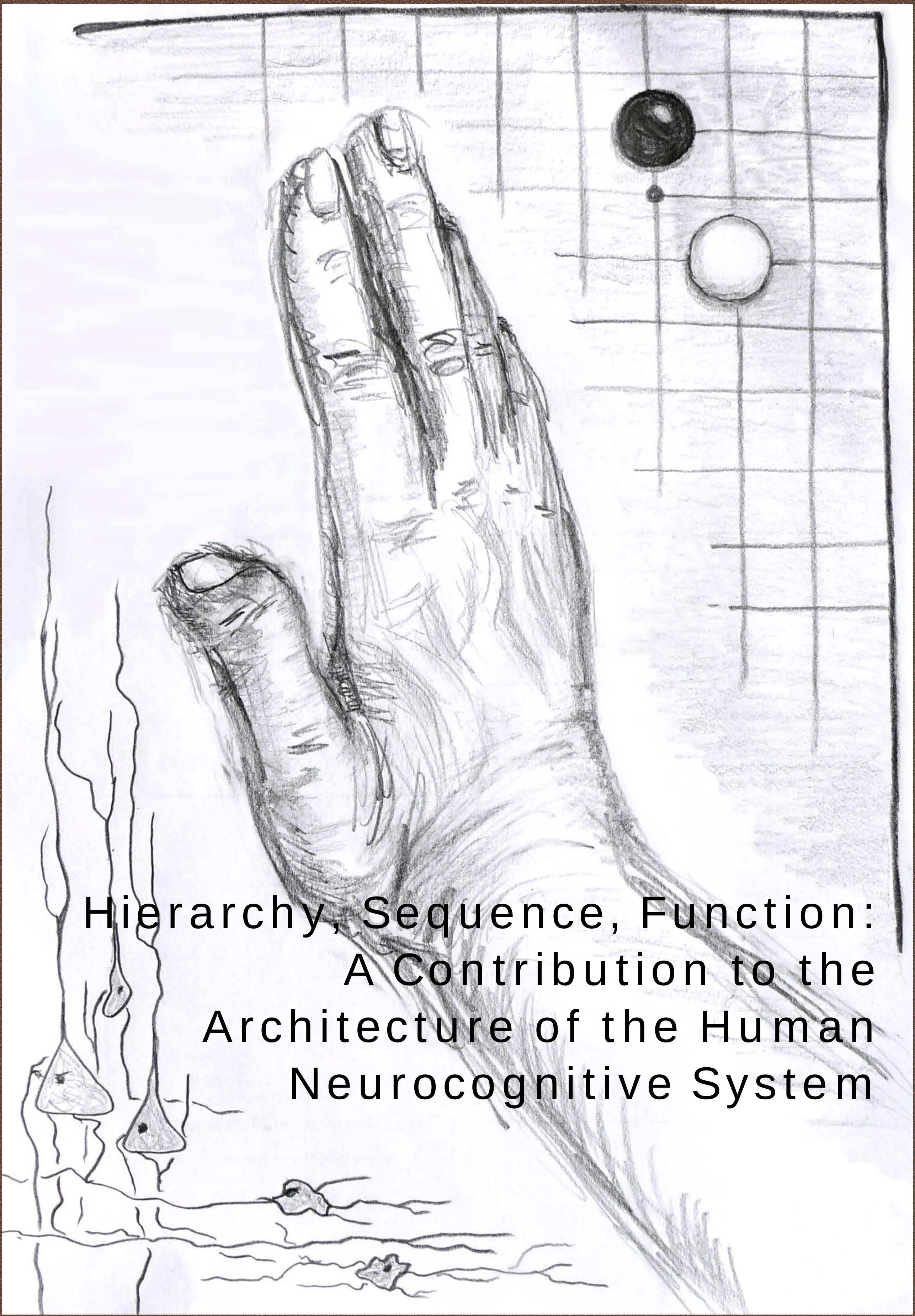

Hierarchy, Sequence, Function: A Contribution to the Architecture of the Human Neurocognitive System

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Part I

Synopsis

Introduction

The aim of the presented research is to improve our understanding of the human cognitive system, its functions and how it produces various sequences of behaviour. Wherever possible the neurophysiological underpinnings of the cognitive functions will be taken into account. A central hypothesis is that internal, cognitive functions can be characterised by hierarchical kinds of processing or representations. Some of the issues and open research questions will become more graspable when considering how long people have been looking for answers and how according concepts developed and changed over time. Therefore, I will very briefly look into how humans approached the questions of cognition, its structure and control of behaviour and, moreover, how these questions were tied to the neural system.

