administering the standardized questionnaires USOIMM77 (Antonietti & Colombo, 1996-1997), Motor Imagery Questionnaire-Revised (Hall & Martin, 1997), and Verbal-Visual Strategies Questionnaire (Antonietti & Giorgetti, 1996). USOIMM77 was developed to assess the spontaneous occurrence of mental visualization in thinking; the Motor Imagery Questionnaire-Revised was developed to examine kinesthetic and visual movement imagery ability; the Verbal-Visual Strategies Questionnaire was developed to measure the cognitive disposition to use visual or verbal thinking strategies.

Two performances were recorded after each practice period to control for the variability in individual fluctuations that emerged in the pretest phase of the experiment, with some subjects performing better at the first recording due to short-term memory resources, and others at the second due to initial disorientation. The better performance of the two was selected for further evaluation. This selection was done according to the ratio score (see below) computed for both performances. The first recording was found to be the best in four subjects for MP, in three subjects for PP, in 8 subjects for MP+PP, and in 12 subjects for PP+PP.

Note-by-note recordings of the performances were acquired with a MIDI piano. Error detection analysis was done manually by the first author. Wrong notes were defined as any notes not corresponding to the prescribed note on the original score; an omitted note,

as well as an undesired additional note was treated as a wrong note. MIDI data were used to compute two objective parameters of performance: 1) the absolute number of notes played and 2) the ratio between the number of wrong notes and the total number of notes played. The ratio score represents performance accuracy, scaled by the length of the performance. This allows discriminating between subjects who made a similar number of errors but played a different extent of the piece. For example, a subject who played 10 wrong notes out of 100 total notes would have a better (that is, lower) ratio score (ratio = 0.1), compared with another subject who made the same number of mistakes while playing only 50 notes of the piece (ratio = 0.2). DVD recordings of the performances were independently evaluated by three professional musicians (one pianist and piano teacher, one pianist, one professional flutist and amateur pianist). The professional experience of these evaluators ranged from 16 to 40 years in their fields. Raters were blind as to which practice condition preceded the recorded performances and were provided with the written scores. All performances were rated on four dimensions: 1) correctness of notes; 2) articulation and phrasing; 3) dynamics and expression; 4) global score. The first three features are typically examined during piano performance auditions and competitions, and have been used in past research on MP (Theiler & Lippman, 1995); an additional “global score” was collected to incorporate all aspects of music performance. Raters judged these dimensions on a Likert scale ranging from “1” (“poor”) to “7” (“excellent”). For the “correctness of notes” dimension, raters were asked to take into consideration not only the correctness according to the score (already computed in the ratio), but also how well the notes, even wrong notes, fit the context. The “global score” dimension was independent of the quantity of music played. Recorded videos of the 30 min of MP (Phase 1-3) were used to quantify the time each subject spent in the following overt behaviors: 1) moving the fingers only; 2) singing only; 3) listening to the audio reproduction of the piece only; 4) moving the fingers while singing; 5) moving the fingers while listening to the audio track; 6) total time moving the fingers (even if other overt operations were going on); 7) total time singing (even if other overt operations were going on); and 8) total time listening to the audio track (even if other overt operations were going on). The time spent on these operations was expressed in seconds. This quantification was done by the first author.

- Statistical Analyses

Statistical analyses were run on SPSS 15.0. Normal distribution of the variables was assessed by means of the Kolmogorov-Smirnov test. In consideration of the small sample size, a conservative p value of .10, instead of .05, was assumed for this assessment. For each of the four dimensions of the rating, a measure of inter-rater reliability was obtained by averaging the Pearson correlation coefficient from each possible pair of raters, a method already used in past research on MP (Lim & Lippman, 1991; Theiler & Lippman, 1995). Separate repeated-measures analyses of variance (ANOVA) were conducted for each performance parameter, in order to evaluate differences in performance between MP, PP, MP+PP and PP+PP. Post hoc tests were computed using the Bonferroni correction for multiple comparisons. Partial eta squared (η^2_p) was assumed as a measure of effect size. Potential associations between individual features (initial questionnaires, imagery test) or strategic data (overt behavior, TMQ) and performance scores were assessed by the Pearson correlation coefficient. For the Pearson correlation coefficient, the 0.05 level of significance was assumed to be two-tailed for all variables, with the exception of the score on the musical auditory imagery test in relation to practice outcomes. The use of imagery during MP and PP was compared by means of two-sample dependent t -tests. Imagery during PP was compared with the theoretical “pure” absence of mental imagery by means of one-sample t -tests, with “1” as the test value; we therefore compared subjects’ actual answers with the mean of an hypothetical group of subjects that successfully avoided mental imagery while doing PP (“1” = “not at all” answer on the TMQ). The validity of the TMQ was assessed in a one-sample t -test by comparing the scores obtained in the validation questionnaire with “3” as the test value. We therefore tested whether subjects’ actual answers were significantly shifted toward the high values, compared with the mean of a hypothetical group of subjects that rated the questionnaire as just “intermediately” relevant and clear. Except for normal distribution, all analyses were evaluated at the 0.05 level of significance.

2.3 Results

The average level of agreement between the three raters was .79 for correctness of notes, .63 for articulation and phrasing, .58 for dynamics and expression, and .75 for global score. Compared with previous studies (Lim & Lippman, 1991; Theiler & Lippman, 1995), inter-rater reliability was considered high enough to warrant averaging the three raters' independent judgments for each performance. Each of the four dimensions of rating showed a high level of correlation with the others (average correlation for correctness of notes: $r = .84$; articulation and phrasing: $r = .84$; dynamics and expression: $r = .80$; global score: $r = .85$); these dimensions were therefore collapsed into a single "rating" indicator by summing up the score on each dimension for each subject (rating range: 4-28). This procedure was done to decrease the possibility for Type I error variable-wise, considering the relatively small sample size. All variables showed normal distribution, with the exception of the following MP strategies: formal analysis as reported in the preliminary questionnaire, and auditory imagery as reported in the preliminary questionnaire and in the TMQ. For these variables, the nonparametric Spearman's rho was used instead of the Pearson correlation coefficient. The two sonatas did not show differences in their degree of difficulty in any of the four conditions (MP, PP, MP+PP, PP+PP: $p > .05$ for number of notes, for ratio and for rating). The TMQ validation process provided support for its validity: Each of the seven items received a rating that was significantly better than "intermediate" for both clarity and relevance (one-sample t -test: all $p < .001$; all means > 3.87). The overall clarity and relevance of the questionnaire also received a satisfying evaluation, clarity: $4.86 \pm .83$; $t(37) = 31.74$, $p < .001$; relevance: $4.05 \pm .94$; $t(37) = 26.20$, $p < .001$. Concerning the musical auditory imagery test, it appeared to have a good internal consistency (Cronbach' alpha = .77). All items appeared to be worthy of retention: The greater increase in alpha would come from deleting item 1, but removal of this item would increase alpha only by .02. All items correlated with the total scale to a good degree (lower $r = .31$).

- Qualitative Evaluation of Subjects' Background

On the initial questionnaire, subjects most frequently reported the MP strategies of mentally hearing the sound of notes and using formal analysis (on average mentally

hearing: $8.8 \pm 1.9/10$; formal analysis: $7.7 \pm 2.1/10$); visualizing movements was the least commonly used (on average $5.9 \pm 2.9/10$), mentally feeling movements and visualizing the score occupied an intermediate position (on average feeling movements: $6.9 \pm 2.8/10$; score visualization: $6.8 \pm 2.9/10$). Despite the high level of proficiency in piano playing and knowledge of MP skills, none of the subjects reported relying on MP as a major practice strategy.

- *MP*

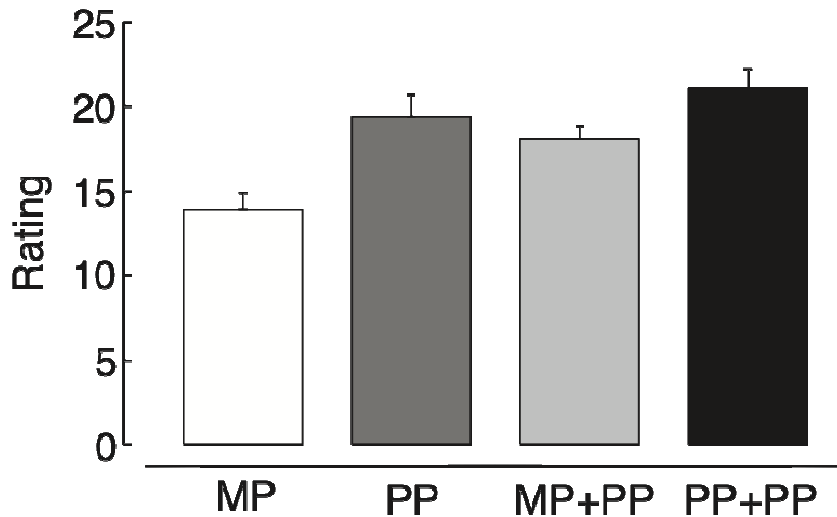
After 30 min of using MP, subjects were able to perform by memory on average 242 ± 110 notes (range: 112-387), corresponding to $63 \pm 28\%$ of the piece. The mean ratio (ratio wrong notes/total notes played) score was $.17 \pm .17$ (range: 0 - .62). Mean scores for number of notes and ratio are reported in Table 2.1. Rating scores from the expert raters are reported in Figure 2.2.

Table 2.1. Performance scores

	Number of notes	Ratio wrong notes/ total notes
MP	242 ± 110	$.17 \pm .17$
PP	326 ± 101	$.08 \pm .11$
MP+PP	319 ± 96	$.07 \pm .08$
PP+PP	349 ± 86	$.04 \pm .04$

MP = Mental practice; PP = Physical practice.

Figure 2.2. Expert raters' scores



MP = Mental practice; PP = Physical practice. Expert raters scored performance with reference to: i) correctness of notes, ii) articulation & phrasing, iii) dynamics & expression, iv) global evaluation. The four dimensions were collapsed into a single Rating indicator, shown in this figure. MP alone is significantly less effective compared with PP. However, with the addition of a short session of PP, MP resulted as effective as continued PP.

- MP vs. PP

The analysis on the number of notes revealed significant main effects for the practice condition, $F(3, 12) = 11.51, p < .001, \eta^2_p = .43, \text{power} = .99$. Post hoc tests revealed that fewer notes were played after subjects used MP compared with the other conditions (PP: $p = .02$; MP+PP: $p = .03$; PP+PP: $p = .004$); no significant differences could be seen in the notes count between MP+PP and PP, or between MP+PP and PP+PP ($p > .05$). The analysis of the ratio also revealed a significant main effect for the practice condition, $F(3, 12) = 7.99, p < .001, \eta^2_p = .34, \text{power} = .98$. Post hoc tests showed a poorer (i.e., higher) ratio score for MP compared with PP ($p = .04$) and MP+PP ($p = .02$); a similar tendency could be observed for PP+PP also ($p = .056$), which did not reach statistical significance (possibly because of greater fluctuations in ratio scores after PP+PP, compared with the

other conditions). No significant differences could be observed between the ratio values of MP+PP and PP, or between those of MP+PP and PP+PP ($p > .05$). Analysis of the ratings revealed significant main effects for the practice condition, $F(3, 12) = 26.21$, $p < .001$, $\eta^2_p = .64$, power = 1. Post hoc tests revealed lower ratings after the subjects' use of MP compared with all other conditions ($p < .001$). No significant differences emerged between PP and MP+PP ($p > .05$), while a qualitatively small but significant difference could be observed between MP+PP and PP+PP ($p = .02$). PP+PP scores on all three dimensions were possibly conditioned by a ceiling effect, given the nonsignificant differences between PP and PP+PP ($p > .05$).

- MP: Strategies and Outcomes

The main association between MP strategies and post-MP outcomes are summarized in Table 2.2. In the next paragraphs, results will be displayed for each of the MP component we evaluated, following the order of the hypotheses we outlined in the Introduction.

Table 2.2. Mental practice strategies and outcome

	Number of notes	Rating score	Ratio wrong notes/ total notes
Formal analysis (PRE-Q)		+	
Auditory imagery (PRE-Q)	+	+	
Auditory imagery (TMQ)	+	+	
Visual imagery - motor (TMQ)	-		
Auditory models (PRE-Q)			+
Auditory models (overt)		-	

Note. “+” indicates that a higher score on the item is related with a better post-MP performance; “-“ indicates that a higher score on the item goes together with a worse post-MP performance. PRE-Q = Preliminary questionnaire; TMQ = Ten Minute Questionnaire, administered during mental practice; overt = overt behavior during mental practice, quantified from the video-documentation.

- Formal Analysis

Stronger reliance on formal analysis for music memorization, as reported in the initial questionnaire, resulted in better post-MP rating score (Spearman's rho, two-tailed: $r = .77, p < .001$), and a similar tendency was observed for the number of notes also ($r = .47, p = .06$). Self-reports of harmonic, melodic, or rhythmic analysis during the 30 min of MP (TMQ data) did not show any association with post-MP performance during MP ($p > .05$).

- Auditory Imagery

The score on the musical auditory imagery test was positively related to post-MP performance: Subjects with more developed aural skills were able to play more notes (Pearson correlation, one-tailed: $r = .45, p = .04$), had a better ratio score ($r = -.43, p = .048$), and got a higher rating score ($r = .45, p = .04$). Pitch imagery as a means to support music memorization, as reported in the initial questionnaire, was positively correlated with post-MP rating score (Spearman's rho, two-tailed: $r = .65, p = .007$) and number of notes ($r = .53, p = .033$), with a similar tendency for ratio ($r = -.48, p = .06$). Pitch imagery as a strategy reported during the 30 min of MP (TMQ data) was also correlated with a better rating score (Spearman's rho, two-tailed: $r = -.50, p = .049$) and greater number of notes played ($r = .51, p = .045$).

- Motor Imagery

On the basis of the initial questionnaire and TMQ data, no associations could be detected between the strategy of motor imagery and performance scores.

- Visual Imagery

Subjects who relied more often on movement visualization, as reported while using MP (TMQ data), gave a poorer post-MP performance according to the number of notes (Pearson correlation, two-tailed: $r = -.54, p = .03$). No interactions could be found between the score on the Motor Imagery Questionnaire-Revised "visual" subtest and the use of visual imagery of movements from the TMQ in predicting post-MP performance.

- Auditory Models

The strategy of frequently listening to experts' performances, as reported in the initial questionnaire, was associated with a better ratio score (Pearson correlation, two-tailed: $r = -.64, p = .008$). On the contrary, time spent listening to the auditory model (without moving fingers or singing) during the 30 min of MP was associated with a poorer post-MP rating score ($r = -.58, p = .018$). Moreover, the subjects who reported in the initial questionnaire to rely on mentally hearing the sound of notes listened less to the audio recording during MP (Pearson correlation, two-tailed: $r = -.58, p = .018$).

- Other Overt Behaviors

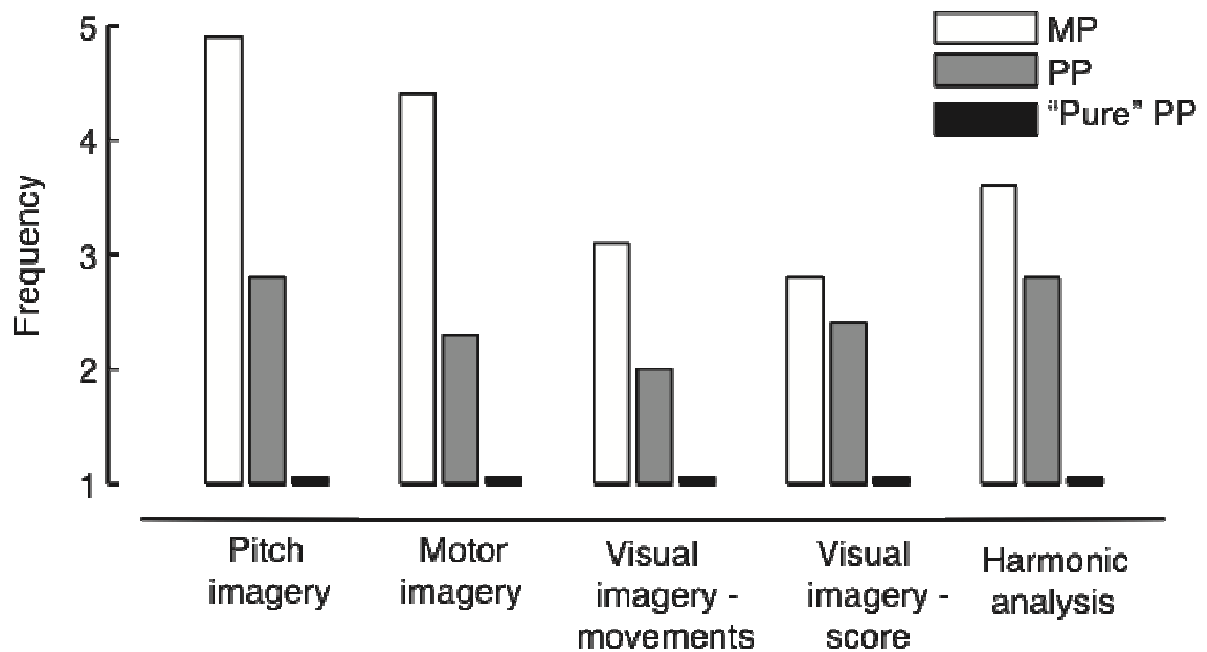
No associations could be detected between the time spent moving fingers or singing and performance outcomes ($p > .05$)

- Mental Imagery During MP and PP

Figure 2.3 shows the mean frequency of reliance on different mental strategies during practice. Consistent with the instructions given, subjects reported (TMQ data) having used MP strategies significantly less during PP compared with MP (MP vs. PP, dependent t -test for mentally hearing the sound of notes: $t = 16.35, p < .001$; mentally feeling movements: $t = 15.69, p < .001$; mentally visualizing movements: $t = 8.61, p < .001$; mentally visualizing the score: $t = 3.34, p = .001$; harmonic analysis: $t = 3.52, p = .001$; melodic analysis: $t = 4.48, p < .001$; rhythmic analysis: $t = 5.73, p < .001$). Reliance on mental strategies was reduced in the PP condition also during the last 10 min of practice, when all subjects were allowed to physically play the instrument (MP+PP vs. PP+PP, mentally hearing the sound of notes: $t = 2.52, p = .017$; mentally feeling movements: $t = 5.80, p < .001$; mentally visualizing movements: $t = 2.35, p = .025$; harmonic analysis: $t = 2.81, p = .013$; rhythmic analysis: $t = 3.87, p = .002$). However, these findings also indicate that mental practice processes were always active during PP, although subjects were asked to avoid them and although they were trying to comply with this request. In fact, differences between the actual use of mental strategies during PP and the theoretical "pure" absence of these strategies (TMQ score = "1", "not at all") are constantly significant (one sample t -test for PP Phase 1-3: mentally hearing the sound of

notes: $t = 6.13$; mentally feeling movements: $t = 5.14$; mentally visualizing movements: $t = 4.85$; mentally visualizing the score: $t = 6.14$; harmonic analysis: $t = 7.12$; melodic analysis: $t = 11.15$; rhythmic analysis: $t = 7.50$; all $p < .001$).

