1 Introduction

In the first part of his two-volume magnum opus “The World as Will and Representation” [*Die Welt als Wille und Vorstellung*], which was first published in 1819, the German philosopher Arthur Schopenhauer made the following statement about the acting and perceiving subject: “Every genuine act of his [= the subject’s] will is at the same time and inevitably also an action of his body: he cannot actually will the act without realizing at the same time that it manifests itself as an action of the body. The act of the will and the action of the body are not two objectively discernable, disparate states, which are connected by the bond of causality, their relation is not one of cause and effect; but rather they are one and the same, if only presented in two entirely dissimilar ways: the one quite directly, and the other in the observation of the mind. The action of the body is nothing else but the objectified, that is, the perceivable act of the will. Furthermore it will show that this accounts for all possible actions of the body, not only for those that arise from motives, but also for those that involuntarily arise from simple stimuli, indeed, that the whole body is nothing else but the objectified, that is, the internalized will […]” (Schopenhauer, 1968, pp. 157-8, translation by the author).

This is quite a remarkable statement. Especially so, because for a long time into the 19th century, the scientific and the philosophical world (psychology was to become an independent scientific subject only some time later) had held the belief that, ontologically and epistemically, the mind and the body must be viewed as two absolutely independent entities. This belief had been expressed and made popular by the French philosopher René Descartes in his work

“Meditations on First Philosophy” [*Meditationes de Prima Philosophia*], first published in 1631. Descartes described the world as consisting of two independent entities, the *res extensa* (all things physical, including the body) and the *res cogitans* (the mind). One implication of this “Cartesian” dualism was the belief that the mind is not susceptible to scientific investigation. Accordingly, with the rise of the natural sciences, a more unified view of the world became popular, which tried to reconcile phenomena of the mind with physical principles.

However, apart from such epistemic issues, the considerations of Schopenhauer are also remarkable in another respect. Schopenhauer implies that an “act of the will” is at the same time an “action” of the body. Or, to turn it the other way round, a bodily action (that is, a movement) is nothing else but a “perceivable act of the will”. Other philosophers of the 19th century have expressed similar ideas, as I will show later. In terms of modern cognitive psychology, this conjecture suggests a very close relationship of *sensory* and *motor* processes. In fact, modern cognitive science has gathered a large amount of empirical evidence for such a close relationship. This evidence, as well as the underlying theoretical considerations, will be described in the following sections.

But before I go into the views of modern cognitive psychology in more detail, another quotation. This time, it is not from a philosopher, but from a performer of classical music. In his 1986 book “The Inner Game of Music”, contrabassist Barry Green writes about the performance of music: “When you can hold the sound and pitch of the music clearly in your head […] performing it accurately becomes easier. Your body has a sense of its goal […] Effectively, you are playing a duet between the music in your head and the music you are performing.” (Green & Gallwey, 1986, p. 75).

Note the similarity of the experience of Barry Green and the considerations of Schopenhauer. Both, the subjective experience as well as the analytical philosophical view, express the idea of a very close sensory-motor coupling, which directly manifests itself in the ability of people to control bodily action by means of the voluntary imagination of an intended goal. However, there is also a significant difference. In contrast to Schopenhauer, Green not only speaks of a self-contained action of the body, but also of a goal that lies *beyond* the bodily action. For him as a musician, the goal of his body movements is the production of musical sounds (on the piano, the trumpet, the contrabass,…). However, this ability to perform proper actions on a musical instrument can hardly be supposed to be present *per se*. He as a musician must have *learned* this ability of performing certain movements in relation to certain sounds.

Several questions arise from this point. First, is there empirical evidence for such phenomena of sensory-motor coupling, as presumed generally by Arthur Schopenhauer, and specifically for music by Barry Green? Second, if there is empirical evidence, what might be the underlying structural and functional principles for such effects? And third, what might be the use of such structural and functional principles in the machinery of the mind? The central motivation of the present work has been to investigate the above-mentioned issues in more detail. Thus, the main aim of this dissertation is the investigation of sensory-motor coupling in experienced musicians in a theoretical and empirical manner.