Mankind has been interested ever since in the functions of the human cognitive apparatus (historically also called ”psychological faculties”). Alkmaion of Kroton related cognitive functions[1] for the first time empirically to the brain in ancient Greece during the sixth century BC which was later accepted by Hioppocrates of Kos. (Aristotle, in contrast, claimed the heart to house perceptual and cognitive functions in his work *On the soul* (1947) and thereby encouraged a fundamentally different approach.) Nerve fibres as distinct tissue connecting the body's periphery with the brain were discovered independently by Herophilos and Erasistratus (both Greek physicians) during the third century BC (cf. Oeser, 2002; Oeser, & Seitelberger, 1989). Importantly, this finding provides an empirical basis for an explanation of the brain's control of behaviour and body sensations. Later, the famous Greek physician Galen of Pergamon promoted the brain's role in sensation, cognition and behaviour and influenced the scientific perspective for centuries even though Aristole's concept was also widely used.

From ancient times through the middle ages, three cognitive domains (”faculties”) were mostly distinguished but their functional relationship was hardly addressed. Above the level of modality-specific, sensory processing the three domains *sensus communis* (amodal perception), *vis cogitativa* sometimes incl. *phantasia* (reason and/or imagination of percepts in

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[1] The terms used here are nowadays approximate equivalents for better understanding. There may be interesting, conceptual differences among the various terms but this project does not focus on precise historical conceptions.

the absence of sensory stimulation) and *vis memorativa* (memory) were distinguished and believed to serve human thinking (cf. Oeser, & Seitelberger, 1989; Clarke, & Dewhurst, 1973). These domains were assigned incorrectly to three cells (i.e., compartments) located within the brain (corresponding to the four ventricles) for a long time.[2]

Needless to say, the cognitive influence (presumably to be understood as *voluntary* influence) on behaviour was also recognised in those early times, but it was hardly integrated into the concepts of the cognitive apparatus. A theoretical motor component, *membro motiva* (alluding to the body impulsion and associated with the fourth ventricle), appeared in some works during the 15th century but this concept might be traced back to Galen's work (Clarke, & Dewhurst, 1973, p. 29 & 33).

To be clear, there was a strong emphasis on the brain's and the body's structure rather than on the functions which were more deeply considered since about the 17th century (Putscher, 1972, pp. 88). However, even those early concepts distinguished at least two cognitive levels of processing and recognised (very few) distinct cognitive domains. Importantly, if there is any functional relationship expressed, it was a linear propagation of information[3] into the cognitive apparatus (from the senses through an integrated perception, *sensus communis*, towards the last domain of the "input path," namely memory; Oeser, & Seitelberger, 1989, pp. 10) and out again (which was hardly specified).

Without reviewing the history of cognitive (neuro)science, an important discovery for the present work (habilitation) is the electrical excitability of the cerebral cortex by Fritsch and Hitzig in the 19th century (e.g., Gross, 2007). This discovery is, of course, the basis for the non-invasive, in vivo recording of the electrical brain activity, the electroencephalogram (EEG) which was first applied to humans by Berger in 1929. One advantage of the EEG methodology is that it is very well suited to investigate temporal aspects of the neurocognitive system but spatial aspects are more difficult to assess by means of EEG.