Figure 2.3. Mental strategies used during practice



Averaged reliance on different mental strategies in different practice condition, derived from averaged TMQ data. All mental strategies are used maximally during mental practice (MP). However, also physical practice (PP) is accompanied by imagery strategies, significantly more than one would expect in a hypothetical practicing condition with no use of imagery ("pure" PP).

2.4 Discussion

A sample of pianists practiced to perform from memory two pieces of music of comparable length and difficulty. One piece was practiced by means of MP and the other by PP.

The comparison between post-MP and post-PP performances showed that MP alone allowed a level of proficiency between 40% and 60% of that achieved by PP. Moreover, combining an intense mental practice (30 min) with a relatively short physical practice session (10 min) led to results almost indistinguishable from those following 30 min of continued PP. These results are of immediate interest to musicians willing to: a) optimize the time available for practicing, b) have a deeper comprehension and stronger mental representation of the pieces they are practicing, or c) avoid massive physical practice and thus prevent playing-related disorders. All of these goals can be achieved by mental and physical practice properly combined, without a significant loss in terms of performance.

In a previous investigation involving behavioral and neurophysiologic recordings, MP alone resulted in significant learning, but did not result in as much performance improvement as PP alone (Pascual-Leone et al., 1995). In fact, at the end of five days of practice, the mental practice group's performance was at the same level as that of the group that had used PP for only three days. However, the plastic changes in the motor system following the use of MP alone were the same as those occurring by repeated PP; moreover, after a single PP session, the MP group's performance improved to the level of the group using PP for five days. As was suggested by Jackson (Jackson, Lafleur, Malouin, Richards, & Doyon, 2001), part of the behavioral improvement seen due to MP may be latent, and would thus become evident after the musician engaged in minimal physical practice. Mental practice could thus have a preparatory effect on the task, which increases the efficiency of subsequent physical training (Kopiez, 1990). With specific regard to music memorization, it is also interesting to look at the study on MP by Lim and Lippman (1991), which employed a rating system by expert judges very similar to the one presented in our study. The average ratings reported in Lim and Lippman's study closely matches those reported in our study, with subjects rating MP in the range of 3-4 on the 7-point Likert scale in both studies. Similarities also can be seen when comparing measurements of quantity of music that could be recalled after MP. Both ours and

Highben and Palmer's (2004) study report that MP yielded 75% of the result following PP (however, the way music memorization is quantified in the two studies is not identical). We can therefore conclude that while present and past studies differed in terms of the degree of their ecological validity, they rendered a very similar picture considering the effectiveness of MP. Two explanations could account for this result. First, depending on subjects' aural skills and familiarity with MP, the lack of clear instructions on how to use MP may have led expert subjects to completely display their abilities, and hesitant subjects to get confused and misled. This could be particularly relevant when considering that none of our subjects reported systematically using MP while practicing, a detail that supports the training of subjects in MP before they are tested in experimental studies. Second, this result may be due to the fact that past studies also could not completely rule out the subjects' free use of MP, since the "undesired" cognitive operations implied in MP are unlikely to have been effectively switched off during the experiment. In fact, the TMQ data showed an aspect that has been partially neglected in previous research: PP intrinsically implies MP processes, despite the subjects' honest attempt to avoid them. From a cognitive point of view, MP appears to be an automatic rather than voluntary strategy used when facing a musical task. A musician can only partially regulate the degree of the ongoing MP, and in any case, it seems impossible to turn it off completely. In this respect, our data are in line with neurophysiological investigations showing automatic auditory-motor coactivation in musicians' brains during musical tasks (Bangert & Altenmüller, 2003; Haslinger et al., 2005). Thus, a dichotomy between MP and PP (or between different forms of MP), which in practical terms seems evident, appears to be rather arbitrary in terms of cognitive and neurophysiological processes. This has already been recognized by psychoneuromuscular theorists, who have shown physiological activity in the form of electromyographic action potentials as a result of mental simulation of movements (Grouios, 1992; Hinshaw, 1991). Particular care to this ambiguity should be paid in the research context in which PP is often considered a control condition for MP and vice versa. Nevertheless, contrasting MP and PP still holds a practical significance for musicians. The proper experimental design of this contrast requires the scientist to be conscious of these tight links; "pure" PP, obtained by asking

subjects to avoid mental imagery and rehearsal, appears to be an invalid control condition.

The present investigation has provided a novel contribution in understanding the relation between individual differences in practice strategies and practice outcome. In fact, the adoption of an ecologically valid perspective allowed for the first time to directly address the question, which strategies effectively support memorization in the absence of the physical instrument? Based on the assumptions of the expert memory theory (Ericsson & Kintsch, 1995) and its revision for the musical domain (Chaffin et al., 2009), we have put forward specific hypotheses for each component of MP that can now be discussed in light of the data.

Formal analysis as a MP strategy was expected to be associated with better performance. This was found to be true, but only to a certain degree. We found a significant association between the general habit of using formal analysis for music memorization, as reported in the initial questionnaire and performance results. This likely happens because building a formal structure of the piece allows the performer to use a retrieval, hierarchical scheme that results in a better organization of both practice and memory (Chaffin & Imreh, 1997). In this respect, formal analysis would facilitate the organization of the material to be remembered in chunks of information (Miller, 1956), that could be later recalled as units, thus optimizing the encoding and the retrieval of memories. The use of the formal structure of a piece to organize practice and aid memory is a standard recommendation of piano pedagogues (Leimer & Giesecking, 1931; Sandor, 1981); consistently, experts and advanced performers appear to utilize analytical strategies frequently, while inexperienced performers do not (Hallam, 1997; Williamon & Valentine, 2002). However, no direct associations could be found between the actual implementation of formal analysis during the experiment and performance outcomes. Three interrelated explanations can be proposed for this unexpected finding: First, particularly for experienced musicians, formal analysis may occur as a background, semi-unconscious process that actually shapes the way the pianist reads and practices music without necessarily becoming a deliberate and explicit tactic. As such, it is more likely to be consistently reported as a general attitude in an initial questionnaire as opposed to a TMQ-like formulation. Second, the time constraints we implemented could have further

influenced the choice of practice strategies toward implicit formal analysis, so the subjects could spare the most time for directly practicing the retrieval from memory. It is possible that in a more relaxed setting, as the one described by Chaffin and Imreh (2002), different choices would have been reported. Third, at a conscious level, the use of formal analysis might have been obscured by the use of another, closely connected mental strategy: pitch imagery.

In fact, pitch imagery was expected to be a central element of effective MP. This hypothesis was confirmed by a tightly interconnected array of results, showing that better post-MP performance was achieved by subjects who a) had more developed aural skills, b) reported a general reliance on pitch imagery to aid music memorization, and c) reported the actual use of pitch imagery during the experiment. The other forms of mental simulation -- motor and visual imagery -- showed no association with effective performance (or even a negative relation in the case of mental visualization). These observations lead to the conclusion that effective memorization of a piece of music by mental practice requires the mental representation of how the music sounds. Indeed, it is most likely that this key information serves as raw material for building a higher-level, hierarchical representation such as the structural one. These empirical findings from a novel experimental setup substantiate practical teaching and pedagogical literature (e.g., Gordon, 1997; Leimer & Geiseking, 1931) as well as previous experimental results with a different methodological background (Highben & Palmer, 2004). The potential of pitch imagery in mental rehearsal can be also appreciated when considering how it has been shown to engage the brain. Neuroimaging studies have shown that neural activity within regions of the secondary auditory cortex can occur in the absence of sounds, and this likely mediates the phenomenological experience of imagining music (Zatorre, 2007).

Representations of how the music looks or feels seem more epiphenomenal, being more likely to distract than to empower music memorization. Future studies will determine whether a different set of strategies might be predictive of optimal performance for tasks with stronger emphasis on the motor, rather than on the cognitive aspects of piano playing (e.g., playing in a fast tempo, solving technical difficulties).

Turning to the role of external, auditory models, the literature we reviewed in the introduction has shown that external, transitional formats of representation are helpful to

a certain extent (Theiler & Lippman, 1995). However, experts in a certain field tend not to use them (Hatano & Miyake, 1977). A very similar picture emerges from the present results: The habit of enriching internal representation by collecting, reviewing, and matching external enlightening models may have a long-term impact on the ability to reproduce such models on one's own. In this way, when faced with the situation, one can rely on already developed and stored representation, without wasting resources on external models that are likely to be more time consuming, less integrated with the other ongoing processes, and that possibly even conflict with one's own models (Lim & Lippman, 1991). We can hypothesize that the higher the level of internal auditory/structural representation, the less effective an auditory external model will be, and vice versa. Interestingly, while these considerations apply well to auditory models, they seem not to account for finger movements. No relation could be observed between the strategy of simulating piano playing on the table and practice outcomes. Even more surprisingly, continuously moving fingers was the strategy used by many of the more -- as well as less -- proficient subjects in our sample. For some, moving fingers seemed to lead to stable and reliable traces that physically shaped a robust structural comprehension of the piece; for other subjects, it seemed a blind, mechanical short cut that produced a blurred and weak performance. These results may open a debate that may be answered more conclusively with a larger sample. In any case, the present results challenge the validity of studies that force subjects toward predetermined ways of mental practice.

Altogether, these findings have practical implications for the way musicians could rehearse or memorize new repertoire when the instrument is not available: First, imagery of the sounds should be a default operation, a foundation on which other operations rest. Second, analyzing the structure of the piece in terms of harmonic relations, melodic phrases, and rhythmic structures is another key component of effective MP. This applies to formal analysis not just as a deliberate, explicit operation, but also as a background process that runs parallel to the auditory/motor rehearsal. Third, reliance on external models can be an effective way to support practice, as long as it is clear that the goal is to build up an auditory/structural mental representation that holds even when the model is no longer present. Finally, motor and visual cues as well as overt finger tapping could be of occasional help, depending on the specific nature of the piece and the subject's

preferences. However, they alone do not provide a reliable foundation for mental study, and in some cases they might even become a source of distraction.

Another question that prompted the present study was whether there are common MP profiles. From a qualitative overview of overt and covert practice strategies, mental practice for music memorization appeared to exist in two different forms. On the one hand, there was a mostly “mental” use of MP. Subjects who applied this type of MP were mainly focused on their internal processes, sometimes aiding their mental representations by listening to the auditory model. They showed almost no overt behavior, and they were focused on the abstract-formal analysis of the piece, without spending particular effort on the imagery of the precise movements. On the other hand, a more physical form of MP was observed. Subjects who applied this type of MP frequently supported their internal operations with overt behaviors such as moving fingers and/or singing, and balancing their internal operations between formal analysis and movement imagery. Interestingly, our data do not show an advantage of one category over the other, as the main discriminating factor between these groups -- finger movements -- was not associated with practice outcomes. Both kinds of patterns may lead per se to good or poor results, and probably each musician should find a personal, optimal balance between the two, also depending on the task.

While providing new insights into the mechanisms and possible applications of MP, this study presents the following limitations: a) The subjects’ selection. Although all our subjects were familiar with MP, none relied on it as a major practice strategy; b) The small sample size. Results await to be confirmed by a larger sample; c) The task. To perform a novel piece of music by memory after a short practice session is not a very common task, as already noted by Theiler and Lippman (1995). This problem is likely to interact with our subjects’ lack of expertise with MP, since even those who really had some MP skills probably never used them when faced with this kind of task; d) “Pure” PP as a control condition for MP. Although we were aware that inclusion of “pure” PP in our experimental design could have presented methodological problems, these problems had never been addressed or quantified in previous studies. The present investigation sought to demonstrate these problems and, thus, eliminate a source of ambiguity for future

research. This intention, however, limits the ecological validity of our control condition, keeping a component of unnaturalness in our investigation.

Such limitations may interestingly guide the next steps for further research on MP. First, one could train subjects in MP prior to the study. The quantification of MP skills could be related in diaries for daily-use report as well as measured objectively (e.g., musical auditory imagery test, solfège, sight-reading, improvisation, ear-learning). A detailed entry file would allow researchers to keep even low-experienced subjects and to make separate analyses for subjects with different skill levels. Second, an exploratory, qualitative survey aimed to describe how and when musicians typically apply MP could precede a novel experiment employing more widely used tasks in an ecologically valid setting. Third, MP could be contrasted with “ecologically valid” PP (not assumed to exclude MP processes). Greater effort could be used to describe MP processes: TMQ reliability could be improved by randomizing the order of the item and reversing the scales to better disrupt memory for the previous rating assigned; think aloud procedures could also be considered. Finally, designs with free MP-PP combinations could be developed, giving, for example, percentage-time for each condition as the only constraint. Developing research in these directions will be of great interest in both theoretical and applied frameworks. The results from the present, methodologically “open” study represent an encouraging step toward a deeper comprehension of the mechanisms by which memorization of complex tasks can be improved. No less important, conclusions from this line of research could have a direct impact on the possibility for musicians to better cope with health risk factors and to promote their own well-being.

3. Mental practice in fine motor control: Evidence for motor anticipation

[This study was conducted as a collaboration between the University of Milano-Bicocca and the Music Conservatory G. Verdi (Milano, Italy). This chapter is partly based on a paper currently submitted to Behavioural Brain Research].

3.1 Introduction

When sequential skilled movements must be executed, the motor system must cope with two main issues: *a)* performing each single component movement in a fast and precise fashion, and *b)* binding the component movements together so that the sequence can unfold smoothly and fluently (Ghilardi et al., 2009). Changes in movement velocity are often regarded as indications of improvements in single movements, while movement anticipation, which is the main focus of the present investigation, is considered an expression of sequence optimization. It has been argued that one hallmark of a performer's fluency is his or her ability to prepare for upcoming events (Dalla Bella and Palmer, 2011). A well-known example is coarticulation in speech in which fluent speech production is achieved when upcoming events influence the production of the current event (anticipatory pattern), and the production of the current event is modulated by the events that preceded it (carryover pattern) (Hardcastle and Newlett, 1999; Ostry et al., 1996). Analogue phenomena have also been described for hand movements, such as fingerspelling (Jerde et al., 2003) and piano playing (Engel et al., 1997).

Among the strategies for improving motor performance, mental practice (MP) has received substantial attention. MP is usually defined as the cognitive rehearsal of a task in the absence of overt physical movements, and it has been shown to improve actual performance, although not to the same extent that physical practice (PP) does (Driskell et al., 1994). The mechanisms responsible for these achievements are the focus of an increasing number of investigations (Munzert et al., 2009). Recent studies have shown that MP enhances movement speed in a sequential pointing task (Gentili et al., 2010). However, to our knowledge, no direct effects on movement anticipation have yet been described. On the one hand, a possible explanation could be that MP's impact is limited to the single-elements component of the motor task. Current models of motor control explain MP's effectiveness using the concept of forward internal models: that is, imagining a movement may generate an efferent copy of the motor command, and this efferent signal could be used to make predictions about the future states of the effector (Gentili et al., 2010; Wolpert et al., 1995). However, because the state estimates in MP derive from the forward model alone without any sensory feedback, the training signal could be too poor to faithfully represent the subtle motor nuances required to shape the

coarticulation dynamics. On the other hand, it is known that the efficacy of MP is higher for the cognitive and strategic than for the motoric components of a motor performance (van Meer and Theunissen, 2009). On this basis, the sequencing component could hypothetically benefit from mental rehearsal, given the declarative format that is intrinsic to this process and the mind's capability to plan and build representations of complex event sequences (Palmer and Pfordresher, 2003). If this were the case, the emergence of movement anticipation should be detected following MP training for complex movements.