The work consists of three major sections. In the first section, a review of the empirical and theoretical literature on sensory-motor coupling, generally as well as specifically for music, is given. The second section describes and discusses experiments that have examined sensory-motor coupling in musicians in three domains: the harmony dimension of music, the melody dimension of music, and the question of instrument specificity in sensory-motor coupling. In the third and final section these empirical results are discussed more broadly, and are related to the theoretical premises, which have been established in the initial section.

2 Review of Literature

In the following, I will give a review of the relevant empirical and theoretical literature on sensory-motor coupling. The section is ordered into three major parts. In the first part, empirical evidence of sensory-motor coupling is discussed. After a description of a number of exemplary studies, effects of sensory-motor coupling are reviewed in two categories: effects that derive from *hard-wired* sensory-motor linking, and effects that derive from *learned* sensory-motor linking. The latter category mainly focuses on action-effect linking, which is also central for the empirical section of this study. The second part discusses theoretical accounts of sensory-motor coupling. These include accounts based on associative learning theory, computational models, and the ideomotor theory of voluntary action. The third and final part focuses on sensory-motor coupling in musicians. The ability to play an instrument is discussed as a specific form of expertise, which necessarily involves increased sensory-motor coupling. Furthermore, previous empirical studies on sensory-motor coupling in musicians are reviewed.

2.1 Empirical Evidence of Sensory-Motor Coupling

Most studies on sensory-motor integration and interaction have used a *perception-on-action* approach in their experiments: the performance of people in a certain task that involves doing certain actions is examined under varying conditions of perceptual stimulation. Instances of the influence of perception on action have been reported in a number of areas. These include the involuntary imitation of observed movements (Brass, Bekkering, & Prinz, 2001; Brass, Bekkering, Wohlschläger, & Prinz, 2000; Craighero, Bello, Fadiga, & Rizzolatti, 2002), the influence of irrelevant stimulus dimensions on responses (Eriksen & Eriksen, 1974; Kornblum & Lee, 1995; J. R. Simon, 1990; J. R. Simon & Rudell, 1967), and, more recently, the influence of (potential) action effects on action performance (Beckers, De Houwer, & Eelen, 2002; Elsner & Hommel, 2001; Kunde, 2001; Ziessler & Nattkemper, 2001). To a somewhat lesser degree, the case of *action-on-perception* influence has been examined as well, for example in visual discrimination (Müsseler & Hommel, 1997; Müsseler, Steininger, & Wühr, 2001; Wohlschläger, 2000), the perception of apparent motion (Wohlschläger, 2000), and temporal action-effect binding (Haggard, Clark, & Kalogeras, 2002). These latter studies show that, under certain circumstances, action preparation and/or execution can influence perceptual processing.

The studies, which are most relevant for the present work, are discussed in the following. An adapted version of the classical S-R-C model (see Tolman, 1932) may serve as an organizing framework. In the classical S-R-C black box model, the cognitive system is supposed to get input from perceptual *stimuli* (S), which give rise to a *response* (R), which in turn is followed by a certain *consequence* (C). A stimulus directly evokes an associated response. If the response is followed by a consequence of positive valence (a "reward"), the S-R association is strengthened (the "law of effect", Thorndike, 1911). However, if we concede that people are not simple automatons that follow mechanistic rules (see for example Allport, 1980, for such a model), it is more useful to apply the term *action* (A) instead of *response*. The definition of "action" takes into account the goal-directedness of most human behavior, and emphasizes intrinsic rather than extrinsic control. To give a clear definition, actions are "goaldirected activities that consist of body and/or limb movements" (Magill, 2001, p. 3).