Spatial differences in the neural processing and representation of cognitive functions, i.e., the concept of a functional localisation has been disputed over centuries before Bell and Magendie showed empirically for the first time a functional dissociation between the ventral and the dorsal nerve fibres of the spinal cord in the early 19th century which is now known as the *Bell-Magendie law*. Higher functions have subsequently been localised; Fritsch and Hitzig found the motor area in animals (rabbits & dogs), Munk localised visual processing in the occipital lobe (cf. Oeser, 2002; Shiraev, 2015) and, as it is well-known, Broca and Wer-

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[2] Sometimes the cognitive domains *estimativa*, *imaginativa* or *rationalis* are added within the same cells (Clarke, & Dewhurst, 1973, pp. 18).

[3] Actually, *pneuma psychikon* (spiritus animalis) was assumed to be transported which means that pneuma was assumed to have material features, however, "pneuma" was not well-defined. In any case, *pneuma* had conceptually material *and* spiritual features.

nicke localised expressive and receptive language functions in the posterior frontal and the posterior temporal cortex, respectively (Broca, 1861; Wernicke, 1874; Dronkers, Plaisant, Iba-Zizen, & Cabanis, 2007). Nowadays, localisation aspects do not depend on evidence from lesion studies or patient studies alone but neuroimaging methods such as functional resonance imaging (fMRI) are available since the early 1990s to investigate spatial aspects of neurocognitive functions non-invasively also in healthy humans.

In this project, I try to make a contribution to our understanding of the human neurocognitive system. That is, it is examined whether processing in (some) cognitive domains interacts with one another and how the according functions can be related to neurophysiological brain processes (for a tight relation between brain and mind see already Lurija's work) (e.g., 1970). Specifically, event-related potentials (ERPs; calculated from the EEG) will be used for assessment of the brain's electrical activity and fMRI will be employed to determine the functional neuroanatomical localisation of given effects. Furthermore, behavioural and cognitive measurements will provide evidence to understand the functional significance of the observed effects.

Based on the thesis that the human cognitive system is action-centred, i.e., optimised for adequate behaviour in an evolutionary sense, and the insight that serial processing alone is not sufficient to explain human behaviour (e.g., in stimulus-response or response-response associations), various cognitive domains will be investigated regarding the hierarchical processing of information or hierarchical representations thereof. In particular, the domains of language (production & comprehension), action control, and to some extent visual (sequence) perception will be addressed.

The perspective taken here, puts an emphasis on the cognitive influence on behaviour (i.e., voluntary movements; cf. Prinz, 1990; Jeannerod, 2006), less on sensorimotor control processes, especially in the work on action control. This perspective can be related to cognitive models of perception and/or action such as, for example, *common coding* (Prinz, 1987, 1990, 1997), *theory of event coding* (Hommel, Müsseler, Aschersleben, & Prinz, 2001), *anticipative behavioral control* (Hoffmann, 1993; Hoffmann, Butz, Herbort, Kiesel, & Lenhard, 2007) and *cognitive architecture of action approach* (CAAA, Schack, 2010; Schack, & Ritter, 2009, 2013) which assume an internal, hierarchical architecture of the cognitive system, rather than a (mechanistic) linear processing chain. Many of these theories can be traced back to the ideomotor approach that dates back to Lotze (1966/1852) and James (1890; cf. Shin, Proctor, & Capaldi, 2010) and incorporates the idea of bi-directional connections between sensations and actions. That is, imagined (or anticipated) action effects (i.e., sensory action consequences) can facilitate the execution of the imagined action

(Herbart, 1968/1850, §§129 & 155). Also, more central, cognitive domains such as language (e.g., Levelt, 1989; Caramazza, Laudanna, & Romani, 1988; Pinker, 1991; Roelofs, 1998; Friederici, 1995; Hagoort, Brown, & Osterhout, 1999; Marslen-Wilson, & Welsh, 1978, from the vast amount of language research) can tie together perceptual and action processes as in almost all conversations there will be an exchange of comprehension (listening or reading) and speaking (or writing). Moreover, during language translation comprehension and speaking occur almost simultaneously. So, the perspective taken here construes the cognitive system as a hierarchically organised architecture of domains (or modules; Norman, 1980; Velichkovsky, 1993). The domains are supposedly interactive (or they shared processing resources) and processing is effect-related, that is, behaviour should be organised in a manner to optimally fulfil the task demands (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001; Prinz, 1990; Marken, 1986).