The present study was designed to determine whether MP's impact on motor performance extends to the sequencing component. Several aspects of the previous research might have limited the possibility of detecting changes in coarticulation dynamics following MP: a) *Task complexity*: It has been noted that "previous investigations used relatively simple motor tasks that did not require high spatiotemporal or dynamic control of the action" (Gentili et al., 2006). In these simple motor tasks, fine motor adjustments are unlikely to be detected because they are not necessary and/or because they are already present at the baseline level. b) *Subject selection*: It has been shown that wide differences exist within individual imagery abilities (Guillot et al., 2008), and that an adequate level of prior knowledge is required for MP to be effective (Finke, 1989; Ginns et al., 2003); however, study participants are often not trained in MP and/or are not trained in the type of task employed. c) The notion of anticipation is partially related to the presence of an internal representation of the task. Tasks with poor ecological validity, such as those sometimes used in previous research, likely limit the possibility that changes in coarticulation dynamics will occur. To overcome these possible limitations, the present study employed a piano playing task, as piano playing is known to involve highly complex sensorimotor control and a unique amount of independent motion of the fingers (Furuya et al., 2011). The subjects were all expert pianists, and each subject received explicit training in MP before the experimental session. The main goal was to assess whether movement anticipation dynamics (sequencing component), increases in movement velocity (single-element component) and overall performance improvement could be detected after MP. Additionally, we sought to identify associations between specific mental strategies and changes in different

aspects of motor control. Based on previous studies, we hypothesized that motor imagery plays a role in increasing movement velocity and auditory imagery for the emergence of movement anticipation (Keller and Koch, 2008; Williams et al., 2012).

3.2 Materials and methods

• **Participants**

Sixteen pianists (10 females) were recruited on a volunteer basis from local music conservatories. To be included in the study, they had to have completed at least the intermediate level of piano training (“*Compimento medio*”), which corresponds to 8 years of formal piano instruction. All participants had at least 9 years of individual piano instruction. The participants were randomly assigned to one of two groups: the mental practice (MP) group or the physical practice (PP) group. The average total lifetime practice time was $17,006 \pm 11,110$ hours for the MP group and $17,030 \pm 6,976$ hours for the PP group. The average age was 30 ± 10 years for the MP group and 31 ± 9 years for the PP group. All subjects were currently performing or teaching piano at a professional level, and all gave their informed consent to participate in the study. All experiments reported in this study were in accordance with the ethical standards established in the 1964 Declaration of Helsinki.

• **Preparation phase: MP training**

Before the testing session, each participant individually underwent two one-hour MP training sessions. The first training session took place approximately one month before the test session. During the training session, the participants completed a preliminary self-report questionnaire assessing their familiarity with MP strategies. For each statement, they provided a score on a 1 (*never*) to 7 (*always*) Likert scale (e.g., “*When you study a piece of music that contains motorically challenging sequences, how often do you imagine the movements without actually moving?*”). After completing the questionnaire, the subjects followed a standardized training procedure derived from Klöppel’s mental training manual (Klöppel, 2006). This procedure included a) a concentration exercise focused on listening to the breath, b) an exercise focused on the subject’s own

proprioceptive and somatosensory internal feelings, with a specific focus on the right hand, c) reading and applying step-by-step instructions for learning to play a fast musical passage using MP. Exercises a) and b) were adapted from classic exercises used in mindfulness-based intervention and were administered by a psychologist trained in mindfulness intervention. Exercise c) was an adaptation of a detailed example from Klöppel's manual (2006, pp. 64-66). At the end of the session, the subjects received a diary for recording the daily time devoted to MP or PP. Furthermore, all participants were asked to practice MP every day, from the first day of training until the day of the testing session. Diary reports confirmed that the subjects had completed daily MP exercises. The second training session took place approximately two weeks after the first one and two weeks before the testing session. In this second training session, for familiarization purposes, the participants underwent a procedure identical to the one employed in the testing session (see paragraph 2.5) to ensure that the subjects were not applying MP under unexpected conditions/requests on the day of testing. This training session differed from the testing session only in the musical piece chosen, which was Liszt's Transcendental Etude No. 7. According to the local music school's teaching program, Liszt's etude is considered significantly more difficult to play than the etude that was used for testing (see paragraph 2.4). This choice was made to ensure that well before the testing phase, all of the participants had tried at least once to apply MP to a level of musical motor complexity higher than the one that was actually tested in the experiment itself, thus limiting noise in the data due to possible disorientation. Liszt's etude was not part of any of our subjects' repertoire, and only one subject in the sample had studied it in the past.

• Apparatus

The subjects were seated comfortably in front of a Roland RD-700 GX digital piano. The Roland RD-700 GX piano was connected to a computer, and MIDI data were recorded using SONAR LE software. Reflective markers were used to collect motion capture (MoCap) data with a three-dimensional optoelectronic movement analysis system (6 cameras, 120 Hz; SMART, BTS, Italy). For this purpose, three hemispherical markers with a 5-mm diameter were applied on the right hand to the a) thumb tip, b) little finger

tip and c) styloid process of the ulna. All practice sessions and performances were video recorded using a digital video camera and showing the pianist from the front.

- Stimuli

The arpeggio model from the first bar of Exercise 5a (WoO 6) for right hand only, from the 51 Exercises for piano composed by Johannes Brahms (1833-1897), was used in the testing session (Fig. 3.1). We diatonically developed the model from C2 to C3 so that the total length of the exercise was 8 bars. To ensure that all of the pianists performed the piece the same way, the fingering was constrained so that for each bar, notes 1,3,5 had to be played with the thumb and notes 2,4,6 had to be played with the little finger. A pace of 112 beats per minute for the quarter note was set as the tempo, thus requiring pianists to play a note every 178 msec.

Figure 3.1. Music piece

The image displays a musical score for a piano exercise. It is divided into two systems. The first system contains four bars of music in 2/4 time. The right-hand part features a sequence of notes with fingerings indicated by numbers 1 and 5. The first bar has notes with fingerings 1, 5, 1, 5. The second bar has notes with fingerings 1, 5, 1, 5. The third bar has notes with fingerings 5, 1, 5. The fourth bar has notes with fingerings 5, 1, 5. The left-hand part plays a simple bass line. The second system contains four bars, starting with a measure number '5' above the first note. The right-hand part continues the sequence, and the left-hand part has rests.

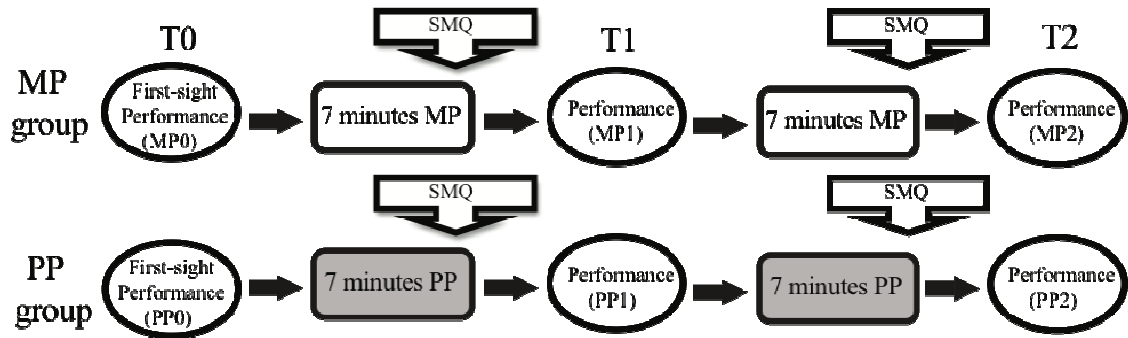
The numbers over the notes represent the constrained fingering (1 = thumb, 5 = little finger). The piece had to be performed at a speed of 112 beats/minute for each quarter note.

The following criteria lead to the choice of this piece for the present investigation: a) It is essentially a motor-technical exercise, without specific musical character or expressive intent; as such, it does not lend itself to subjective spontaneous interpretations and tends to be performed consistently by different pianists with a neutral, “technical” character. b) It is not included in any ordinary piano training program; this makes the piece unknown to the majority of pianists. c) It is motorically challenging in terms of spatial accuracy (hitting the correct keys), timing (keeping up with the fast tempo) and coordination. d) It is not *too* challenging, so that it can be roughly sight-read by any pianists with the minimal skill level we set; as such, it allows the recording of a meaningful baseline (see paragraph 2.4). e) It implies fine motor control of both the proximal (e.g., wrist) and distal (e.g., fingers) segments of the upper limb, thus allowing the study of different motor performance mechanisms. f) It is suitable for a motion-capture setting; in fact, it does not require significant covering of the reflective markers and allows the gathering of the relevant information from a small set of markers.

• Procedure

Before the experiment started, all participants a) familiarized themselves with the instrument, b) confirmed that the reflective markers applied to their right hand did not interfere with their playing and c) confirmed that they did not already know the piece. The procedure, summarized in Fig. 3.2, began with the collection of a baseline performance (T0 = baseline; MP0, PP0) in which the subjects performed the Brahms exercise once by first-sight reading. The tempo was provided by a metronome for the duration of the performance. The subjects were explicitly asked a) to use the written fingerings, b) to play in synchrony with the metronome, c) to perform the piece at *mezzoforte*, with regular force dynamics, d) to perform the piece only once and from the beginning to the end, without interruptions or repetitions.

Figure 3.2. Experimental paradigm



MP = Mental practice. PP = Physical practice. SMQ = Seven-minute questionnaire aimed at describing the mental strategies used during practice.

The second phase differed for the subjects in the two groups. The subjects in the MP group received the following instructions: *“You have 7 minutes to practice this piece using MP and then you will perform it again. You can freely use whatever mental practice method you prefer, but you must avoid actual movements of your fingers/hands.”* During MP, the subjects had to position their right hands on the keyboard, which was fully covered by a rigid cover so that they could neither see nor feel the keys. Hand and finger stillness was monitored both visually and with continuous motion capture acquisition. After 7 minutes, the subjects completed a short questionnaire about the mental strategies they used during MP (see paragraph 2.7) and then performed the piece at the keyboard (T1, MP1), following the same criteria as in the baseline performance. After this performance, the MP subjects had 7 more minutes to practice the same way as before; then they received another short questionnaire and gave a third performance (T2, MP2). Thus, the MP subjects had a total of 14 minutes of mental study interspersed with one performance. The duration of the entire session was calibrated according to the results of past research that indicated that approximately 20 minutes was the optimal time for an MP session (Driskell et al., 1994). In contrast, the subjects in the PP group received the following instructions: *“You have 7 minutes to practice this piece and then you will perform it again. You can freely use whatever practice method you prefer, as long as it includes physically playing the instrument.”* The PP subjects were not asked to avoid or limit their mental operations during practice, as these constraints have been

proven to be confounding and relatively ineffective (Bernardi et al., in press). This choice designated our PP condition as the “natural”, ecologic practice condition and the one with which the subjects were more familiar. This condition has been shown to combine the physical operations of piano playing with several mental operations, including those applied during MP, such as formal analysis and auditory and motor imagery (Bernardi et al., in press). After the 7 minute practice session, the subjects completed a short questionnaire about the mental strategies they used during PP and then performed the piece again (T1, PP1) following the same criteria used for the baseline performance. After this performance, the PP subjects had 7 more minutes to practice in the same way as before, followed by another questionnaire and a third performance (T2, PP2). Thus, the PP subjects had a total of 14 minutes of physical study, interspersed with one performance.

- Data analysis: Accuracy

Objective evaluations of performance accuracy were derived from the MIDI data. Two aspects of performance were evaluated: 1) spatial accuracy and 2) temporal precision. Spatial accuracy measures were obtained by counting the number of wrong notes. A wrong note was defined as any note not corresponding to the prescribed note on the original score; omitted notes and undesired additional notes were treated as wrong notes. Errors were detected manually. Temporal precision was expressed as a timing-error value. For each couple of notes, we calculated the difference between the prescribed inter-onset interval (178 msec) and the actual inter-onset interval that was performed. Error values were averaged across each performance, resulting in a single timing-error value (in msec) for each performance.

- Data analysis: Movement kinematics

In the selected Brahms exercise, two repeated distinct phases involving only the right effector can be identified. The first phase, which we labeled the *Forward phase* (Frw), requires pianists to initially execute a fast wrist movement from left to right, followed by a rapid opening of the little finger relative to the thumb (notes 3-4) to catch the highest note. Following the Forward phase, the pattern is reversed, and the pianists must make a

fast wrist movement from right to left, followed by a rapid opening of the thumb relative to the little finger (notes 6-7) to catch the lowest note; this sequence can be regarded as the *Backward phase* (Bck). This entire pattern is transposed identically for each of the seven notes of the C major scale, so that the exercise comprises 7 Frw and 7 Bck movements (14 movements overall). Critical aspects of performing the Brahms exercise are a) the wrist movement and b) the opening movement of the thumb and little finger. Therefore, the kinematic analyses focused on these aspects.

For each trial, kinematic data were analyzed offline for each of the 14 movements. The kinematic raw data were first filtered using a low-pass Gaussian smoothing filter with a sigma value of 0.93. Movement onset and offset were determined following the 5% peak velocity rule. The data were then averaged separately across all the Frw and Bck movements for each performance, resulting in a single mean and standard deviation value for the Frw movements and another mean and standard deviation value for the Bck movements. The following kinematic parameters were computed for the wrist marker (W) using the scalar value of the 3D velocity vector: 1) Wrist peak velocity (WPVel) and 2) Time to wrist peak velocity (TimeWPVel). Regarding the two finger markers (F), the following kinematic parameters were computed on the 3D distance between the thumb and little finger markers: 1) Finger opening peak velocity (FOpenPVel) and 2) Time to finger opening peak velocity (TimeFOpenPVel).

The pattern of coordination between the fingers and the wrist was assessed using the cross wavelet transform (for further details, see e.g., Grinsted et al., 2004, Mallat, 1999, Torrence and Compo, 1998), a time-frequency analysis method previously shown to be well suited for the analysis of the interaction between two signals in human movement studies (Issartel et al., 2006). This method exposes regions with high common power spectra and reveals information about the phase relationship. Of particular interest for the present investigation was the phase angle between the wrist and finger movements. The cross wavelet transform was therefore computed between the wrist velocity and the velocity of the opening/closing of finger markers using the complex Morlet wavelet. The phase angle between the two signals was expressed in degrees as a value spanning from 180° ($f = p$) to -180° ($f = -p$). A phase angle of 0° represents perfectly in-phase relationships in which the wrist and finger peak velocities happen in the same time of the

oscillatory dynamic. Phase angles progressively farther away from 0° represent an anti-phase pattern between the two oscillations, in which the movement in one effector happens while the movement in the other effector is still in preparation; angles of $\pm 180^\circ$ represent a perfect anti-phase pattern. An increase in the absolute value of the phase angle following practice was interpreted as an indicator of coarticulation dynamics. Although the cross wavelet transform provides information about regions of high common power, it does not reveal information about the local correlation between the two time series in the time/frequency space. Therefore, to enhance the meaningfulness of the results, we first computed the wavelet coherence between the signals to detect locally phase-locked behavior, and we restricted the analysis of the phase angle to frequency bands showing a reliable level of coherence. We searched for the frequency bands in which the most statistically robust coherence could be detected ($p < .05$ along the entire time course of each recording and across the entire sample of 16 subjects). Only one frequency band showed overall reliable coherence (see paragraph 3.2.4); therefore, subsequent analyses were focused only on this band. For each subject, the circular mean of the phase angles along the whole track was computed (see Zar, 1999 for the circular mean formula). To evaluate the variability of phase angle, we estimated the concentration parameter (*kappa*) of the Von Mises distribution (Mardia and Jupp, 2000) of phase angles along the entire track for each subject. Larger *kappa* values describe a distribution with a stronger concentration around the mean angle and therefore lower variability. The Matlab tools for analysis and the Montecarlo simulation provided by Grinsted (the functions *xwt*, *wtc*, *anglemean*; Grinsted et al., 2004; The MathWorks, Inc.) were used for these analyses.

- Questionnaires

Apart from overt movements, we deliberately did not constrain the MP subjects' strategies to allow the emergence of potential relationships between the individuals' choices and MP outcomes (see Bernardi et al., in press, for a discussion of the limitations of constrained MP). Using a structured questionnaire, we sought to describe the use of different imagery modalities during the practice session. At the end of each 7-minute practice block, all 16 subjects were asked to report the mental strategies they may have

been using on the *Seven Minutes Questionnaire* (SMQ). The subjects were asked to use a Likert scale from 1 (*never*) to 7 (*continuously*) to describe how often they used the following strategies: “Mentally hearing the sound of notes”; “Mentally feeling the movement of fingers/hands”; “Mentally visualizing the movements of fingers/hands”; “Mentally visualizing the score”; “Harmonic analysis of the piece”; “Rhythmical analysis of the piece”; and “Melodic analysis of the piece”. This test was validated in a previous study (Bernardi et al., in press), and every item proved to have an adequate level of clarity and relevance.