Furthermore, with the *consequence* of an action is usually denoted an event of either negative or positive valence (more explicitly: punishment or reward). However, any event that follows an action (mostly: that is caused by that action) can be perceived as a "consequence" of the action. Therefore, it is more useful to speak of the *effect* (E) of an action. Here, it is important to differentiate between proximal and distal action effects (see Prinz, 1990). *Proximal* effects are sensory events that are immanent to the movements of the acting person. In a way, to the actor a proximal effect is the movement itself. It is represented as kinesthetic, proprioceptive, tactile, and also visual information. As such, an arm movement, for example, is represented as what a person perceives, when he moves his arm. For the most part, proximal information is characterized by the fact that it is accessible only to the acting person (see also Metzinger, 2000, for an analysis of the first-person perspective). Proximal effects can be linked to *distal* effects by way of cause and effect. Distal effects are fed back to a person by far-reaching sensory modalities, like vision and audition. In most cases, the causation of a distal effect is the actual goal of a movement. A pianist, for instance, produces piano tones as distal effects (and even more distal, perhaps, positive emotional responses within the listeners).

If we follow this S-A-E model, sensory-motor interaction can arise from several sources. Perception-on-action effects can arise from perceived sensory events: this is the case when pre-action stimuli (S) or post-action effects (E) influence the control of actions (A). Effects of action-on-perception can arise when action control processes (A) influence the perception of sensory stimuli (S) or of ensuing effects (E). In the following, the major focus will lie on those studies, which have examined the influence of action effects (or stimuli that usually *are* action effects) on action performance. These studies are most relevant for music-related issues, which will become clearer later on.

2.1.1 Examples and Classification

Let me begin with a few exemplary examples that have demonstrated effects of sensory-motor coupling. Some of them directly relate to the present work. A study by Schubö, Aschersleben and Prinz (2001) may serve to illustrate what is meant with sensory-motor interaction. In this study, participants carried out movements on a writing pad, while they observed motions on a computer screen. The observed movement on the computer screen in a trial *n* was to be carried out on the writing pad in the subsequent trial *n* + 1. The results of this study showed a contrast-like effect of stimulus motion on performed movement: perceiving a small motion while performing a medium-sized movement increased movement size, while perceiving a large motion led to a decrease. Thus, the *perception* of visual events had directly influenced the *execution* of actions. One experiment even showed an opposite effect, that is, an influence of an executed action on visual perception.

Another example for the influence of perception on action is the involuntary imitation of observed actions. This has, for instance, been demonstrated in a study by Brass et al. (2000). In this study, participants carried out finger lifting movements (index or middle finger) in response to symbolic cues. Concurrently with the imperative cues, task-irrelevant picture sequences of finger movements were presented, which could be congruent or incongruent with the required response. Results showed both interference (higher RTs in the incongruent condition) and facilitation (lower RTs in the congruent condition), as compared to a baseline condition with only the imperative cue. When the distractor was made more dissimilar to the response (tapping the finger instead of raising it), interference was reduced, while facilitation disappeared entirely. No interference or facilitation effects were observed, when finger movements were used as imperative stimuli, and symbolic cues as distractors. It seems that the perception of the finger movements *involuntarily* triggered the corresponding movements. Arbitrary symbolic cues (single digits, in the experiments) were not associated with any response from the first, therefore they did not effect in any specific distraction. Similar effects of involuntary imitation have even been found in a simple response task (Brass et al., 2001).

Craighero et al. (2002) were able to demonstrate analogous effects for rotational hand movements. In their study, participants prepared rotational grasping movements, which were to be carried out on presentation of a visual stimulus (showing a mirror image of the hand). Results showed faster responses, the more the mirror image resembled the actual movement in terms of orientation. Even more interesting, these effects were the higher, the more similar the mirror image was to the *final* position of the movement, which was to be carried out. This study primarily illustrates the relevance of the movement goal. It seems that, in involuntary imitation, the most relevant aspect is not the movement itself, but its aimed-for end-state.

How can effects of sensory-motor interaction, as described in the examples above, be accounted for? For such effects to happen, it is necessary that sensory and motor processes are linked by some structural and/or functional principle. There are two possible sources for such sensory-motor linking: it may be hard-wired in the system, or it may be learned. Any *hard-wired* sensory-motor linking has its foundation in the underlying structures of the nervous system. Neurophysiological examples of hard-wired sensory-motor connections include low-level connections, like the monosynaptic reflex circuit (see Chen,