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Human Action Control

From Intentions to Movements

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Preface

The purpose of this textbook is to provide insight into the areas of action planning and action control. These two areas are still relatively separated, and many of the topics we will be discussing are studied in different disciplines and subdisciplines, such as cognitive vs. motivational psychology, movement and sport sciences, neurophysiology, and biology. Unfortunately, this diversity has generated different kinds of scientific jargon and theorizing, which is difficult to relate to one another. Despite the varied studies throughout multiple disciplines, action still plays an underprivileged role in psychology. It does not feature as a relevant topic in 99 % of psychological introductory textbooks. We believe that every effort has to be taken to better integrate action into psychology's canon of knowledge. To do so, we have taken an uncommon route.

Generally speaking, textbooks provide a more or less exhaustive overview of a research area or topic and discuss the most recent findings and trends therein. The advantage of this strategy is obvious: the reader is provided with maximum information and, thus, with the opportunity to make up her own opinion. But, there is also an often overlooked disadvantage: while experts have enough background to structure new information in the most efficient way, novices can be over-challenged by the sheer amount of information that standard textbooks provide and, often, are not able to appreciate all the subtle implications that the most recent findings might have. This is, at least, the experience that we have had when we were students and that our current students often report when struggling with textbooks.

We therefore opted for another strategy. It consists of focusing on, in our opinion, the most basic principles and theoretical figures of thought in the historical development of the research area. As a result, we have used only a few empirical findings as examples for how theory and data are connected. Also, we translated domain-specific jargon into our own preferred terminology, which makes it easier to relate the concepts we discuss. Furthermore, we offer a general organizational framework of how we think action planning and action control is working, which will help the reader to organize the information we provide. Our approach has obvious disadvantages: it is necessarily much more selective and often refers to classical papers that have introduced particular lines of thought rather than the most recent applications of these thoughts, which explains why the average age of the literature we cite is unusually high. Most importantly, this selectivity implies that this textbook is likely to reflect the theoretical preferences and biases of its authors more than others. It is, thus, important that the reader does not forget that our approach is just one of several possible approaches. “Doubt comes *after* belief,” Wittgenstein says in his last book, *On Uncertainty*, meaning that we can start doubting only once we are done with building up our basis of knowledge. It is in this sense that we encourage readers to use this book as a jumping board to build their first basis and later try questioning it based on what other authors say, wherever appropriate and necessary.

Many of the questions that we discuss in the following chapters, and many of the answers that we suggest, emerged from Nattkemper and Hommel’s numerous collaborations with members of the “Cognition & Action” Unit of the Munich Max Planck Institute for Psychological Research and its spiritual leader, Wolfgang Prinz. We were unable to reconstruct exactly which ideas and speculations have motivated which of the considerations that we will present in the following chapters, but we are 100 % certain that our theoretical preferences and biases, and the style of reasoning about cognition and action, were strongly shaped by “Cognition & Action.”

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About the Authors

Dr. Stephen B. R. E. Brown studied developmental and cognitive psychology at the University of Amsterdam. After obtaining his Master's degree there, he moved to Leiden University to obtain a Ph.D. under supervision of Professors Sander Nieuwenhuis and Bernhard Hommel. His dissertation focused on the locus coeruleus, a brainstem nucleus that provides the entire brain with the neuromodulator noradrenaline, which is released whenever we experience arousal. Currently, Dr. Brown works as a postdoctoral researcher at Leiden University, and studies heart rate variability as a predictor of psychosocial stress in collaboration with Professor Jos Brosschot. He is also employed as an instructor at the University of Amsterdam, where he coordinates and teaches a course on Cognition for interdisciplinary students.