In addition to determining the imagery that the participants used during the experiment, we sought to assess pre-existing individual differences in mental imagery. These were evaluated after the last performance using the following standardized questionnaires: a) the *USOIMM77* questionnaire, which assesses the spontaneous occurrence of mental visualization in thinking (Antonietti and Colombo, 1996; the short version was used for this experiment); b) the *Motor Imagery Questionnaire-Revised*, which was developed to examine both kinesthetic and visual movement imagery ability (MIQ-R, Hall and Martin, 1997); and c) the auditory subscale of the *Questionnaire of Mental Imagery*, which provides self-reported ratings of the vividness of auditory imagery (QMI-Auditory, Olivetti Belardinelli et al., 2009). Additionally, we employed a non-self-report *Auditory Imagery Test* (AIT). The test is based on the task described by Highben and Palmer (2004) to investigate auditory imagery in mental practice research. The participants were shown the score of a single-line melody (9 to 12 pitches) and simultaneously heard a melody that was either the same as the notated melody or differed by one pitch. The stimuli were adjusted by making the one-note difference a difference of 1 to 2 semitones; the total number of changes that moved up or down in pitch were balanced. Twelve of the sixteen melodies presented had a one-note difference. The sixteen melodies were played via loudspeakers, and the subjects were asked to identify any pitch differences between the melodies presented over the loudspeaker and the ones presented on the scores. This test was validated in a previous study (Bernardi et al., in press) and showed satisfying internal consistency (Cronbach’s $\alpha = .77$).

• **Statistical analyses**

Statistical analyses were conducted using SPSS 15.0. Repeated measures analyses of variance (ANOVA) with Time as a three-level within-subject factor (T0, T1, T2) and Practice as a two-level between-subjects factor (MP, PP) were conducted to assess changes in performance and movement kinematics. Movement variability was assessed using ANOVA based on the standard deviation values of the velocity kinematic records. Post-hoc tests were computed using Sidak correction for multiple comparisons. Partial eta-squared (η^2_p) was assumed as a measure of effect size. Pearson's correlation coefficient (2-tailed) was employed to evaluate associations between changes in performance or kinematic parameters and the MP strategies used or the individual features from preliminary tests or questionnaires.

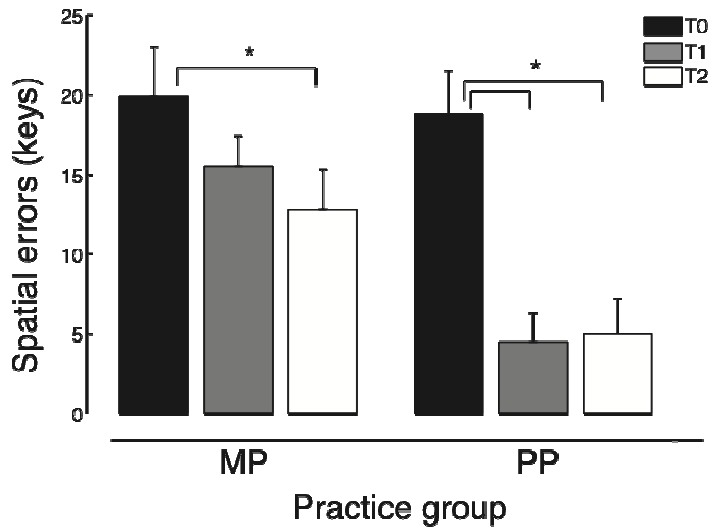
3.3 Results

The MP and PP groups were homogeneous with respect to age and total lifetime practice time (independent t-test: both $p > .05$). All performance and kinematic parameters were tested for between-groups differences in the baseline, and an acceptable homogeneity of the MP and PP groups was confirmed (independent t-test: all $p > .05$). All variables showed normal distribution, as confirmed by the Kolmogorov-Smirnov test (all $p > .05$).

• **Accuracy**

An ANOVA of spatial errors showed a main effect of Time ($F_{(2,15)} = 23.96$, $p < .001$, $\eta^2_p = .63$, power = 1) and a significant Time x Practice interaction ($F_{(2,15)} = 4.62$, $p = .018$, $\eta^2_p = .25$, power = .73). Post-hoc tests revealed that 14 minutes of MP produced a significant reduction in spatial errors (Fig. 3.3) compared to the baseline ($p = .047$). A significant improvement compared to the baseline was detected for PP at T1 ($p = .001$) and again at T2 ($p < .001$). PP resulted in fewer spatial errors compared to MP at both T1 ($p = .001$) and T2 ($p = .034$). Timing errors did not show any significant difference with respect to Time or Time x Practice interactions ($p > .05$).

Figure 3.3. Spatial errors



MP = Mental practice. PP = Physical practice. Both MP and PP significantly improved spatial accuracy. PP was effective after the first practice block and resulted in significantly better performance.

- Movement kinematics

A summary of the kinematic data is reported in Table 3.1.

Table 3.1.
Performance and Kinematic Parameters

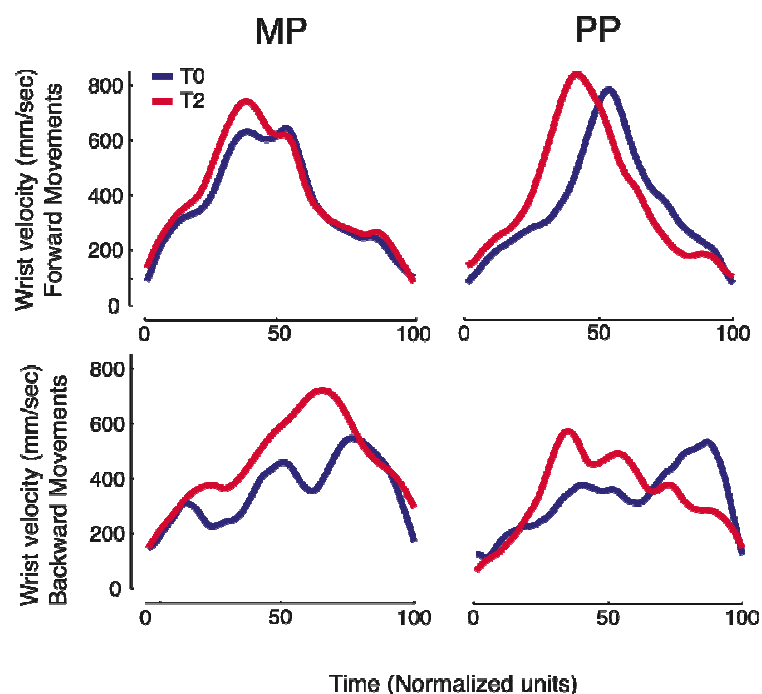
	MP			PP		
	T0	T1	T2	T0	T1	T2
Time WPVel Frw (msec)*	259 ± 20	256 ± 16	229 ± 17	258 ± 18	224 ± 8	218 ± 8
Time WPVel Bck (msec)*	312 ± 45	244 ± 36	229 ± 34	268 ± 53	208 ± 28	183 ± 13
WPVel Frw (mm/sec)*	725 ± 38	762 ± 39	773 ± 34	771 ± 34	831 ± 23	863 ± 28
WPVel Bck (mm/sec)*	614 ± 34	680 ± 41	713 ± 38	683 ± 39	675 ± 38	670 ± 39
FOpenPVel Frw (mm/sec)	998 ± 44	1118 ± 68	1001 ± 69	1170 ± 88	1340 ± 84	1363 ± 82
FOpenPVel Bck (mm/sec)	801 ± 75	775 ± 70	765 ± 63	770 ± 54	849 ± 66	891 ± 63
Time WPVel Frw (SD), (msec)	58 ± 12	56 ± 9	56 ± 11	52 ± 13	24 ± 3	21 ± 5
Time WPVel Bck (SD), (msec)	86 ± 29	53 ± 14	40 ± 11	28 ± 12	34 ± 11	23 ± 5
WPVel Frw (SD), (mm/sec)	69 ± 9	92 ± 6	102 ± 13	76 ± 10	60 ± 6	49 ± 8
WPVel Bck (SD), (mm/sec)	94 ± 11	77 ± 15	91 ± 17	77 ± 9	38 ± 4	37 ± 5
FOpenPVel Frw (SD), (mm/sec)	192 ± 30	164 ± 26	214 ± 39	213 ± 49	139 ± 32	122 ± 14
FOpenPVel Bck (SD), (mm/sec)*	149 ± 28	125 ± 18	130 ± 14	178 ± 30	89 ± 12	78 ± 6
Wrist-fingers phase (°)*	100 ± 5	109 ± 4	108 ± 4	96 ± 5	106 ± 4	108 ± 3
Phase angle concentration	10 ± 6	9 ± 7	13 ± 16	18 ± 16	80 ± 54	126 ± 106

Data are reported as means ± standard error. MP = mental practice; PP = physical practice. T0 = baseline performance; T1 = performance following 7 minutes of practice; T2 = performance following 14 minutes of practice; Frw = forward movements; Bck = backward movements; WPVel = wrist peak velocity; FOpenPVel = peak velocity of finger opening; SD = standard deviation. Asterisks denote parameters for which significant changes ($p < .05$) were observed in the MP group between T0 and T2.

- Movement kinematics: timing

Examples of wrist velocity profiles are shown in Fig. 3.4. An ANOVA of the time to wrist peak velocity for the Frw movements showed a main effect of Time ($F_{(2,15)} = 13.15$, $p < .001$, $\eta^2_p = .48$, power = .99) and no significant Time x Practice interaction. The time to wrist peak velocity for the Frw movements decreased between T0 and T2 ($p = .001$) and between T1 and T2 ($p = .008$) with no significant differences between the two practice groups. An ANOVA of the time to wrist peak velocity for the Bck movements showed a main effect of Time ($F_{(2,15)} = 9.53$, $p = .001$, $\eta^2_p = .41$, power = .97) and no significant Time x Practice interaction. The time to wrist peak velocity for Bck movements decreased between T0 and T1 ($p = .009$) and between T0 and T2 ($p = .022$) with no significant differences between the two practice groups. No significant effects were detected in the time to peak velocity of finger opening for either the Frw or the Bck movements.

Figure 3.4. Wrist velocity profiles



Wrist velocity profiles from four representative subjects are shown. For visualization purposes, the time dimension was normalized to 100 units. For each subject, each depicted profile is the average of all seven movements in the baseline (T0) and after 14 minutes of practice (T2). It can be observed that at T2 the wrist peak velocity occurs earlier, showing movement anticipation. This can be seen for both the MP and the PP group. Moreover, the peak velocity of wrist movements increases compared to the baseline.

- Movement kinematics: velocity

An ANOVA of wrist peak velocity for the Frw movements showed a main effect of Time ($F_{(2,15)} = 13.41$, $p < .001$, $\eta^2_p = .49$, power = .99) and no significant Time x Practice interaction. The wrist peak velocity of Frw movements increased from T0 to T1 ($p = .038$) and from T0 to T2 ($p = .001$) regardless of whether mental or physical practice was used. No differences were found between the MP and PP groups at either T1 or T2 ($p > .05$). An ANOVA of wrist peak velocity for the Bck movements showed a main effect of Time ($F_{(2,15)} = 3.72$, $p = .037$, $\eta^2_p = .21$, power = .63) and a significant Time x Practice interaction ($F_{(2,15)} = 6.32$, $p = .005$, $h^2_p = .31$, power = .86). Post-hoc tests revealed that only MP increased wrist peak velocity, both from T0 to T1 ($p = .046$) and from T0 to T2 ($p = .003$); no significant changes were observed for the PP group. No differences were found between the MP and PP groups at either T1 or T2 ($p > .05$). An ANOVA of the velocity of finger opening for the Frw movements showed a main effect of Time ($F_{(2,15)} = 7.71$, $p = .002$, $\eta^2_p = .36$, power = .92) and a significant Time x Practice interaction ($F_{(2,15)} = 3.35$, $p = .05$, $\eta^2_p = .19$, power = .59). Post-hoc tests revealed that only PP increased finger opening velocity from T0 to T1 ($p = .013$) and from T0 to T2 ($p = .017$). A difference between the PP and MP groups was found at T2, with PP subjects showing a higher peak velocity ($p = .005$). No significant effect of Time or Time x Practice interaction were detected for the velocity of finger opening for Bck movements.

- Movement kinematics: timing variability

An ANOVA of the variability of time to wrist peak velocity for Frw movements revealed a main effect of Time ($F_{(2,15)} = 4.52$, $p = .02$, $\eta^2_p = .24$, power = .72) and a significant Time x Practice interaction ($F_{(2,15)} = 3.52$, $p = .04$, $h^2_p = .2$, power = .61). A decrease in the variability of wrist timing was observed between T0 and T2 ($p = .016$). However, post-hoc tests on the interaction revealed that this effect was present only in the PP group (T0 vs. T2: $p = .002$); no changes were present in the MP group ($p > .05$). Moreover, the wrist timing of the PP group was significantly less variable than that of the MP group at both T1 ($p = .008$) and T2 ($p = .013$). No effects were detected in the variability of wrist

movement timing for the Bck phase. No effects were observed in the variability of time to peak velocity of finger opening for either the Frw or Bck movements.

- Movement kinematics: velocity variability

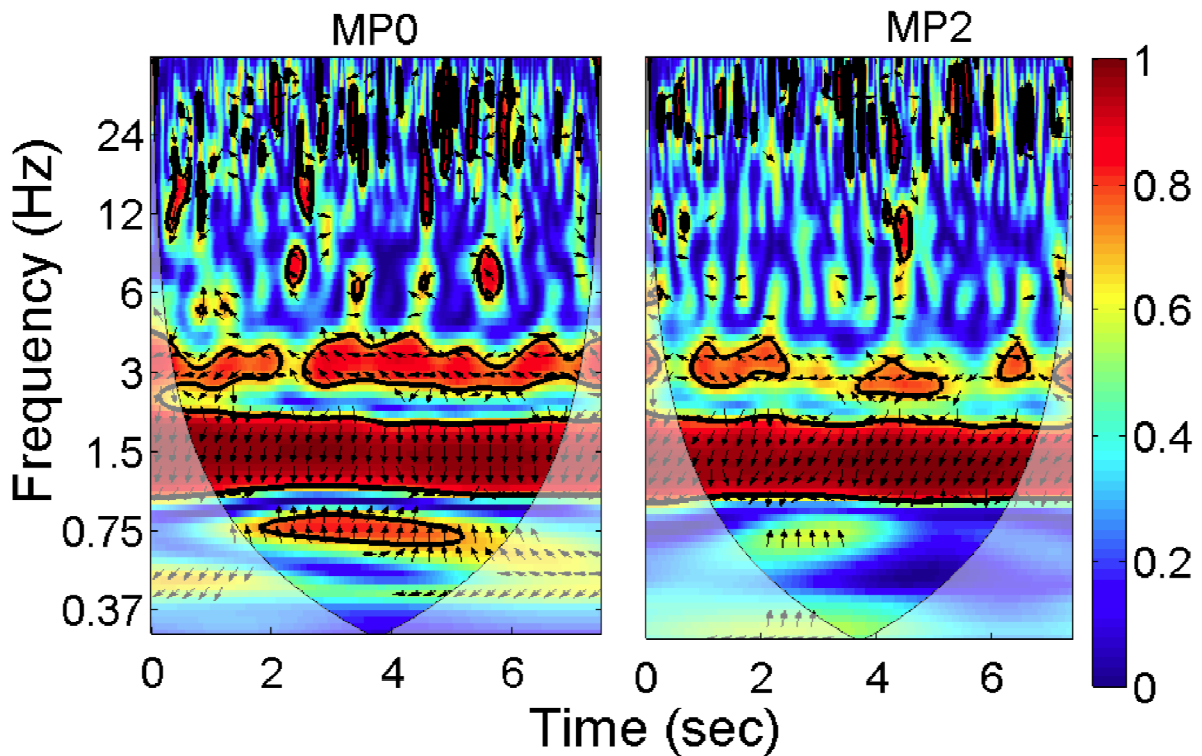
An ANOVA of the variability of wrist peak velocity for Frw movements revealed a significant main effect of Practice ($F_{(2,15)} = 8.83$, $p = .01$, $\eta^2_p = .39$, power = .79). Post-hoc tests showed that the PP group was significantly less variable than the MP group was at both T1 ($p = .003$) and T2 ($p = .004$). The variability of wrist peak velocity for Bck movements showed a significant main effect of Time ($F_{(2,15)} = 8.48$, $p = .001$, $\eta^2_p = .38$, power = .95) and no Time X Practice interaction; however, reliable differences could be found only between T0 and T1 ($p = .004$). The change between T0 and T2 was only marginally significant ($p = .062$), likely because of the high variability in the MP group. An ANOVA of the variability of the peak velocity of finger opening for Frw movements revealed a significant Time x Practice interaction ($F_{(2,15)} = 4.04$, $p = .029$, $\eta^2_p = .22$, power = .67). Post-hoc tests showed that the PP subjects' variability decreased from T0 to T1 ($p = .04$) and from T0 to T2 ($p = .034$). Moreover, the PP subjects were significantly less variable than the MP group were at T2 ($p = .044$). An ANOVA of the variability of the peak velocity of finger opening for Bck movements revealed a main effect of Time ($F_{(2,15)} = 6.6$, $p = .004$, $\eta^2_p = .32$, power = .88). This variability decreased from T0 to T2 ($p = .043$), and there were no significant differences between the two practice groups.