In what follows, I will briefly discuss aspects of the (neuro)cognitive system that are relevant for the presently proposed perspective. Specifically, I will talk about the role of hierarchical processing and representations and whether the cognitive system should be conceived of as consisting of distinct modules (Ch. 1). Wherever it is adequate, I will make reference to publications that are relevant for the habilitation project throughout this synopsis. I will then discuss some relevant aspects of *action control*. A classification of responses will be presented and some experimental work that is related to the architecture of movement control. Furthermore, recent advances in neurophysiological methodology for action research and movement science will be presented (Ch. 2). Next, I will discuss recent experimental contributions to the domain of *language processing* (production & comprehension) in Ch. 3 with a focus on lexical processing and more specifically on compound words. In Chapter 4 (*Domain interactions*), I will provide evidence for an influence of prediction on early neurophysiological processes of language comprehension and, more generally, report on interaction effects among the cognitive domains of motor control (grasping), language, and working memory. Here; I will also touch briefly the visual domain. Shared neural resources for non-verbal sequence processing and verbal sequence processing (grammar) will be discussed before, finally, summarising the findings. Part II provides a list of publications for the habilitation and Part III contains the original prints of these publications (Kumulus).

Chapter 1

The (neuro)cognitive system

The aim of this project is to advance a perspective on the cognitive system that considers the exchange of information among domains, that is, whether and how specific domains interact or share processing resources. To this end some empirical evidence will be provided for the domains of *language processing, action control* and *visual perception.* At times, the relevant cognitive functions will be tied to neurophysiological underpinnings and also related in a functional sense to behavioural data. More specifically, after discussing some relevant aspects of the cognitive system regarding the control of behaviour, this project investigated cognitive processes in the fields of speaking, language comprehension, visual sequence processing and action control and possible relations among some of these fields (e.g., MacKay, 1987). In these fields, hierarchical processing or representations play a functional role which may, arguably, not be completely identical across these fields (or all cognitive domains). Within this project, hierarchical processing or representations will be considered as a potential common feature of the various domains of the human cognitive system, especially regarding action effects.

At the beginning of empirical scientific approaches to psychology, introspection provided a prominent theoretical framework since the late 19th century. When introspection has been criticised for its limited objectivity, behaviourism emerged as a contrasting framework during the early 20th century. Here, the serial nature of behaviour was emphasised as expressed in the concept of stimulus-response (S-R) associations[1] and for more complex behaviour in response-response associations or chains. That is, for complex behaviour, some motor activity was assumed to act as a stimulus through its sensory consequences (e.g. proprioceptive) for the subsequent motor activity. The serial nature of this S-R model goes back to the proposition of Pavlov and Bekhterev that psychological process are reflex mechanisms of the brain

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[1] For operant conditioning, these associations include reinforcement: Stimulus-Response-Reinforcement, but this difference does not change the present argument.

in analogy to the physiological reflex associations. The S-R model is a mechanistic approach which, therefore, permits clear predictions. Hence, it can be considered to be very objective (cf. Shiraev, 2015).

The S-R model has not only been applied to motor behaviour but also to language processing (Skinner, 1957). Skinner who was interested in the whole organism not only in separable responses believed that all behaviour is conditioned, i.e., acquired through experience. Consequently, also language is assumed to be determined by reinforcing conditions. In other words, language would be learned as any other behaviour. Conversation partners are seen as providing reinforcement and speaking would, accordingly, be a complex chain of responses emphasising the serial nature of language (comprehension & production). The linearity of the S-R model has been criticised for both domains, action and language (Lashley, 1951). Bernstein pointed out that goals of an action are necessary to explain motor control (for an extension, see also Velichkovsky, 1993). Actually, they are more important for motor control than the current body state of the actor[2], see also Rosenbaum, Jorgensen and colleagues (Rosenbaum, Marchak, Bames, Vaughan, Siotta, & Jorgensen, 1990; Rosenbaum, & Jorgensen, 1992). Goals represent, obviously, higher levels of representation than motor commands and, therefore, imply a hierarchical conception of action control (Bernstein, 1967, Ch. 2, originally published in 1935). Also, Lashley (1951) argued that an explanation of complex actions (incl. language) requires a "generalized schema . . . which determines the sequence of specific acts" because the specific acts do not contain sequential information (p. 122; see also MacNeilage, & MacNeilage, 1973). Similarly, Chomsky (1959) famously pointed out that language processing needs hierarchical representations because corresponding words can be separated by a number of other words which cannot be explained with associations between adjacent words (i.e., long-distance dependencies). Moreover, people can create truly novel (correct) sentences which should not be possible if grammatical phrases depend on reinforcement learning, i.e., repeated encounters. These early arguments and investigations suggested that a serial conception of the human cognitive system is too limited and needs some modifications such as a vertical dimensions (i.e., a hierarchical organisation; Velichkovsky, 1993).