Dr. Bernhard Hommel holds the chair of "General Psychology" at Leiden University since 1999, after having worked as senior researcher at the Max-Planck Institute for Psychological Research (Ph.D. at the University of Bielefeld in 1990; Habilitation at the Ludwig-Maximilians University of Munich). He is a co-founder and board member of the Leiden Institute for Brain & Cognition (LIBC), secretary of the International Association for Attention and Performance, and member of the German National Academy of Sciences. His research focuses on cognitive, computational, developmental, neural, and neurochemical mechanisms of human attention and action control, and the role of consciousness therein. Recent work also addresses the role of emotion, creativity, and religion in human cognition. He is chief editor of two journals and has (co-)authored more than 300 articles in international journals and more than 60 chapters in readers and psychological textbooks, (co-) edited three books on action control and the relationship between perception and action, and (co-)edited several special issues on attention and action control.

Dr. Dieter Nattkemper studied psychology at the University of Münster. His professional career started at the University of Osnabrück where he was engaged in investigating mechanisms of eye movement control in reading. In the 1980s, he worked (with W. Prinz) at the University of Bielefeld on issues related to understanding how internal, cognitive models of the environment contribute to controlling human behavior and how these supposed internal models are generated, consolidated, and modified in response to changes in our external world. He achieved his Ph.D. at the University of Bielefeld with studies elucidating the role of eye movements in tasks that require processes of continuous selection (continuous visual search). Thereafter, he joined the research group “Cognition and Action” of the Max-Planck-Institute for Psychological Research (headed by W. Prinz) where his research focused on questions relating to the mechanisms governing performance in serial reaction tasks. At the end of the past century, he moved to Humboldt University Berlin where he studied (with M. Ziessler and P. Frensch) the mechanisms underlying human action planning. Dr. Nattkemper has co-authored several articles in international journals, chapters in readers and psychological textbooks, a German textbook on human action planning and control (with B. Hommel), and co-edited a special issue on human action control. Due to steadily increasing problems caused by multiple sclerosis, he finished his professional career as an experimental psychologist and retired at the end of 2013.

Chapter 1
Introduction and Overview

The theme of the present textbook has accompanied the discipline of psychology for a long time, without actually being considered to be a core area. Textbooks on cognitive psychology generally only discuss perception, attention, memory, and cognition, without taking into account to what purpose (i.e., to control which actions) people use these cognitive processes. Of course, history has seen different approaches that have attempted to complete the cycle from perception to action and back, such as Lotze's (1852) considerations on executive ignorance, James' (1890) treatise on the human will, Woodworth's (1938) psychomotor studies, and many behaviorist programs (e.g., Thorndike 1898). However, in principle, cognitive psychology remained focused on the registration of information from the environment, and the processing thereof through increasingly higher-level cognitive processes. Some authors have even gone so far as to restrict their definition of the entire field of research to this processing (e.g., Neisser 1967). Historically, psychology as an autonomous science has preferentially focused on understanding the cognitive operations that serve to take information from the environment and to establish mental representations of the outside world. By contrast, studies on **action and motor control** had only modest presence in psychological research, to the extent that it has even been called the "Cinderella of psychology" (Rosenbaum 2005).

1.1 Action and Movement as a Theme in Psychological Research

It has only been recently that psychology has succeeded to study action once again. Various trends are responsible for this development. Firstly, the victory march of the **cognitive neurosciences** has made the various subfields of psychology draw closer to each other. From a neuronal point of view, it is indeed less crucial to tease apart where, for example, perception ends and memory starts, or which processes still represent perception, and which ones already constitute attention. This also concerns the apparently clear distinction between perception and action, especially

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because many more sensory and motor brain areas are occupied with the transition from perception to action than with local processing issues.

Secondly—this trend is not completely independent of the first—the various scientific disciplines have been drawn closer together. In psychology, the traditional borders between cognitive psychology and neighboring areas like social psychology or developmental psychology are clearly disappearing slowly, which has led to new descriptive terms like "**cognitive social neuroscience**" or "**the social neurosciences**."