- Movement kinematics: Coarticulation

Coherence analysis was performed on the entire movement recording. Testing the reliability of the coherence between the wrist and finger velocity profiles revealed a consistent statistical significance for the frequency of 1.53 Hz (Fig. 3.5). At this frequency, the coherence was significant ($p < .05$) at every single time point in 89% of the recordings (43/48). The five exceptions were two MP0, two MP1 and one MP2 recordings. Significant coherence at 1.53 Hz in these five files was maintained for 31.4% and 87.5% of the timeline in the two MP0 files, for 85.04% and 85.6% in the two MP1 files and for 80.9% in the MP2 file. The frequency of 1.53 Hz describes events happening

approximately every 650 msec. Interestingly, this value is close to the prescribed periodicity of the Frw and Bck phases. In fact, both the Frw and Bck phases consist of three notes, each with a prescribed duration of 178 msec, so that $178 \text{ msec} * 3 = 534 \text{ msec}$.

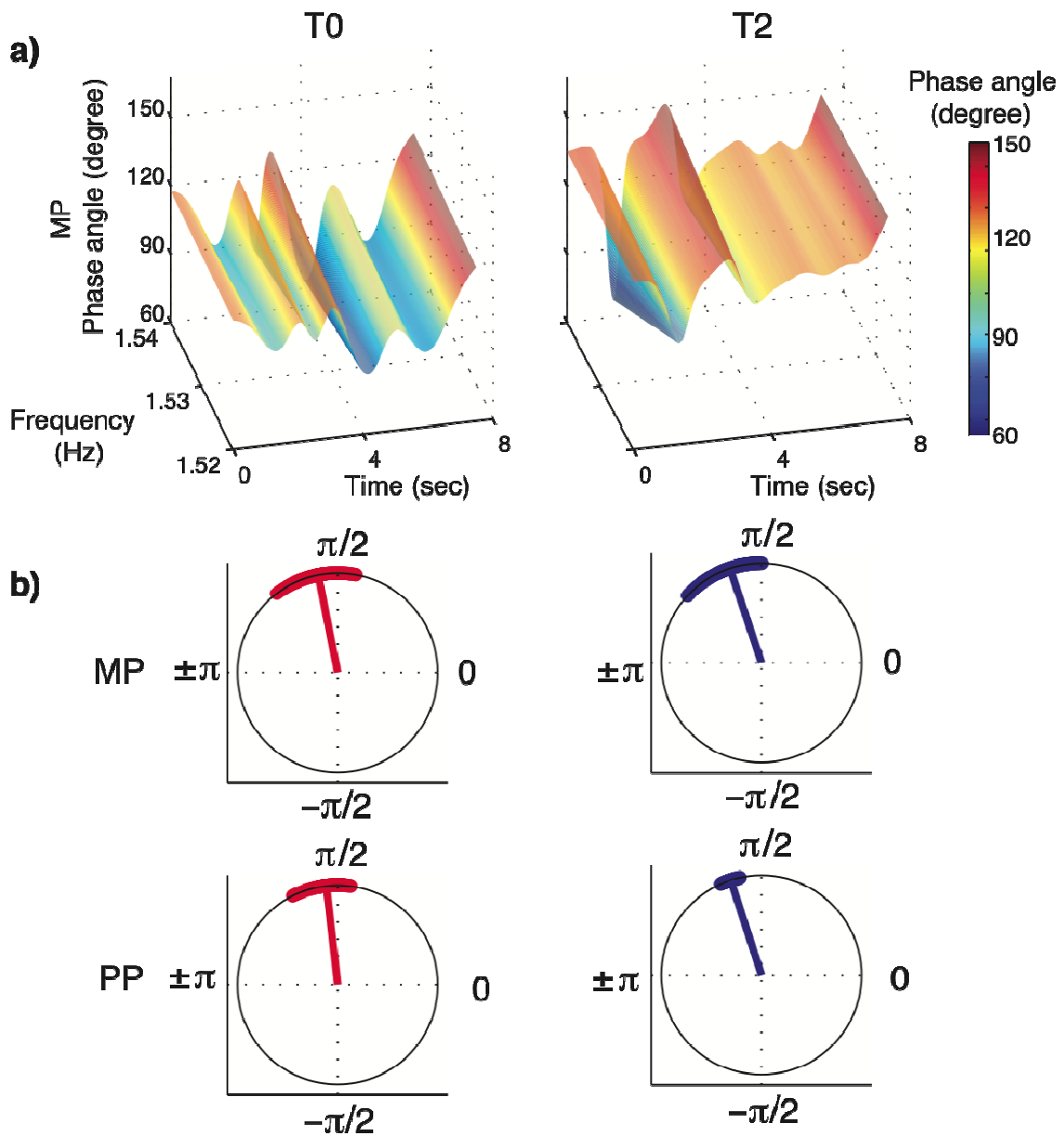
Figure 3.5. Coherence between the wrist and finger velocity



Example of the coherence between the wrist and finger velocity profiles for a representative subject. The 5% significance level against red noise is shown as a thick black contour. The relative phase relationship is shown as arrows, with in-phase arrows pointing right and anti-phase arrows pointing left. The cone of influence, where edge effects might distort the picture, is shown as a lighter shade. A strip of significant coherence can be noted around 1.5 Hz. From MP0 to MP2, that strip becomes better defined, and the phase relationship tends to shift toward a stronger anti-phase (that is, more arrows pointing leftward; see also Fig. 3.6).

An ANOVA of the phase angle between the wrist and finger velocity profiles at 1.53 Hz, averaged across the whole performance, revealed a main effect of Time ($F_{(2,15)} = 11.88$, $p < .001$, $\eta^2_p = .46$, power = .99). For both the MP and the PP groups, the phase angle increased from T0 to T1 ($p = .006$) and from T0 to T2 ($p = .003$; see Fig. 3.6a for an example from an individual MP subject). This means that with practice, the wrist and finger velocity profiles moved toward a stronger anti-phase pattern of reciprocal coordination. No differences were found between the two groups at any time point. Similar results were found when the phase angles were averaged separately for the Frw and the Bck movements. Instead, an ANOVA of the variability of phase angle revealed a main effect of Time ($F_{(2,15)} = 5.62$, $p = .009$, $\eta^2_p = .29$, power = .82) and a Time X Practice interaction ($F_{(2,15)} = 5.1$, $p = .013$, $\eta^2_p = .27$, power = .78). The phase angle variability significantly decreased (that is, the concentration increased) from T0 to T1 ($p = .016$) and from T0 to T2 ($p = .044$). However, a significant decrease in variability with time was observed for the PP group only (for PP, T0 vs. T1: $p = .001$; T0 vs. T2: $p = .006$; for MP, all $p > .05$). Despite the two groups' similar variability at T0 ($p > .05$), the PP group showed lower variability than the MP group did at both T1 ($p = .003$) and at T2 ($p = .01$). Fig. 3.6b shows the phase angle distributions averaged separately for the two groups.

Figure 3.6. Phase relationship between the wrist and finger velocity profiles



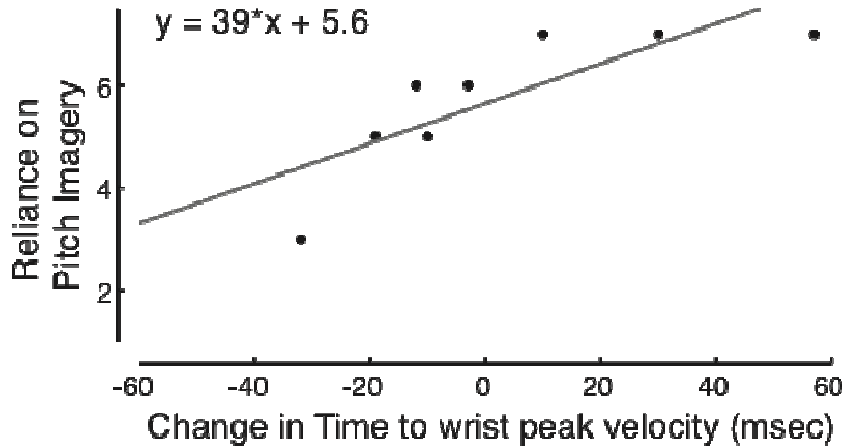
6a. The phase angle between the wrist and finger velocity profiles is displayed in the time/frequency space for one representative subject. From MP0 to MP2, the phase angle increases toward more anti-phase values, describing a coordination pattern in which peak velocity is achieved by one effector while the other is preparing the successive movement.

6b. Circular plot of phase angles between the wrist and finger velocity profiles, averaged separately for the MP and PP groups, at T0 and T2. The dots along the circumference represent the distribution of phase angles during performance averaged across all subjects at each time point (for the purpose of this plot, the times have been normalized to 1000 points). The radius represents the circular mean of these angles. For both MP and PP, the phase angle increases from T0 to T2. However, only after PP does the distribution of phase angle become narrower, implying greater consistency of the phase angle during performance. Circular plots were created using the scripts provided by Berens (2009).

- Strategies and outcomes

One of the goals of the present investigation was to reveal potential associations between mental practice strategies and practice outcomes in the mental practice group. The preliminary questionnaire administered in the first training session revealed the participants' long-term developed habits of musical mental practice. Information about the practice strategies that were actually applied during the experiment was derived from the two SMQ questionnaires. Because our aim was to investigate relationships between the questionnaire's scores and the effectiveness of practice, correlations were not based on the raw performance or kinematic data. Instead, for each performance and kinematic parameter that showed significant improvement, we computed differential scores that expressed the *change* in the values a) in the early phase of practice, from T0 to T1 (Diff1 = MP1- MP0) and b) across the whole practice session, from T0 to T2 (Diff2 = MP2 – MP0). Regarding the early phase of practice, significant correlations were found for motor imagery and auditory imagery. Subjects who were more familiar with motor imagery exhibited a greater enhancement of wrist peak velocity, as shown by the correlation between the Diff1 scores for wrist peak velocity and the habit of relying on motor imagery, as reported in the preliminary questionnaire (Pearson's correlation coefficient, 2-tailed: $r = -.73$, $p = .043$). The correlation between Diff1 scores for wrist peak velocity and the actual use of motor imagery, as reported in the first SMQ, was marginally significant ($r = -.69$, $p = .058$). Regarding pitch imagery, the use of this strategy during MP was connected to successful movement anticipation (Fig. 3.7): Diff1 scores for the time to wrist peak velocity, for Frw movements, were significantly correlated with self-reports of pitch imagery use from the first SMQ ($r = .81$, $p = .015$).

Figure 3.7. Auditory imagery and movement anticipation



In the MP group, the development of movement anticipation from MP0 to MP1 (measured as the difference in time to wrist peak velocity) is related to the use of auditory imagery (pitch imagery). The more the subjects reported having used auditory imagery, the more they showed anticipation of wrist peak velocity.

When the practice session was considered as a whole, two other associations could be detected. A decrease in the number of wrong notes was associated with the habit of relying on external auditory models (e.g., recordings of experts' performances), as reported in the preliminary questionnaire. Subjects with a more established auditory modeling habit achieved greater spatial accuracy improvement after 14 minutes of MP ($r = -.725$, $p = .042$). In comparison, subjects who more frequently engaged in harmonic analysis of the piece throughout the MP session (SMQ1 + SMQ2 scores for Harmonic analysis) showed smaller increases in wrist peak velocity ($r = .78$, $p = .023$). No associations were observed between practice outcomes and individual differences in the use of different imagery formats, as reported in the USOIMM77, MIQ-R, QMI-Auditory and the AIT.

- Control experiment

The data present above showed an effect of MP on movement accuracy and kinematics. However, it cannot be excluded that these effects were solely due to the fact that at T1

and T2 pianists were performing the task for the second and third time. We therefore studied an additional group of pianists ($n = 8$; 1 female; age = 32 ± 9 years; total lifetime practice = $17,020 \pm 11016$ hours) to serve as a control group (group C). These subjects received the same training in mental practice as described in paragraph 2.2. However, on the day of testing, after having first-sight played the exercise (C0) they were not allowed to practice the piece. Instead, they were engaged in filling the same questionnaires about mental imagery (USOIMM77, MIQ-R, QMI-Auditory) that were administered to the other subjects after the last performance. After 7 minutes C subjects performed the piece again (C1), in the same conditions as in the baseline. Following this performance, C subjects continued filling the questionnaires for 7 more minutes, followed by the last performance (C2). Thus, C subjects had a total of 14 minutes of questionnaires completion, intermingled by one performance. The mental operations required from these subjects in order to fill in the questionnaires were in general very similar to those used during MP (e.g., motor, auditory, visual imagery), but for C subjects these operations were not focused on practicing the piece. Repeated measures analyses of variance (ANOVA) with time as a three-level within-subject factor (T0, T1, T2) were conducted to assess changes in performance and movement kinematics in the C group.

Significant changes were found for the variability of wrist timing in the backward movement ($F_{(1,7)} = 8.78$, $p = .003$, $\eta^2_p = .56$, power = .93) and for the velocity of finger opening in the forward movement ($F_{(1,7)} = 4.31$, $p = .035$, $\eta^2_p = .38$, power = .65). Post-hoc tests showed that the variability of wrist timing in the backward movement decreased from T0 (95 ± 36 msec) to T1 (36 ± 20 msec; $p = .002$). However, no differences were found between T0 and T2 (65 ± 50 msec, $p = .4$) or between T1 and T2 ($p = .13$). Regarding the velocity of finger opening in the forward movement, post-hoc tests showed an increase from T0 (1044 ± 271 mm/sec) to T1 (1178 ± 303 mm/sec; $p = .009$). However, no differences were found between T0 and T2 (1198 ± 425 mm/sec, $p = .16$) or between T1 and T2 ($p = .99$). No significant differences were found in any other kinematic or accuracy measure.

3.4 Discussion

The present investigation yielded two main novel results. First, mental practice produced significant improvements in performance on a highly skilled task, implying fine motor control modulation. Second, MP increased single movement velocity and, more importantly, induced movement anticipation. Additionally, we documented associations between specific components of MP (motor imagery, auditory imagery) and changes in different aspects of motor control (speed, anticipation).

- Mechanisms of MP

Recent models of motor sequence learning emphasize the existence of two main processes subserved by partially distinct brain networks (Ghilardi et al., 2009; Hikosaka et al., 2002; Penhune and Steele, 2012). The first process pertains to the motor optimization of the single elements of the sequence. This process is believed to rely mostly on implicit learning, and its implementation is indicated by increases in movement velocity and stability. The second process concerns the strengthening of element sequencing and the binding of each single movement into a smooth continuum. This process is believed to involve greater amount of resources from explicit memory, and its implementation is indicated by the emergence of coarticulation and movement anticipation.

Within this schema, the present study provides new understanding of the role of MP in sequential motor skill learning. First, our results have shown that MP effectively optimizes motor performance at a single-element level. The peak velocity of skilled piano movements increased relative to the baseline, despite the fact that no movements were allowed during the practice period. This result is consistent with those previously reported for such tasks as arm pointing (Gentili et al., 2010) or circle drawing (Yaguez and Nagel, 1998). Current theories of motor control explain these effects as consequences of the estimations derived from the internal model: the use of the forward internal models would allow the prediction of the future sensorimotor state of the limb based on both its current state and the efferent copy of the motor command (Gentili et al., 2006). To the degree that this estimate is accurate, training through the forward model alone can refine future actual motor commands and lead to effective plastic neural changes (Desmurget

and Grafton, 2000; Pascual-Leone et al., 1995). The absence of sensory feedback, however, should leave a greater margin for variability, a result that has been previously observed (Courtine et al., 2004; Papaxanthis et al., 2002) and that we have further confirmed in the present work.