Historically, other frameworks of that time, such as *psychoanalysis* or *Gestalt psychology*, contrasted with *behaviourism*. Another strong alternative, namely the *information processing* account, emerged in the mid-20th century and is largely accepted in current cognitive psychology. Cognitive models often incorporate hierarchically organised processing levels. At the same time, they shifted the focus of inquiry towards central, cognitive processes (i.e.,

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[2] For example, Bernstein investigated trajectories of hammering movements in experts and novices and found that experts hit a chisel with higher precision although the movement trajectories varied on every strike (Feigenberg, 2014, p. 42).

reasoning Miller, 2003; Walach, 2013), such as thinking, problem-solving, or (conceptual) memory, with little connection to action control. At least in relation to the research effort on the ”input” side, one can say, the ”output” side, i.e., action control has been neglected to some extent (Jeannerod, 1985; Rosenbaum, 2005). Even though scientific investigations used to a substantial part very simple actions (e.g., button-press responses which can be accomplished by contracting one muscle) as an experimental model of behaviour, at least the notion of an internal, mental model for the control of (complex) behaviour has been introduced from a process-oriented (Miller, Galanter, & Pribram, 1960) and a content-oriented perspective (Bandura, 1965; Kanfer, & Phillips, 1970, Chaps. 5 & 8). The notion of internal models is still widely accepted.

However, only recently research has begun to examine complex human action control more widely, for example, the above-mentioned studies in the tradition of the ideomotor approach (e.g., Prinz, 1987; Jeannerod, 1985, 2006; Rosenbaum, Marchak, Bames, Vaughan, Siotta, & Jorgensen, 1990; Schack, 1999, 2010, Prinz, Beisert, & Herwig, 2013). Clearly, more research is required that examines the control of complex actions for a broad understanding of human behaviour.

1.1 An action-centred approach

Within this project, I would like to argue that theories of the cognitive system should not neglect action control. From an evolutionary point of view, cognitive functions, no matter how complex or ”high” they are in terms of abstract capabilities, seem to have evolved in the service of optimal control of behaviour (e.g., Hoffmann, 1993; Nitsch, 2000; Llinás, 2001). In this sense, human life is action-centred (and meaning-driven[3]) and, therefore, a theory of the human cognitive system should not only incorporate but also focus on action control. In fact, if behaviour is not narrowly defined as muscle activity but to include all related structures and sub processes, especially control processes for complex actions, then behaviour more widely defined can be seen to contain a vast range of responses **(Koester, & Schack, 2014)**[4]. As shown in Figure1.1, human responses can broadly be classified in overt vs. covert responses (incl. mental processes) and further into central vs. peripheral responses. Accordingly, any organ of the human body can be involved in one type of response or another which is good reason to consider action control in theories of the human cognitive system.

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[3] I would like to mention in passing that optimal human behaviour can probably not be reduced to mechanistic processes as our cognitive system is more governed by semantic associations than by rational or logic relations (Fischler, Bloom, Childers, Roucos, & Perry, 1983; Kahneman, Slovic, & Tversky, 1982; Kahneman, 2011) or cognitive heuristics (Gigerenzer, & Brighton, 2009, for review)

[4] References to publications for the habilitation will be typeset in boldface.