Thirdly, cognitive psychology has rediscovered the concept of the will, although it is now referred to as "**cognitive control**" or "**executive functions**." The increase in our knowledge of the frontal cortex (mainly through studying patients with lesions in this brain area) and the increasing interest in the question of how people are able to perform various tasks with the same environmental stimuli and actions and can construct and implement different strategies has focused the research interest on processes that precede the processing of environmental information. This has led to a clear widening of the identity of cognitive psychology, which had traditionally focused on the processes that occur between the registration of a stimulus and the evaluation thereof through high-level cognitive operations. However, if these operations are not independent of the context and action goals of the person performing them, as is suggested increasingly by research, then the connection between action and the cognitive processes on which these actions depend should also be entered into the theoretical analysis. In other words, pure perceptional, attentional, and memory theories are becoming increasingly more complicated and comprehensive models, that take the action-specific function of cognitive processes into account.

1.2 Deficits in Theory and Research

There are a number of reasons why the psychology of action and movement has been so slow to emerge. We have already mentioned one reason, namely that many disciplines have concerned themselves with this theme, without actually resulting in fruitful interdisciplinary and integrative approaches. However, the various **research traditions** are responsible too, as they have often artificially narrowed the view of the conditions of action control (Hommel et al. 2001).

1.2.1 Sensorimotor Approach

Descartes (1664) instigated a very important and influential research tradition which asserted that **actions** are, so to speak, the **continuation of perception through different means**. As can be seen in Descartes' sketch, perception (in this case visual) leads incoming information to a central cortical coordinating point, where a fitting response is selected and initiated through control of the necessary muscles (Fig. 1.1). Descartes described **three types of processes**, which are important for the control of actions:

Fig. 1.1 Descartes's view on the relation between perception and action (Descartes 1664)

- **Afferent processes**, through which information that enters through the sensory organs is passed to the central organ.
- **Efferent processes**, through which movement commands from the central organ are passed to the musculature of the body's periphery.
- **Central processes**, which generate efferent commands on the basis of afferent information.

Descartes pictured afferent processes as thin threads, which are put in motion by stimulus information that hits the sensory organs, and that connect the specific sensory organ and the brain. Through the movement of these threads, the information from the sensory organs is carried to the pineal gland in the brain—the assumed perception-action interface. There, central exchange between afferent and efferent processes takes place, according to Descartes, because the pineal gland, which itself has been put in motion through the motion of the threads, secretes nervous fluid from its surface, which causes muscle contractions on the efferent side.

This sensorimotor conceptual model remains the theoretical basis of many approaches in contemporary cognitive psychology. Donders (1868/1969) made a significant step forward by proposing to dissect the general processing pathway into **subprocesses**, ranging from the earliest perceptual processes all the way to the subsequent movement, and to attempt to measure the duration of each of these subprocesses. Donders identified no less than 12 processing steps, from the influence of environmental energy on sensory receptors to the overcoming of corporeal inertia through the activation of muscles. Condensing these 12 steps reveals **four processing categories**, which until today remain the basis for stage models of information processing: sensory (pre-)processing, stimulus identification, response selection, and response initiation.

These types of **stimulus-centered linear stage models** are well suited to illustrate the setup of a typical psychological experiment. In such an experiment, a stimulus is generally used to manipulate the independent variable(s) while a given action is signaled, or the preparation of a given action is required. Processes related to an action are then, in fact, a function of stimulus presentation, and one can ascertain which processing stage is particularly affected by the manipulation of the independent variable. **Behavioristic approaches** have also emphasized the crucial role of the stimulus in the description of action control, although interactions with previous learning experiences are also important in these accounts. However, psychological experiments aside, people hardly ever wait for stimulus signals to make decisions on how to act; to the contrary, they often consider stimulus events to be the consequence of such decisions—just like the letters of this sentence were actively generated by the authors of this book. In fact, many actions are planned in the absence of external stimuli, which is less easy to capture in a conventional stage model.

1.2.2 Ideomotor Approach

The **ideomotor approach** has a long and varied history (Stock and Stock 2004), but is associated mainly with the names Lotze (1852), Carpenter (1852), and James (1890). A seemingly simple question underlies this approach: how can we, on the one hand, carry out arbitrary, goal-directed actions, but on the other hand know very little about how we actually do so?