The present study extends these concepts and shows that MP can also effectively improve the sequencing aspect of a complex motor task. First, this is evident from the fact that MP improved piano performance proficiency. This result is in line with previous findings (van Meer and Theunissen, 2009) and provides converging evidence using a new task of unparalleled motor complexity. It is known that a declarative component is involved in most sequence-ordering tasks, and this component has been shown to greatly benefit from MP. In fact, with MP, the mental representation of the sequence can be rehearsed repeatedly and therefore strengthened (Jeffrey, 1976). Second, and more importantly, the present investigation provides the first description of the occurrence of anticipation and coarticulation in motor performance after MP. This result suggests that MP's role in element sequencing likely extends beyond the correct memorization of the events' order. As Penhune and Steele (2012, pp. 2) previously noted, in the context of highly skilled motor sequences, 'the fundamental problem for the motor learning system is not simply acquiring the order of movements, but optimizing the entire sequence for successful performance'. This is also likely to be true for our task in which the sequence itself is of rapid comprehension (i.e., it is a simple pattern of octaves identically transposed on neighboring keys). We believe that the motor anticipation and coarticulation we have documented here reflect an element-chunking process in which the submovements required to produce a number of the sequence's elements are bound together and coordinated in a optimized fashion (Graybiel, 1998; Miller, 1956; Palmer and Pfordresher, 2003). Such a process is likely to share resources with the conscious representation of the sequence order; however, its consequences extend to the domain of implicit motor implementation. MP thus seems to play a special role in the interface between the declarative/explicit and the motoric/implicit components of a skilled motor task. This is in line with previous authors' view that conceptualized MP as an "explicit access" to the otherwise subconscious learning processes involved in the task (Jackson et al., 2001, 2003). The information about motor-skill learning derived from neuroimaging

studies also supports this view. The model proposed by Hikosaka and colleagues (2002) makes a distinction between the explicit/spatial component and the implicit/motor component of a given sequential motor task. The brain areas that play a major role in the first component are the prefrontal and parietal cortices and the basal ganglia and cerebellum, within their associative circuits (Destrebecqz et al., 2005; Ghilardi et al., 2000). In comparison, the implicit/motor component also appears to rely mainly on the primary motor cortex, the basal ganglia and the cerebellum, but on their motor circuits rather than their associative ones (Karni et al., 1998; Muellbacher et al., 2002). Between these two stages, an interface is provided by the supplementary motor area and premotor cortex, which are known to be particularly active during motor planning (Passingham, 1993) and transitions between movements (Shima and Tanji, 2000). Crucially, these are the same brain areas that appear to be systematically activated during motor imagery, along with the prefrontal and cingulate areas (Decety and Michel, 1989; Deiber et al., 1998; Jeannerod and Decety, 1995). This location within the motor system would allow MP to influence both the declarative and the motoric component of a sequential motor task, although MP's declarative influence might be greater. Additionally, MP could also improve motor phenomena at the boundary between explicit sequencing and motor optimization, such as coarticulation and anticipation. The present investigation has provided the first behavioral evidence supporting this hypothesis.

A bias in the interpretation of the outcome of MP could be introduced by the fact that subjects performed the task three times during our experiment. This mere repetition could have alone allowed performance improvements, regardless of the practice content. However, the data from the control group we provided suggest that this is not the case. Subjects that did not engage any practice did not show any improvement in accuracy. In these subjects, changes in movement kinematics appeared to be unstable, being found at the first repetition, but not in the second. Crucially, none of these changes were related to movement anticipation and coarticulation.

- Mental practice strategies

It is known that several imagery modalities and mental strategies can be employed in MP (Roeckelein, 2004). The dominant focus of past research has been motor imagery, which

is reasonable considering that the desired output of practice is in most cases a motor response. However, it appears that the role of complementary sensory modalities has often been neglected; moreover, the view of motor imagery as an exclusive force and effort has been questioned by authors who propose that motor imagery might also include visual and/or spatial components (Callow and Hardy, 2004; Smyth and Waller, 1998). Music performance offers an example in which this issue is particularly evident, given the tight coupling between the motor, the auditory and even the visual representations of performance movements (Haslinger et al., 2005). Systematic investigations of the effectiveness of different mental practice patterns are scarce. In a recent study involving the memorization of a long sonata that was musically complex but motorically easy, Bernardi et al. (in press) found that optimal memorization was achieved by subjects who i) had a stronger habit of formal/structural analysis and ii) particularly engaged pitch imagery during MP. The present results offer a complementary picture. In a task involving the score-supported performance of a short music exercise with minimal musical content but high motor complexity, we found that i) motor imagery was associated with the optimization of the single-element component of performance (movement velocity); ii) formal/structural analysis appeared to have a detrimental effect on the same component; and iii) auditory imagery was associated with stronger element sequencing (movement anticipation). The first finding directly supports the idea that motor imagery might improve motor control through the efferent copy of the motor command, as previously discussed. This result is also in line with the finding that corticospinal facilitation during motor imagery is associated with ease of kinesthetic imagery in both expert athletes (Fourkas et al., 2008) and in the general population (Williams et al., 2012). The second finding underlies the specificity of the linkage between motor imagery and state estimation improvement: a generic understanding of the piece's structure at a conceptual level alone does not lead to increased movement velocity; furthermore, it might even have detrimental effects when, in a limited time-window, it takes resources away from the motor focus. Regarding the third finding, an association between auditory imagery and movement anticipation within a musical sequence has been described in several studies (Keller and Koch, 2006, 2008; Keller et al., 2010). Keller and Koch (2006, 2008) have argued that auditory imagery might enable

rapid and thorough action preplanning via an ideomotor-like mechanism in which actions are triggered and facilitated by the imaginary anticipation of their effects (Hommel et al., 2001; Knuf et al., 1987). The results presented here provide converging evidence for this idea, showing for the first time the emergence of movement anticipation as related to, and possibly as a result of, auditory imagery of the sequence during MP. When these and past results are considered together, auditory imagery emerges as the operational core of MP in the music domain, subserving both the construction of a structural/conceptual representation of the piece and the motor implementation of the precise movements. In this respect, it is interesting to notice how auditory cortical areas can in fact be recruited during auditory imagery, even in the absence of sound (Zatorre and Halpern, 2005). In addition, both the present study and the previous Bernardi et al. (*in press*) study showed how a general habit of auditory modeling (e.g., listening to expert performances as a way to improve one's own performance) tends to improve MP's effectiveness. The role of other strategies may vary depending on the specific task, with formal analysis and motor imagery being relevant for memorization and motor optimization, respectively.

- Practical implications

The present study provides implications for the applied use of MP. First, these results have a straightforward application to musicians' training and the management of health-risk factors. Overuse injuries are the leading cause of playing-related medical problems, and in some cases, such injuries can threaten or end a musician's career (Lockwood, 1989). Previous studies have described the effectiveness of MP in several aspects of music performance (Cahn, 2008; Coffman, 1990; Kopiez, 1990; Theiler and Lippman, 1995), and this study has gathered the first evidence that MP can also be effectively used to rehearse complex motor sequences in the music domain. Fine motor skills practice is crucial for musicians, and most of music students' time is devoted to such practice; therefore, it is potentially more connected to playing-related illnesses. Musicians' practice habits could therefore be enriched by combining their physical practice with mental practice, allowing performance improvements without any further cost to the body. Second, MP is increasingly being considered as a potential tool for motor rehabilitation in stroke patients (Jackson et al., 2001; Barclay-Goddard et al., 2011). With

respect to this application, this study suggests that fine motor skills, involving control of different effectors, could be addressed in the future. This study also suggests that the independent control and coordination/coarticulation of different effectors could be informative of the outcome of mental practice in movement rehabilitation, in addition to the more standard measures of, for example, velocity and force.

In conclusion, this study has shown how mental practice can improve fine motor control, both at a single-element level and in the binding of single elements. Future investigations should address how these processes are handled at the level of the neural bases and to what extent the effects described here are linked to partially distinct brain circuitries.

4. Mental practice in force-field learning: Evidence for somatosensory adaptation

[This study was conducted as a collaboration between the University of Milano-Bicocca (Milano, Italy) and the McGill University (Montreal, Canada). This chapter is partly based on a paper currently submitted to Journal of Neurophysiology].

4.1 Introduction

Observing others while they learn a motor task has been shown to engage the motor system and to result in reliable changes to motor learning. Here, we assess the possibility that the effects of observing motor learning are not solely confined to the motor system, but spread as well to somatosensory representations. We show that there are changes to sensed limb position following observational learning that are similar to those which occur following actual motor learning.

There have been a number of demonstrations that motor learning can occur even in the absence of overt physical practice, as is the case of when one observes motor learning. A series of studies (Mattar and Gribble, 2005; Brown et al., 2009) have shown that subjects who observed a video depicting another person learning to reach in a novel mechanical environment performed better when later tested in the same environment than subjects who observed similar movements that did not involve learning. Similarly, the observation of another individual performing repetitive thumb movements has been shown to alter both the movements and the motor potentials evoked from the stimulation of motor cortex (Stefan et al., 2005). Several studies have shown that similar brain networks are activated during the observation and execution of movement, and in particular, ventral premotor cortex and supplementary motor area, inferior parietal lobule and superior temporal sulcus (see Kilner, 2011 for review).

Several studies have also shown that motor learning is accompanied by adaptation in sensory systems. Learning tasks involving arm movements have been shown to change attributes of sensory function such as sensed limb position (Cressman and Henriques, 2009; Hait et al., 2008; Ostry et al., 2010) and perceptual acuity (Wong et al., 2011). At the neural level, a network has been identified, that is associated with the perceptual changes that occur in conjunction with motor learning. This comprises second somatosensory cortex, ventral premotor cortex and supplementary motor area (Vahdat et al., 2011).

Taken together, these observations raise the possibility that changes in sensory perception could be triggered not only by actual motor learning, but also by observing someone else engaged in a motor learning task. We tested this hypothesis by assessing somatosensory perception before and after a task that involved observation of motor learning. The test

involved two groups of subjects that watched a video depicting an actor learning to reach in a novel mechanical environment. The direction of the perturbation applied to the actor's arm was opposite for the two groups. We found that watching someone else learn not only affected the characteristics of motor learning but also was associated with changes in somatosensory perception. Moreover, depending on the direction of the force-field during the observed learning, the two groups showed changes in sensory perception in opposite directions. The perceptual changes observed here are in the same direction as those previously described following actual motor learning. We conclude that observational learning has effects that spread beyond motor circuits of the brain and contributes to plasticity in sensory systems.

4.2 Methods

- Subjects and experimental tasks

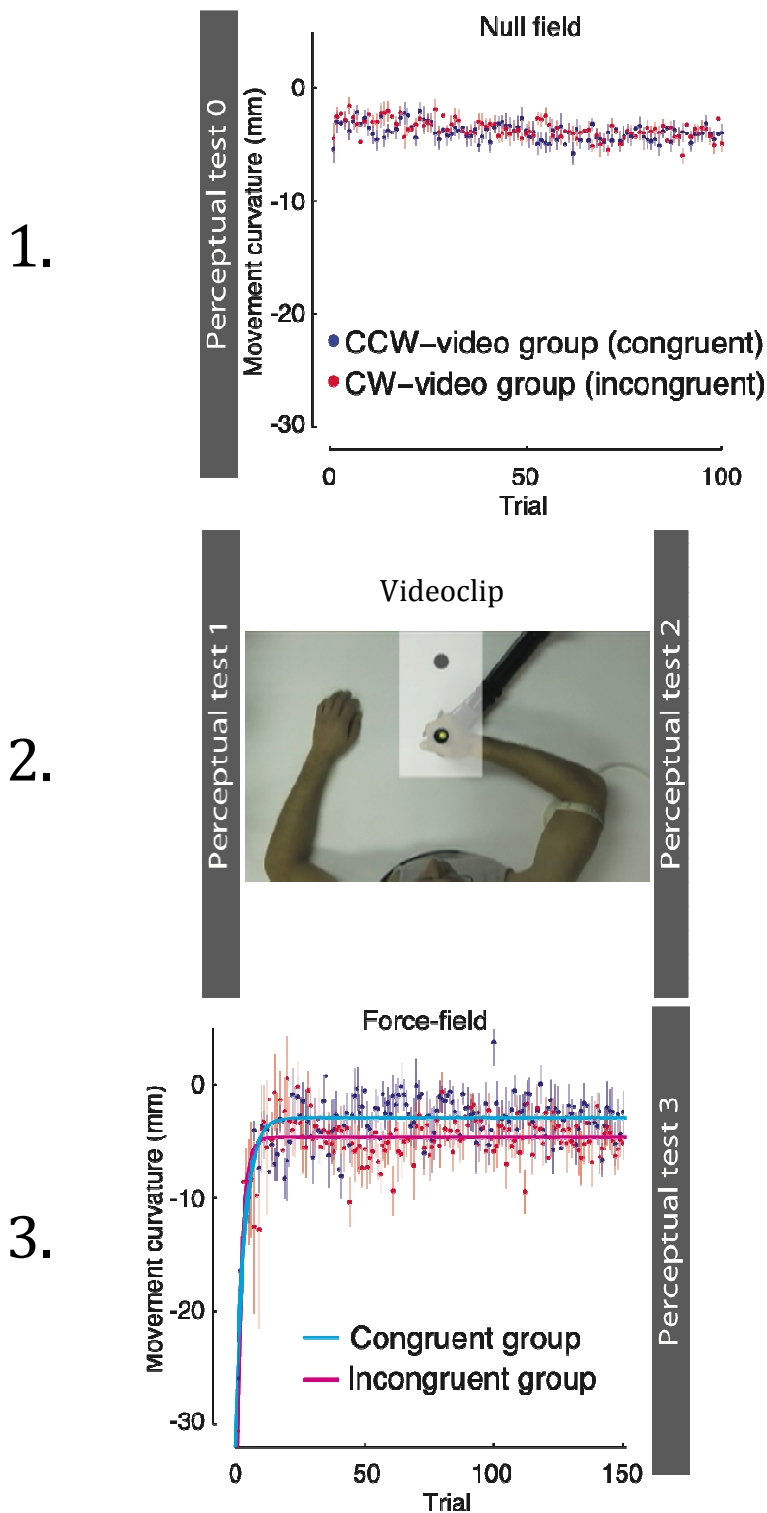
28 subjects of either sex were randomly assigned to two experimental conditions ($n = 14$ each; mean age \pm standard deviation: 20.2 ± 2.5). The conditions differed only in terms of the direction of the force-field observed in the video recording (see below). An additional group of 14 subjects (mean age \pm standard deviation: 21.4 ± 3.1) was recruited and assigned to a scrambled-video control condition (see below). The subjects were all right handed and reported no history of sensorimotor disorders. All procedures were approved by the McGill University Research Ethics Board.

Participants were tested for somatosensory perception at the beginning of the experimental session as well as at several points in the experimental sequence: following reaching movements in the absence of any mechanical load (null condition), following video observation and following force-field learning (Fig. 4.1).

Subjects were tested individually in a single session lasting 2 hours. In all tasks, subjects held the handle of a two degree-of-freedom planar robotic arm with their right hand (InMotion2, Interactive Motion Technologies). Subjects were seated and, in conditions involving movement, the arm movements occurred in a horizontal plane at shoulder height. Vision of the arm was blocked.

At first, subjects were familiarized with the perceptual test and the reaching task. Afterwards, the experiment began with a baseline estimate of sensed limb position. Subjects then performed 100 straight-out reaching movements during which the robot applied no force to the hand (null condition). Immediately following null-field training, a second baseline estimate of sensed limb position was obtained. Subjects were subsequently asked to watch a video recording of another individual performing reaching movements in a velocity-dependent force-field (see below). Following the video observation, another estimate of sensed limb position was taken. Finally, subjects made 150 movements straight-out from the body, in a velocity-dependent force-field, followed by a final estimate of sensed limb position. Subjects were naïve with regard to the purpose of the study, and they received no information about the force applied by the robot, in any stage of the experiment.

Figure 4.1 Experimental design and motor learning curves

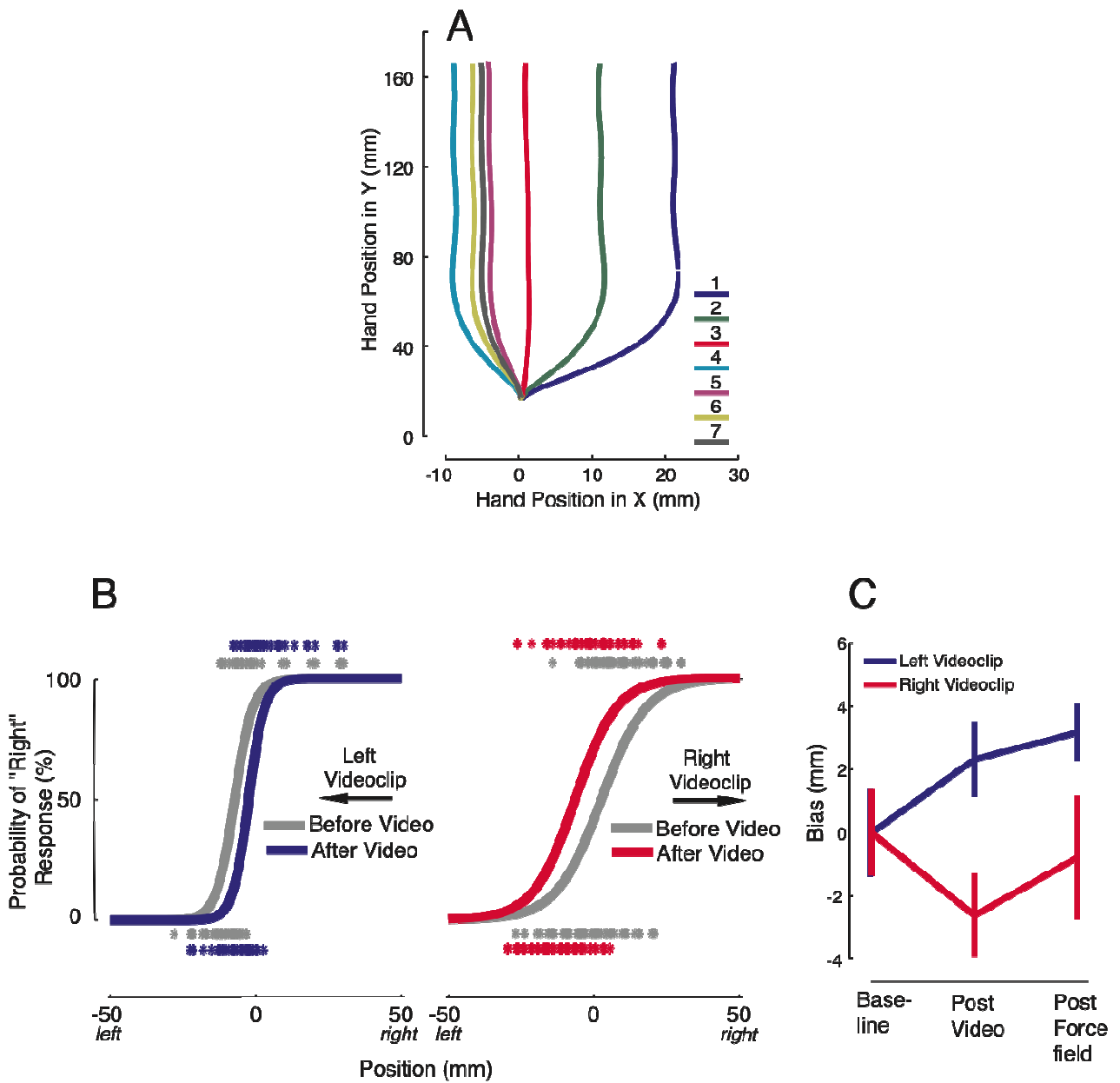


Sequence of procedures and experimental data showing changes in movement curvature (PDmaxv) during training averaged across subjects (\pm SE). Subjects that observed and practiced movements in a CCW field are in blue (congruent group). Subjects that observed a CW field and then trained with a counter-clockwise load are in red (incongruent group). The cyan and magenta lines show exponential fits to the data for the congruent and incongruent groups, respectively.