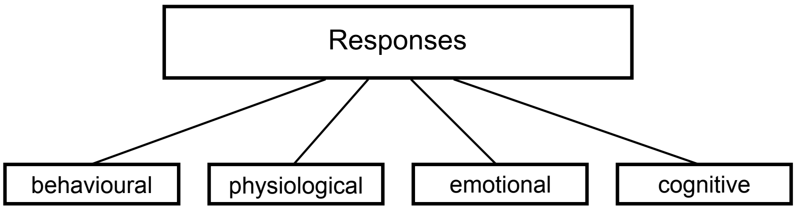

Figure 1.1: Subdivision of responses into multiple response systems

1.2 Hierarchical processing and representations

As mentioned, the motor system is characterised by hierarchical processing. The historical conception of a strict separation of sensory and motor systems as input and output pathways was challenged by the important introduction of an additional process, namely a comparison operation (Miller et al., 1960). Pribram (1971) proposed that the so-called TOTE mechanism (*test-operate-test-exit* as a cyclic process) is a fundamental property of the nervous system as it was now considered an information processing device. The TOTE mechanism refers to a constant comparison between an actual and a ”desired” state (test). If a deviance is detected, a change is prompted (operate); if there is no deviation, no changes are necessary (exit). As an example showing that sensory and motor signal cannot be strictly separated, Pribram (1971, Chaps. 5, 12 & 13) proposed TOTE to function as a servo mechanism for movement control (i.e., muscle activity) which he sees in the reflex arc within the spinal cord. That is, sensory signals (e.g., muscle length measured through neuromuscular spindles) and motor signal (α and γ motor neurons) are interdependent and can be modulated from higher neural centres. (That is, higher centres do not encode muscle contractions but represent modulatory commands for the spinal control mechanism.[5]) This hierarchical organisation of the neurophysiological motor system is still maintained in current reasoning (e.g., Pritzel, Brand, & Markowitsch, 2003; Grafton, Aziz-Zadeh, & Ivry, 2009; Trepel, 2012).

It has not only been argued for a hierarchical organisation of movement control on this ”lower” neurophysiological level (spinal cord) but also on ”higher” levels when it comes to more complex actions involving more muscles or effectors and their co-ordination. Cognitive phenomena such as goals, predictions or intentions are correlated with cortical activity and have also been seen to be effective very early on in human development (Gergely, Bekkering, & Király, 2002, see also Schachner, & Carey, 2013). Gergely and colleagues demonstrated that preverbal infants imitate novel actions (pressing a buzzer with one’s forehead) but only if the hands of the model are constrained and, thus, are not available for the

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[5] Interestingly, Pribram (1971, pp. 250) also assumes that higher level control encodes ”environmental contingencies” of the movement execution, i.e., *anticipated* movement effects.

action. This suggests that infants' actions are influenced by the model's *intention*. Such an early, developmental influence of intentions on action control underlines the fundamental role of cognitive representations for human behaviour (and observation learning). Noteworthy, there is not only a hierarchical organisation across various levels of movement control, from reflex mechanisms (spinal cord), to body postures (among others, cerebral cortex) up to action goals (cognitive representations), but there are also hierarchical relations within the cognitive level. With reference to the ideomotor principle, Wohlschläger et al. argue that goal representations are hierarchically structured, not the according motor programmes or (sub) movements (Wohlschläger, Gattis, & Bekkering, 2003; Whiten, Flynn, Lee, & Lee, 2006). That is, people may execute different movements than observed (during imitation) in order to achieve an inferred goal of a model. Again, these findings point towards an important, maybe fundamental mechanism human action control in that behaviour (and reasoning) is organised in a hierarchical fashion, although it is oftentimes realised in a sequential manner.

Similarly, in language processing, hierarchical structures play an important role too. Here, the empirical research field has evolved sub divisions. With some exceptions (e.g., the *logogen* model beginning with Morton, 1969; Patterson, & Shewell, 1987; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001, computational model rooted in the parallel distributed processing approach; Rumelhart & McClelland, 1986 and McClelland & Rumelhart, 1986) usually aim to connect language input and output [6]), language comprehension is largely investigated separately from language production, roughly corresponding to "input" and "output" streams. On an independent dimension, oftentimes a phrasal (syntactic), a lexical, a phonological and an articulatory level are distinguished and serve as research foci.