Ask yourself *how* you actually ride a bicycle, or *how* you tie your shoelaces. Can you really answer that question spontaneously? Or do you imagine these actions first and then describe what you imagine? If the latter applies to you, then you experience a phenomenon that was referred to as **executive ignorance** by Lotze (cf. Turvey 1977). How one is capable of intentional action, notwithstanding this failing insight in one's own motor functioning, is discussed in greater detail later (Chap. 3).

In brief, the ideomotor theory suggests that intentional action presupposes **knowledge** about what one can attain with a given action; that is, which **action effects** can be obtained with a given action. The choice of an action therefore follows on the basis of a comparison between the expected action effect and the desired action goal: when one wants to tie one's shoelaces, one selects those actions that are expected to result in tied shoelaces.

From an ideomotor perspective, the theoretical analysis of action control does not start with a stimulus that precedes an action, but with an interplay between an intention and actions that support that intention, or properties of those actions. It is thus not external stimulus events that cause actions but the anticipation of their outcome: actions serve for the production of events (action effects), which are perceived and evaluated in light of the current intention. Ideomotor approaches study how this works, but tend to neglect the origin of action intentions and how actions are informed by, and adjusted to environmental conditions.

1.2.3 Interplay of Perception and Action

Sensorimotor and ideomotor approaches clearly reflect their origins. **Sensorimotor approaches** originate from neurophysiology and use the reflex arc as a guiding principle: just as a sudden blast of air induces a blink response of the eyelids, the sight of an undone shoe makes us perform shoelace-tying actions. **Ideomotor approaches**, in turn, stem from the era of introspective psychology and therefore deal with the connection between processes of consciousness, such as the experience of an intention and the conscious execution of an action outcome. However, this is not the only difference. Both approaches concern themselves with two separate halves of what is in fact one **perception-action cycle**.

Various authors have pointed out how strongly perception and action are intertwined. Von Uexküll's (1921) **concept of the subjective environment** encompasses both the perceivable properties of environmental events (*die Merkwelt*, or perceivable world) as well as the activities one can perform with them (*die Wirkwelt*, the operational world). In von Uexküll's model, sensory receptors register properties from the environment and pass them to a perceptual organ, which changes the environmental properties with the help of an operational organ. Neisser (1976) uses a very similar description of a circular relationship between three processes: internal knowledge schemata control the goal-directed exploration of the environment. This leads to the perception of the properties of objects, which either confirm the schema or adapt it (to reality). Neisser considers perception to be the result of a **continuous cycle** from the registration of environmental information, the integration of this information into object schemata, the goal-directed exploration which is controlled by those schemata and leads to more incoming information, and so on and so forth. Perception is also active, because generally, perceivable information generates goal-directed actions. Finally, because eye movements are crucial to visual perception, and hand motions are crucial to tactile perception, actions are also **receptive**, to the extent that they allow for new insights into the world. In the light of this relationship, it might be better to stop referring to perception and action, but to refer to the receptive and productive functions or aspects of human behavior.

In any case, it should be clear that sensorimotor and ideomotor approaches to action control do not illustrate the complex interplay between perception and action comprehensively. Sensorimotor approaches emphasize the influence of environmental factors on action production and generally ignore the antecedents or prerequisites of purposive or voluntary actions that necessitate generating and integrating representations that capture the demands of the task at hand and the means to satisfy them (forming and implementing intentions, planning actions, etc.), which makes actions appear to be stimulus-driven responses. In contrast, ideomotor approaches emphasize the intentional aspects of action control and thereby latently underestimate the contributions of the environment. Due to these blind spots in the theories discussed here, one could consider these approaches to be **complementary perspectives**. Recent years have seen an accumulation of attempts to integrate stimulus-oriented and intentional approaches into more complicated models.