- Perceptual judgments

Subject's perception of the boundary between left and right was estimated using an adaptive procedure, as described previously (Ostry et al., 2010; Vahdat et al., 2011). The perceptual tests were conducted with the eyes closed. The robot was programmed to move the subjects' hand outward from a start position following a fork-shaped trajectory (Fig. 4.2a). Subjects were instructed not to resist the action of the robot. At the end of each movement, the subjects' hand was either to the left or the right of the midline, by an amount that was computed on a trial-by-trial basis. When the robot reached its final position, subjects were asked to indicate whether the hand had been moved to the left or to the right. On each trial, the magnitude of the lateral deviation of the hand was modified in an adaptive manner (Taylor and Creelman, 1967), until an estimate of the perceived boundary between left and right was obtained. Each block of perceptual tests involved 6 runs. Occasionally 4 runs were collected if the perceptual estimates converged slowly. This procedure yielded a corresponding number of estimates of the right-left boundary. On successive runs, the initial displacement direction alternated between left and right. To exclude the possibility of perceptual changes related to active motor outflow (force production) during the perceptual testing phase, we computed the average force applied to the channel walls during the critical, straight-out part of the trajectory of the first (and therefore largest) lateral deflection in each run.

Figure 4.2. Somatosensory testing and results



A, Representative hand paths during perceptual tests. The color code gives the trial number in the testing sequence.

B, Fitted psychometric functions for two representative subjects showing perceptual classification before (gray) and after (red or blue) observational force-field learning. As in previous studies of force-field learning with physical practice, following motor learning by observing the perceptual boundary shifts in a direction opposite to the observed-applied force.

C, Mean perceptual change (\pm SE) following observational motor learning and following actual motor learning, for observation of a CCW (blue) or CW (red) force-field. For visualization purposes, the two groups have been aligned at baseline.

- Reaching movements

In the dynamics-learning task, subjects made reaching movements to a single visual target. The start point was situated in the center of the workspace, ~ 25 cm from the subject's chest along the body midline. The target was located 15 cm directly in front of the start position in the sagittal plane. The start and target positions were represented by white circles, 20 mm in diameter. A yellow circle, 12mm in diameter, provided the subject with visual feedback on the hand's current position. Note that visual feedback was present during reaching movements and was not provided during the perceptual testing phase. Subjects were also asked to move as straight as possible. Visual feedback of movement duration was provided at the end of each reaching movement by a target color change. The feedback was used to help subjects achieve the desired movement duration, but no trials were removed from analysis if subjects failed to comply with the speed requirement. At the end of each trial, the robot returned the subject's hand to the start position. In the force-field-learning phase, the robot applied a counterclockwise load to the hand that primarily acted to deflect the limb to the left. The force was applied to the hand according to the following equation:

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = D \begin{bmatrix} 0 & 18 \\ -18 & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix}$$

where x and y are the lateral and sagittal directions, f_x and f_y are the commanded force to the robot in Newtons, v_x and v_y are hand velocities in Cartesian coordinates in meters per second, and D defines the direction of the force-field; For the counterclockwise (CCW) force-field, D is -1.

- Video recordings

Video recordings provided subjects with a screen-centered, top-down view of another individual's right arm and the workspace within which movements to the target were made. The recording depicted an individual moving to the target as the robot applied perturbing force to the arm. In the CCW video recording, the forces were the same as those later experienced by the observer (Congruent group); in the CW video recording,

the forces applied in the observational phase were opposite to those later experienced by the observer (Incongruent group). These recordings showed the progression from highly perturbed to straight movements typically associated with motor learning. Superimposed on the video image were images of the visual target and a cursor representing the position of the hand (Fig 4.1). Each recording was approximately 3 min in duration and demonstrated a series of 28 movements from the beginning of the force-field training sequence.

A third video was developed for the control experiment. This video comprised the 28 original movements from the CCW video that we utilized for the Congruent group, but in this case the movements were presented in random order. The order was further edited in order to minimize information potentially relevant to learning. Thus, high-error movements were not presented in the first three trials, repetitive sequences of low-error movements were not presented at the end and homogeneous blocks of high or low-error trials were avoided.

All video presentations were repeated 5 times. The subject's task was to observe attentively. No mention was made of the forces applied. To ensure that subjects paid attention to the video recordings, we asked them to monitor the depicted movements and report to the experimenter when movements made by the subject in the video were too fast or slow, as indicated by the targets changing color. We found that subjects were highly accurate (mean score > 90% correct), which provides support for the idea that adequate attention was given to the observational phase of the experiment. During observation, subjects were instructed to keep hold of the robot handle, which was positioned to correspond to the starting position of the actor on the screen.

- Data analysis

The data from all perceptual runs in each phase of the experiment were used to estimate the perceived boundary between left and right. The entire set of measured lateral deviations and associated binary responses were fitted on a per-subject basis with a logistic function that gave the probability of responding “the hand was deflected to the right” as a function of the lateral position of the hand. We used a least-squares error

criterion (glmfit in Matlab) to obtain the fit. The 50% point of the fitted function was taken as the perceptual boundary and used for purposes of statistical analysis.

We assessed motor learning by calculating the perpendicular deviation of the hand from a straight line connecting the start point and the target, at the movement peak velocity (PDmaxv). We assessed the change in PDmaxv over trials by fitting a single exponential function to the data averaged across subjects. The equation takes the form $P = c - ae^{-bn}$, where P is the PDmaxv on trial n . This function is well approximated in the discrete domain by $P(n) = c - a(1 - b)^n$, where b is the rate of learning and c is the asymptotic performance level. Separate fits were conducted for subjects that experienced force-fields congruent with their visual observation and those for which the force-field training was incongruent.

To further investigate potential effects of the video recording on motor performance, we also computed the perpendicular deviation of the hand from the same straight line in an early stage of the movement, 100 ms following movement onset (PD100). This particular variable was chosen for this test because it minimizes the likelihood of feedback based corrections in limb trajectory measures. For both PDmaxv and PD100, we quantified motor learning as the difference in movement curvature between the final 5 and the first 5 movements in the force-field condition. In addition to mean movement curvature, we evaluated the between-subjects variability of motor performance in the first part (10 movements) of the force-field learning task.

Changes in somatosensory perception were evaluated statistically using ANOVA. To compare motor learning in subjects that viewed CW versus CCW force-field learning videos we employed independent-samples t tests. Differences in the variability of motor performance were assessed by using Bartlett's test. The two groups showed similar baseline estimates of sensed limb position, and no differences were found in the two baselines, in either of the two groups ($p > 0.1$). The second baseline was therefore taken as the reference point for subsequent analyses.

4.3 Results

Fig. 4.2b shows estimates of sensed limb position obtained for the two video observation conditions. It is seen that there are shifts in sensed limb position that vary with the pattern

of force-field learning observed in the video. In both cases, there is a shift in the perceptual boundary in a direction opposite to the observed force. Thus, subjects that watched a video of adaptation to a rightward force-field showed a leftward shift in the perceptual boundary and vice versa. This same pattern of perceptual change is observed under actual force-field learning conditions. When subjects were subsequently required to train under actual force-field conditions, further perceptual change was observed. For subjects in which the force-field was congruent with the observed learning, we saw a further shift in the perceptual boundary, in the same direction as that obtained during observational learning. In contrast, when the learned force-field was incongruent with the observed learning, the subsequent perceptual shift was in the direction one would expect on the basis of the mechanical load (and resulted in the elimination of the previous perceptual change).

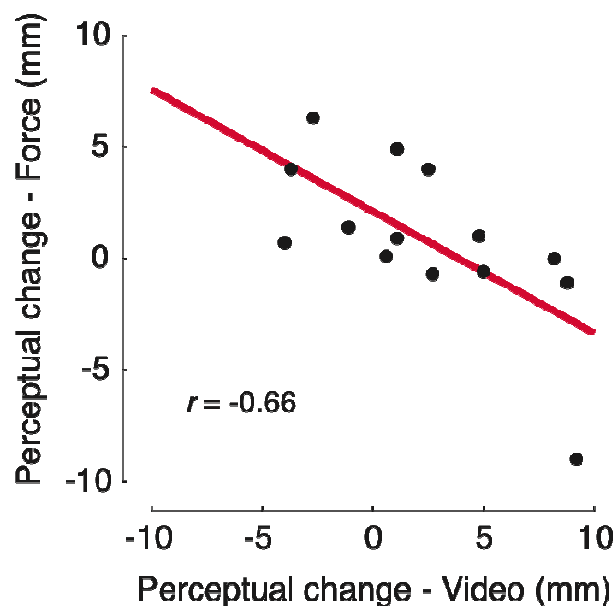
To test the hypotheses of the study, we designed statistical analyses that could assess the specific effect of each manipulation separately. ANOVA was therefore employed to assess perceptual change following video observation (Perceptual test 2 – 1) and following actual force-field learning (Perceptual test 3 – 2). ANOVA revealed that the pattern of perceptual changes differed for subjects in the congruent and incongruent experimental conditions ($F(1,27) = 5.75, p < 0.03$). Following video observation, sensed limb position was different for participants who watched the CW videoclip and those who watched the CCW videoclip (post-hoc comparison: $p < 0.01$). Watching opposite forces led to opposite changes in sensed limb position. The absolute change in sensed limb position due to video observation was reliably different than zero ($t(27) = 2.82, p < 0.01$).

The force-field learning followed video observation and had effects on sensed limb position that differed for the two video observation conditions. The group that watched a CW force in the videoclip and then experienced a force-field in the opposite, CCW direction, showed a significant difference in perceptual change scores (post-hoc comparison: $p < 0.02$). In particular, whereas the CW videoclip resulted in a leftward shift in the perceptual boundary, subsequent training in a CCW field served to create a perceptual change in the opposite direction. In contrast, for the group who first watched and then experienced a CCW force-field, both manipulations resulted in rightward shifts

in the perceptual boundary. The increased shift in the rightward direction shown in Fig. 2C (in blue) was not reliably different in magnitude than that which occurred due to visual observation alone ($p > 0.4$).

We assessed whether the change in sensed limb position following actual force-field learning was related to that experienced following video observation. For the group that observed and experienced forces that acted in the same direction (CCW), a highly significant inverse relationship was observed (Fig. 4.3). Subjects that experienced larger changes in sensed limb position following video observation had smaller subsequent changes following force-field learning ($r(13) = -0.66, p < 0.01$). Subjects that watched learning in one direction and then trained in an opposite force-field showed no reliable correlation in changes in sensed limb position due to the video and the actual force-field ($r(13) = 0.29, p > 0.3$).

Figure 4.3. Somatosensory changes following actual vs. observational force-field learning



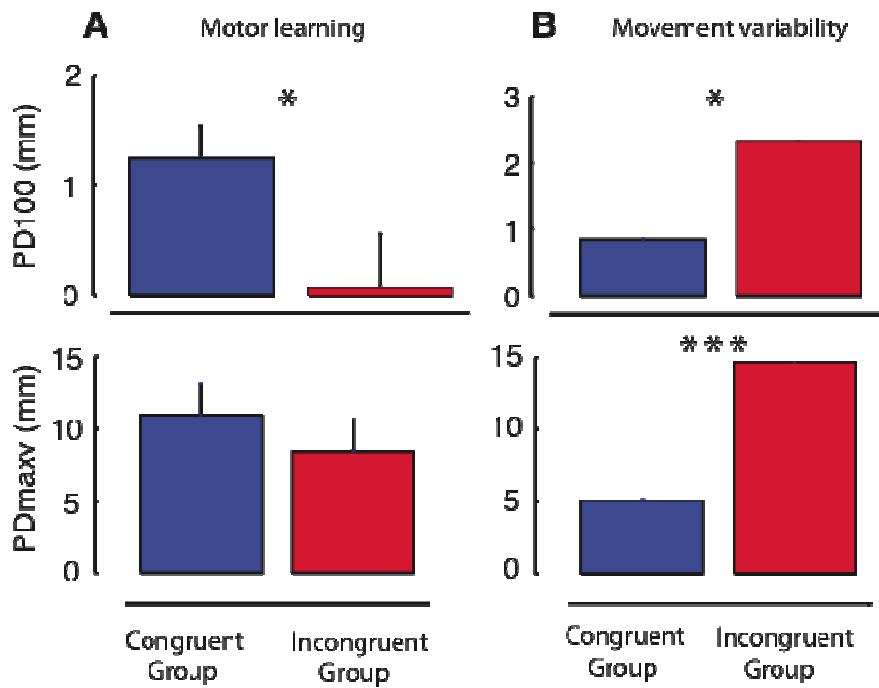
For subjects that both observed and practiced a force-field in a CCW direction, the amount of shift in the perceptual boundary following observational learning is inversely correlated with the change following actual motor learning.

We compared changes in sensory perception following observational learning with those reported previously in the context of actual force-field learning. For this analysis we used the data from a previous study (Vahdat et al., 2011) in which we used a similar experimental protocol (with $n=13$) and the same perceptual testing procedure as employed here. The analysis focused on changes in sensed limb position in the perceptual tests that were conducted following the primary experimental manipulation, that is, immediately following actual versus observational learning. A comparison of the two datasets revealed no differences in the magnitudes of perceptual change between the observational and physical learning conditions ($t(25) = 0.65, p > 0.5$). However, sensory change following actual motor learning showed significantly less between-subjects variability, as compared to motor learning by observing ($t(12) = 10.51, p < 0.002$).

All subjects were tested for motor learning using a CCW force-field. Subjects who had previously watched a movie showing a CCW force (congruent condition) showed better performance in the motor learning task than subjects that watched a CW force-field (incongruent directions) (Fig. 4.1). Asymptotic performance (mean \pm 99% CI) based on exponential fits to the PDmaxv was reliably better for subjects in the congruent (-2.3 ± 0.34 mm) than in the incongruent group (-4.3 ± 0.4 mm). The overall goodness of fit was similar in the two groups ($r^2 = 0.68$ and 0.61 , for congruent and incongruent conditions respectively).

We also evaluated the lateral deviation of the limb at a point 100 ms into the movement (PD100). Fig. 4.4 shows that the amount of learning (that is, the decrease following learning in the magnitude of lateral deviation 100 ms into the reaching movement) was greater for subjects who experienced the same force in the observational and actual learning tasks ($t(26) = 2.16, p < 0.05$). Measures of lateral limb deviation at maximum velocity showed similar patterns, although the difference was not statistically reliable. We observed differences in variability of movement between the two conditions as well. The group exposed to a congruent force in the observational and actual learning task showed less variability in movements in the initial motor learning trials (PDmaxv: $t(13) = 12.64, p < .001$; PD100: $t(13) = 6.49, p < 0.02$).

Figure 4.4. Measurements of movement curvature during force-field learning.



A, Subjects that observed and practiced a force-field in the same direction (congruent group) show greater motor learning than the group that observed and practiced force-fields in opposite directions (incongruent group). PD100 gives measures of lateral deviation 100 ms into the movement. PDmaxv is lateral deviation at maximum velocity. For both measures, motor learning is expressed as the mean difference in deviation scores between the last 5 and first 5 trials.

B, The congruent group shows less variable movements at the beginning of the force-field task, compared to the incongruent group. Variability is expressed as standard deviation across subjects in mm.