In this project, I will mainly focus on the lexical level, that is, on the structure of words and how structural changes of words are processed (*morphology*). For example, "know.ing"[7] (inflection), "un.believ.able" (derivation) and "movement science" (compounding; in English morpheme boundaries are often indicated by a space) are all internally structured words which are thought to reflect three different word formation mechanisms according to standard linguistic theory. In addition to Chomky's arguments mention above against a serial association mechanism for sentence processing, it should be noted that language is inherently hierarchically composed. A finite set of phonemes is used to construct an in principle extendible set of words; a finite set of words is used to form an (in principle) infinite set of sentences and discourse may be seen as another level. That is, linguistic processing units vary in their scope and, importantly, lead to qualitative changes, namely they reflect sounds

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[6] Interestingly, connectionist models have a high biological plausibility. However, the questions of neural implementation and processing mechanisms are independent. Here, I will not discuss aspects of implementation of cognitive models (cf. Yuste, 2015a; Rubinov, 2015; Yuste, 2015b).

[7] Dots indicate morpheme boundaries.

but on ”higher” levels meaning and possibly intentions which may provide a processing connection to action control.

A different stance is taken by computational network approaches. Such approaches usually deny an explicit representation of word structure (morphology). Uninflected words (e.g., ”walk”), for example, are mapped through massively parallel distributed processing units in task-devoted computational networks onto past tense forms (”walked” in our example Pinker, & Ullman, 2002; McClelland, & Patterson, 2002). Interestingly, such networks can also correctly map irregular forms such as ”go” onto ”went.” In this view, morphology itself is not considered necessary for word formation; all apparent morphological effects are thought to result from the (combined) processing of semantic and phonological information, i.e., without an intermediate, connecting level of processing. Oftentime, morphological effects are claimed to result from subtle semantic or phonological differences among stimulus lists (e.g., Joanisse, & Seidenberg, 1999; Plaut, & Gonnerman, 2000).

However, if morphological effects are observed in cases where neither semantics nor phonology differ, one has to consider morphological processing as an effective cognitive mechanism. In fact, morphological priming effects have been shown for compound production (speaking) where the effects resulted from the comparison of the very same words which had been primed differently **(Koester, & Schiller, 2008, 2011)**. The use of a so-called long-lag priming paradigm makes it possible to fully control the influence of semantics and phonology (cf. Zwitserlood, Bölte, & Dohmes, 2000; Feldman, 2000; Dohmes, Zwitserlood, & Bölte, 2004, for compounds). Hence, it is argued that we cannot dispense of morphological processing levels, i.e., hierarchical structure in our models of language production.

For understanding compounds, their morphological structure is also relevant (Downing, 1977; Fabb, 2001). That is, for most compounds, their constituents have to be identified, and their morphological status has to be taken into account in order to correctly interpret the whole compound (e.g., Taft, & Forster, 1976; Marslen-Wilson, 2001). In Dutch, as in English and German, the last constituent in compounds determines the semantic category, again underlining the hierarchical nature of word representations. (This relation varies across languages.) For example, ”movement science” refers to particular field of science, not to a particular sort of movement. One major debate in the area of compound comprehension focuses on whether and how the constituents are separated. That is, how the compound is decomposed (e.g., Sandra, 1990; Zwitserlood, 1994; Baayen, Dijkstra, & Schreuder, 1997; Isel, Gunter, & Friederici, 2003; Koester, Gunter, Wagner, & Friederici, 2004; Janssen, Bi, & Caramazza, 2008). In this context, we pointed out that after decomposition another step is necessary for a successful understanding of the compounds, namely semantic composition, the integration of the constituent meanings taken their morphological status into account (**Koester, Holle, & Gunter, 2009; Holle, Gunter, & Koester, 2010**). This poses the question whether compounds are processed differently than non-compound words and if this is the case, how the processing is controlled. Prosody is a promising candidate as it differs for compound and non-compounds words (Vogel, & Raimy, 2002; Koester et al., 2004) and has been shown to change the brain processing that is presumably underlying the evaluation performance regarding compounds **(Koester, 2014).**