1.2.4 Homunculi

A further problem for research into action control comes from the tendency to build **homunculi** ("little men") into theories. In the first, introspection-based ideomotor approaches from Lotze and James, **the will** is considered to be the decisive force behind goal-directed actions. How exactly this organ comes to its decisions and how it transforms decisions into actions is hardly discussed and is not really reflected by theory. James (1890) explains this reluctance through the self-explanatory nature of the phenomenon: "Desire, wish, will, are states of mind which everyone knows, and which no definition can make plainer" (p. 486). However, modern theories, too, have often done little more than replace the old-fashioned concept of the "will" with more familiar, technologically inspired expressions, without actually defining them, or lending them any theoretical support. For example, Baddeley and Hitchs' (1974) central executive or Norman and Shallice's (1986) attentional supervisory system (Chap. 9) are little more than placeholders for organizational processes that we still do not fully comprehend (Baddeley 1986).

Mysterious, homunculoid systems of this kind often emerge through the common tendency to objectify. Take, for example, the observation that humans do not follow every action tendency: we do not do everything that suits our fancy, do not eat everything that tastes good, and do not buy everything we would like to. The thought of an action can bring about foresaid action, but it definitely does not always do so. There are various theoretical options to account for this phenomenon. According to James (1890), thoughts will only lead to action when they are not in competition with other thoughts (e.g., the desire to eat healthier food) and when they are accompanied by an impulse to act ("fiat"). Freud (1923) claimed that undesirable thoughts could be suppressed actively, which would again imply a suppression mechanism. Although this second solution is more complicated from a theoretical perspective and posits a more intelligent mechanism that is harder to explain (how does it know when to suppress? How does it do that?), it appears to be so evident to many authors that they do not seem to look for and test other solutions (MacLeod 2007). This tendency is not limited to inhibitory models, but can be seen in all areas of cognitive psychology (and science in general): a phenomenon or behavior is described and "explained" through postulating a (functional or neuro-anatomical) system, which produces the exact same phenomenon or behavior. Willed behavior is produced by the system of the will, behavioral suppression by an inhibitory system, selective attention by an attentional system, and so on and so forth. It ought to be clear that, in these instances, sham explanations are provided, which lead to nothing as long as the proposed systems are not analyzed further.

1.3 An Organizing Working Model

The psychological study of action is at a turning point, in which small, partial theories are increasingly integrated into comprehensive models, and borders between sub-disciplines fade away. Clearly, this complicates understanding the field of study. We would therefore like to propose a comprehensive descriptive working model, which should serve to structure the discussion of research results and theoretical concepts in this book (Fig. 1.2; the numbers in the figure refer to the chapter in which the concerned theme is treated). This working model distinguishes several layers that organize the processes of action control regarding their duration and scope.

On the bottommost layer, we find processes that we have already encountered in the context of the sensorimotor approach. Processes that are associated with stimulus processing are summarized with the term **perception**. We do not limit this term to conscious perception, but use it for every type of action-related stimulus processing.