The results show that video observation produces reliable changes in both sensed limb position and in motor performance. However, it is unclear whether the effects depend specifically on the observation of learning or whether they are attributable to the statistical distribution of the events in the visual display. In particular, the videoclips show trajectories that are curved in a single direction, to the left for the CCW videoclips and to the right for the CW clip. Thus, it is possible that the asymmetric distribution of

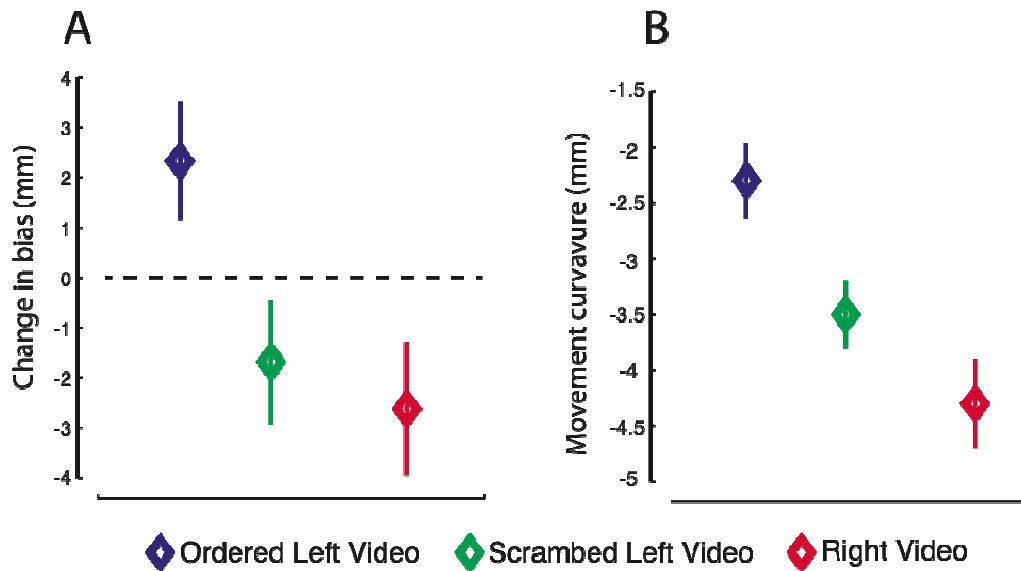
the visual input, rather than the observation of learning, biases subjects toward one side of the workspace, thus producing changes in sensed limb position.

As a control, we tested a further group of subjects that were exposed to the same CCW videoclip employed before, except that in this case the order of the movements in the video was randomized. In this way, the overall visual information presented to subjects in the two experiments was the same. However, the video sequence did not show learning but rather a random mixture of high and low-error trials. If the distributional properties of the visual input are sufficient to induce the effects described above, we would expect subjects to show a pattern of change in sensed limb position similar to that observed for subjects in the congruent condition. A comparable level of motor learning should also be observed.

Fig. 4.5a shows estimates of sensed limb position for the scrambled CCW video observation condition, along with the data from the original video clips. The change in sensed limb position due to scrambled CCW video observation was not reliably different than zero ($t(13) = -1.35$, $p > 0.19$), with half of the sample showing changes in one direction and half in the other. Indeed, the overall pattern was opposite to that of the CCW-video group.

Figure 4.5b shows motor learning data for the scrambled CCW-video group, along with learning data for the two original groups of subjects. Subjects in the scrambled CCW-video group exhibited asymptotic levels of motor learning that were intermediate to the two other groups. Asymptotic performance based on exponential fits to the PDmaxv (-3.5 ± 0.3 mm, mean \pm 99% CI; $r^2 = 0.73$) was reliably better compared than that of the group that observed an incongruent, CW video, but reliably worse than subjects that observed the original CCW video ($p < 0.01$ in each case).

Figure 4.5. Effects of observing a video with movements in scrambled order



Watching a video in which the order of the movements was randomized resulted in no change in somatosensory perception and a reduced benefit to motor learning.

A, Mean perceptual change (\pm SE) following observation of a standard-order CCW video (blue), a scrambled-order CCW video (green) or a standard-order CW video (red).

B, Asymptotic performance (\pm 99% CI) in force-field learning trials for the same three groups, derived from exponential fits to the motor learning data (lateral deviation at maximum velocity, PD_{maxv}).

4.4 Discussion

The present investigation tested the idea that observational motor learning produces changes to somatosensory function, in addition to its effects on motor learning. We found that sensed limb position changed following the observation of an actor learning to reach in a force-field. The direction of the perceptual shift depended on the direction of the observed force. These changes were in the same direction as those previously described following actual motor learning (Ostry et al., 2010; Vahdat et al., 2011). Moreover, consistent with Mattar and Gribble (2005), subjects that viewed videos that were congruent with subsequent force-field learning showed greater amounts of learning and had movements that were less variable.

These effects could not be attributed to the observation of movement error alone. A control experiment showed that observing learning was important. Observing a sequence of movements that randomly varied from high to low-error trials did not produce reliable changes in sensed limb position. Random-video observation also had a reduced impact on motor learning.

A similarity in the processes underlying perceptual change following observational learning and actual motor learning is indicated by two related observations. First, the average change in perception following observational learning is in the same direction and of the same magnitude as the one for actual motor learning. Second, observational learning and real physical practice appear to tap into the same capacity for sensory change in that subjects that showed a greater change following learning by observing showed a reliably smaller change following physical motor learning, and vice versa. At the same time, the sensory outcome of the two procedures is not identical. Compared to the sensory shifts described in previous investigations following physical learning, the changes reported here are characterized by greater between-subjects variability. This is in line with previous investigations showing, for the motor domain, similar performance between the physical and imagined execution of actions, but with higher variability in the case of imagery (Papaxanthis et al., 2002).

The present results show that motor learning affects both motor and sensory systems, regardless of whether the learning is achieved by standard physical practice or by observational learning. In the case of actual motor learning, changes to both sensory and motor function presumably ensure that the systems remain in register. Together with previous observations (Mattar and Gribble, 2005), the present study provides support for a similar effect of observed motor learning on the broader sensorimotor network that is responsible for motor adaptation.

The present findings are complemented by recent neuroimaging studies that have reported the modulation of activity in primary and secondary somatosensory areas during the observation of actions (Avikainen et al., 2002; Cross et al., 2006; Gazzola and Keysers, 2009). These latter findings have been part of an undertaking in recent years to characterize the functional and anatomical properties of an action-observation network,

so called because it includes brain areas that are active both when an action is observed as well as when the same action is actually executed (Di Pellegrino et al., 1992).

The neural bases for the perceptual changes described here are not known. However, in an analysis of connectivity patterns in the resting brain, Vahdat et al. (2011) identified a network whose activation was related to perceptual changes that occurred in conjunction with actual motor learning. This network comprised second somatosensory cortex, ventral premotor cortex and supplementary motor cortex. As described above, the present investigation has found perceptual changes that, at a behavioral level, closely match those of Vahdat's study. It is therefore plausible to hypothesize that a similar brain network could be responsible for the changes in sensory perception following observational motor learning. It is noteworthy that the primary brain areas reported in the action-observation studies, ventral premotor cortex, supplementary motor area, inferior parietal lobule and the superior temporal sulcus (Kilner, 2011) partially overlap those reported by Vahdat et al. (2011) in the context of the perceptual aspects of motor learning.

A previous study has shown that motor learning is similarly influenced by watching a natural progression of learning, a scrambled sequence of high and low-error trials or even a sequence of high-error trials alone (Brown et al., 2010). These results are not consistent with the findings of the present control study which shows that observing a scrambled sequence of movements has no effects on perceptual function and reduced effects on motor learning. The difference in findings may lie in the fact that the previous study utilized videos showing eight different directions of movement, thus providing subjects with more examples of high-error movement, compared to our study in which only one direction of movement was employed. It is possible that in this previous study the amount of error information provided the basis for effective learning even in the scrambled condition. In the present study, the relatively sparse error information uncovered the importance of a coherent learning sequence for the success of observational learning. It should also be noted that this previous study (Brown et al., 2010) did not measure sensed limb position. This leaves open the possibility that their scrambled videos produced only a partial learning, one that involved the motor component but did not extend to the somatosensory system.

The results reported here have potential application in the field of rehabilitation, given the increasing interest in action observation training for the rehabilitation of stroke patients (Celnik et al., 2008). Properly designed action-observation trainings could potentially be used to improve the recovery of sensory function in stroke patients. Additionally, the evaluation of sensory function could become a valuable complementary tool for assessing the outcome of action-observation training aimed at restoring motor function.

5. General discussion

A wealth of research on MP has focused the question of whether MP is or not an effective intervention for improving performance (Driskell et al., 1994). In agreement with these previous investigations, we have shown that MP can in fact result in performance enhancement. This has been documented here in three different tasks with different degrees of cognitive *vs.* motor involvement, such as music memorization of motorically easy but long musical excerpts (Chapter 2), performance of motorically complex music sequences (Chapter 3) and force-field learning (Chapter 4). In addition, this thesis proposed to deepen the level of this investigation by asking two interrelated questions: first, which strategies more effectively support MP; second, what precisely is modified by MP.

The first question was investigated in the musical context, and the following conclusions can be drawn by the experimental data presented: 1) pitch imagery represents the most important format of mental rehearsal, the one that is more generally associated with better performance regardless of the specific nature of the musical task; 2) structural/formal analysis is an important component of mental rehearsal to manage tasks with a high demand on cognitive processing, such as the memorization stage of music sequences learning. 3) motor imagery becomes important when facing the more strictly motoric components of the task.

The question of which strategies more effectively support MP pertains to the nature of the input information. Several formats of imagery information can be fed into the mental rehearsal process, and it would be interesting to understand which are more likely to produce the best outcome. A crucial aspect of this question is defining the context, since clearly the role and effectiveness of different mental strategies will depend on the task. For example, studies within the field of sport psychology have shown that motor imagery and first-person visual imagery are effective strategies, and also that third person visual imagery can become important when imaging certain form-based skills (Hardy & Callow, 1999; White & Hardy, 1995). In the first and in the second study presented here, music performance was assumed as the experimental model to address the question of which

strategies more effectively support MP. This choice rested on the following considerations: First, music performance offers the occasion to study complex cognitive elements as well as fine motor control, in such a way that the weight of these two components can be experimentally manipulated. For example, in the first study presented here the cognitive component was highlighted, while in the second study the motor component was given more importance. Second, performing music is a multisensory task that intrinsically involves auditory, somatosensory, visual and motor information, thus allowing to probe into all these processes and to assess their relative contribution. Third, from the point of view of the participant-musician, performance is something that is natural to provide, thus, being ecologically valid (a critical aspect of several laboratory studies about MP, cf. Mulder et al., 2004). Remarkably, no previous study in the musical context has systematically investigated the role of different imagery modalities. This was partly due to the methodological background that guided previous investigations, dominated by a certain vision of experimental control. The importance of these previous studies is not questioned; however, the present contribution wished to clarify that limitations exist in that approach, and scientifically valid alternatives should be considered. In this thesis, an “open” experimental design was employed, characterized by the fact that subjects were free to choose whatever MP strategy they wished. Self-report instruments were designed and utilized to keep track of the imagery pattern in each participant. This design allowed to create an initial, although comprehensive, picture of the role of different imagery strategies in music performance. As it has been discussed, this picture is entirely consistent with the prediction of the expert memory theory (Ericsson & Kintsch, 1995), of the simulation theory (Jeannerod, 2001) and of the forward model concept of motor control (Wolpert et al., 1995)

Investigating the role of the different practice strategies in performance outcome led to the second question, pertaining to the output level: apart from the performance itself, what precisely is modified by MP? Previous investigations have shown that components such as muscular strength (Yue and Cole, 1992) and movement velocity (Gentili et al., 2006, 2010) can be influenced by MP. The second study presented here investigated a further candidate that still was missing in literature, that is, motor anticipation and coarticulation. The possibility that MP could influence these components of motor

control was highly expected in consideration of the fact that they relate to the sequencing aspect of the motor task. In fact, the sequencing aspect of motor control is considered to be more cognitively accessible, as compared to the optimization aspect, which deals more with the low-level motor implementation. As predicted, significant changes in parameters of motor performance related to motor anticipation and coarticulation were found following MP. This pattern was very similar to that observed following physical practice, but it was not found in a control group that did not engage in any practice. This investigation also informed about what is *not* modified by MP: no improvements of movement variability were seen, for the sequencing as well as for the optimization components of the movement, another finding that fits with the understanding of MP in terms of training through the forward model (Gentili et al., 2010).

It is also important to notice that the investigation at the level of the output is not independent from that at level of the input: in fact, hypotheses were proposed that linked specific mental strategies with changes in specific components of motor performance. The second study presented here documented an association between auditory imagery and the sequencing component, and an association between motor imagery and the optimization component. Once again, music performance served as a good model to test this hypotheses, because it naturally combines the aspect of fine motor control with that of a sequential structure.

Altogether, these results have shown a considerable potential of penetration for MP into the motor processes. Interestingly, recent studies have questioned the purely “motoric” nature of motor learning, showing for example that physical practice is associated with changes of somatosensory function (Haith et al., 2008; Ostry et al., 2010; Vahdat et al., 2011). The third study presented here therefore extended the investigation at the level of the output of MP by asking whether the influence of MP could spread to sensory function, as it has been documented for physical practice. To test this hypothesis, force-field learning was employed as the experimental model for motor learning, because in this context the changes of somatosensory function following learning can be reliably assessed. Also, observational learning, instead of imagery, was employed as the vehicle of MP. In fact, force-field learning paradigms are hard (if not impossible) to be imagined prior to their learning. This is shown for example by the fact that no published studies

exist that document practicing in a force field by pure motor or visual imagery; only one study, by Anwar and collaborators (2011), employed motor imagery in force-field learning, but in this experiment motor imagery was continuously intermingled with physical practice. Instead, it has been shown that force-field learning can be faithfully acquired by movement observation (Mattar and Gribble, 2005; Brown et al., 2009, 2010), and a rich literature exists showing that movement observation partially recruits brain networks involved in action production (see Kilner, 2011 for a recent review). Intriguingly, recent studies have shown that also somatosensory cortices are active during action observation (e.g., Gazzola and Keysers, 2009). The third study presented here showed that, following observation of force-field learning, somatosensory function was altered, both in direction and in magnitude, in a manner similar to that which occurs when motor learning is achieved through actual physical practice. This similarity was further underlined by the fact that subjects showing a greater change due to MP showed a reliably smaller change when additionally exposed to physical practice. This study also confirmed the differences between MP and physical practice, showing greater variability in the somatosensory estimates following observational learning.

To conclude, a recent quotation by Christian Collet comes in to my mind, stating: “it is evident that (...) there are significant conceptual and methodological barriers to the integration of motor imagery research findings between the two dominant disciplines in this field – cognitive neuroscience and sport psychology” (Moran et al., 2012, pp. 227). This is probably even truer when considering the case of mental practice. This thesis sought to provide a contribution toward a productive convergence between cognitive and applied studies on this topic. The question that is critical for the applied perspective, that is, is MP effective, has been fully considered here. This investigation has confirmed previous results about the degree of MP effectiveness in the domains of music memorization and force-field learning, and has also provided the first evidence in the domain of complex music motor sequences. In addition to that, these studies have been shaped in order to address questions of broader interest for the cognitive science. The first, pertaining to the role of different imagery strategies, has revealed the task-independent role of auditory imagery in the musical context, and the task-dependent role of structural analysis and motor imagery. The second, pertaining to the exact mechanisms

underlying performance improvement, has revealed changes in motor anticipation, coarticulation and somatosensory function. Finally, as an important component of the above mentioned “barriers”, the concern about ecological validity has been addressed in the realization of the study, for example constructing “open” practice research designs and spending effort in training subjects before the actual testing session.

Several questions remain to be answered, as well as barriers to be demolished.

For example, the neural basis of the changes described here are still to be clarified. On the other side, the heuristic potential of “open” designs, and the question of their proper implementation in a rigorous setting, have received just an initial exploration here. It is particularly along these two lines of research that I see a great potential for future investigations.

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7. Appendix

Ten Minute Questionnaire (TMQ)

The following statements describe strategies that a musician might use while using mental practice.

According to the way you practiced, rate each statement from 1 to 5 using the following scale:

1 = never

2 = seldom

3 = sometimes

4 = often

5 = very often

1. How often did you imagine the sound of notes?
2. How often did you imagine the feeling of the movement of your fingers or hand?
3. How often did you visualize in your mind the movement of your fingers or hand?
4. How often did you visualize in your mind the music score?
5. How often did you analyze the harmonic structure of the piece?
6. How often did you analyze the melodic structure of the piece?
7. How often did you analyze the rhythmic structure of the piece?

Supplementary Figure 1. Excerpt from Sonata K 72

Piano

The image displays a musical score for a piano piece, identified as an excerpt from Sonata K 72. The score is presented in three systems, each consisting of two staves: a treble clef staff on top and a bass clef staff on the bottom. The word "Piano" is written to the left of the first system. The music is written in a common time signature (C). The first system shows a treble staff with a melodic line and a bass staff with a rhythmic accompaniment. The second system continues the melodic and accompaniment lines. The third system shows a more complex melodic line in the treble staff and a corresponding accompaniment in the bass staff.

Supplementary Figure 2. Excerpt from Sonata K 113

Piano

The image displays a musical score for piano, consisting of three systems of music. Each system is written for a grand piano, with a treble clef on the upper staff and a bass clef on the lower staff. The key signature is three sharps (F#, C#, G#), and the time signature is common time (C). The first system shows a melodic line in the treble clef with eighth and sixteenth notes, and a bass line with quarter and eighth notes. The second system features a more active treble clef with sixteenth-note patterns and a bass line with quarter notes. The third system continues with similar textures, including sixteenth-note runs in the treble and quarter-note accompaniment in the bass.