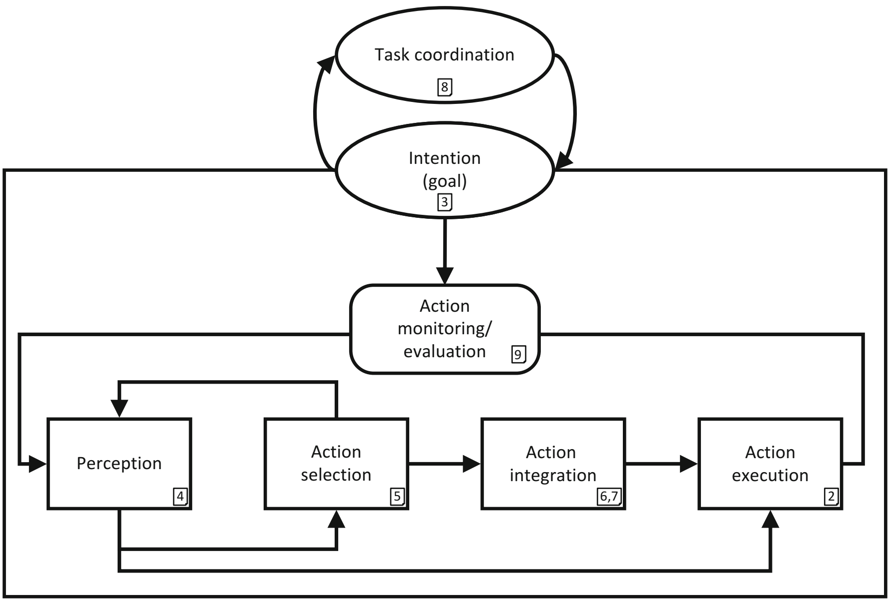

Fig. 1.2 Organizing working model

The outcomes of these processes are used both to select and to adapt actions (Chap. 4). Chapter 5 is devoted to processes that **select actions** and determine the properties of an intended action. As depicted in Fig. 1.2, they work in close coordination with perception. The next step consists of the **planning** of actions through the **integration** of action features (Chap. 6). It shall be made clear that action representations are not autonomous units, but networks of many different perceptual and action-related codes that, at least in some cases, should be integrated so that an action can be performed. Integrative processes are particularly important when complicated **action sequences** are being planned, such as the preparation of a meal (Chap. 7). As soon as a plan of action is finished, it can be executed. The **performance** requires the **translation** from a cognitive representation of a given action into muscle activity (Chap. 2).

The processes on the lowest performance level have a relatively short duration: once a particular action is set, perception and action specification can be devoted to other tasks. Once an action is performed, other actions can be integrated and performed. The scope of these processes is relatively clear too: they will mainly interact with the processes which cause the effects necessary for the first processes, or with processes that need input from these lower processes. The process of **action control** on the next, somewhat higher middle level, generally has a longer duration and takes more information into consideration; therefore, it is more integrative. It **monitors** whether actions that are about to finish are actually in accord with the actual intention, that is, with the action goal (Chap. 9). **Intentions** organize and instrument the processes of perception and action planning in a way that allow, if all is well, the realization of a set goal (Chap. 3). Finally, in Chap. 8 we discuss how **action goals** themselves are controlled and implemented. Everyday actions often require simultaneously pursuing various goals, also known as **multitasking**, and **switching between goals**. This raises the question of how various functions are actually coordinated. However, let us first look into the most important **neurobiological foundations** of human action control.

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Chapter 2
Neurobiological Foundations of Action Planning and Execution

In the mid-1800s, Phineas Gage worked on the construction of railroads in the United States, and his job as a foreman was to get rid of annoying masses of stone by blowing them up with explosives. Unfortunately, during one explosion, his **frontal cortex** was pierced by a chisel. In 1868, the physician John M. Harlow describes in great detail how Gage's serious wound was treated successfully, and how he started to work again after a few months. However, colleagues and superiors had to conclude that he was "no longer Gage": he lacked motivation, had difficulty in making plans, and showed strong **personality changes**, which were not in his benefit. Nevertheless, he was still able to work, and so he took a job in a horse stable; however, he found it increasingly difficult to develop action plans and to translate them into appropriate actions. Harlow described Gage as a person who always made plans for future activities, only to abandon them and to replace them with other, apparently better plans.

The analysis of the case, and especially the skull of Phineas Gage, has made substantial contributions to our **understanding** of the interplay between the human brain, cognitive processes, and action control (cf. Sect. 2.6.2). In fact, the actual performance of cognitive functions is usually understood best when they cease to exist for some reason, be it through lack of exercise, natural aging, illness, or accidents. This does not just apply to perception and memory, but also to the planning of actions and action control.

Particularly interesting in this context, are patients who show deficits in the planning or execution of actions, for example, as a result of **brain lesions**. This is interesting because the failure of control of action in patients with specific, accurately described lesions in the brain can give us preliminary insights into which brain areas are involved with action control. Additionally, results from **physiological animal experiments** and **neuroimaging methods** (Box 2.4) have contributed to a better understanding of the neuronal foundation of human action control. Although the mapping and understanding of the neuronal basis of the processes of action planning and action control is currently not as detailed as, say, that of the visual cortex,

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