In any case, it is highly implausible that the language system is organised in a non-hierarchical manner. Whereas computational, connectionist model make the claim that structure lexical processing (morphology) can be dispensed of, it is inconceivable how such a system would deal with sentence processing. Especially Chomsky's (1959) argument that humans can create and understand sentences that they have never perceived before, seems not to be reconcilable with fundamentally associative processing mechanisms. Even simpler theories of syntax include a considerable amount of rules, i.e., non-associative mechanisms (e.g., Culicover, & Jackendoff, 2005).

Turning to the visual domain, i.e., reading, structural (word) information can also be found employed by readers. Generally, it is obvious from eye movements during reading that text is not read, i.e., scanned linearly (Clifton Jr., Ferreira, Henderson, Inhoff, Liversedge, Reichle, & Schotter, 2016; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Neither letters nor words are serially fixated and there is a considerable amount of re-fixations as well as frequent skipping of words, especially functions words. Specifically, for compound words we could show in Dutch, where compounds are written without spaces (e.g., "bewegingswetenschappen," "beweging" [movement] + "wetenschap" [science]), that letter combinations that can only occur at morpheme boundaries are used as signals for decomposing the compound word which helps in determining the meaning of the whole word **(Lemhöfer, Koester, & Schreuder, 2011)**; the role of similar segmentation cues has previously been discussed (e.g., Inhoff, Radach, & Heller, 2000; Bertram, Pollatsek, & Hyönä, 2004).

Taken together, it appears obvious that complex actions and language are governed to some extent by hierarchical processing and representations. However, it still remains to be clarified what are the precise functional neuroanatomical and temporal characteristics of the underlying biological processes. At least three aspects seem to be characteristic of hierarchical representations. First, *categorisation* is a necessary but not a sufficient condition. If only instances of objects or events could be recognised, it would seem impossible to treat equivalent objects or events in the same way. Second, *recursion* can be expected to be possible in hierarchical representations. That is, categories of objects or events can be repeated or embedded, even in themselves. This feature permits the creation of, in principle, an infinite number of sequences and the creation of novels sequences. The TOTE mechanism can be seen as a simple mechanism featuring recursion. Third, *long-distance dependencies* are a typical aspect of hierarchical representations. That is, specific objects or events are not determined by the preceding element but by elements at a further distance such as subject-verb agreements in longer sentences where the subject and the verb are separated by intervening words or a phrase. The same holds true for complex actions where preparatory sub movements (e.g., the run-up in long jump, impacts later, non-adjacent sub movements (e.g., the landing). These aspects do not have to be found in conjunction and not in every representation that is hierarchical; hierarchical representations seem to require categorisation. Recursion and long-distance dependencies appear to be indicators of hierarchical processing or representations, that is they are not *both* necessary.

1.3 Modularity

As said, action control can be seen as a bridge to connect various cognitive domains which have been investigated separately because the concerted cognitive activities should optimise the behaviour (Norman, 1980; Hoffmann, 1993). Under ordinary circumstances, our subjective experience of the world is coherent and united. We do not, for example, experience objects as consisting of separate features such as colour, shape texture or size; we experience *one* object.[8] Contrary, to such a unitary subjective experience, psychological science largely approached its subject matter analytically as many sciences do. One wants to find and understand the fundamental mechanisms and principles that provoke and govern the phenomenon of interest. This reductionist approach aims to explain human experience and behaviour with a limited set of underlying, causal factors. Regarding the human cognitive system, this approach leads to a modular architecture in which it is assumed that the human mind consists of modules that are informationally encapsulated. That is, the modules are impenetrable (i.e., domain specific & autonomous), quick and have specialised cognitive functions (Coltheart, 1999). Such a modularity was prominently proposed by Fodor (1983, for further discussion, see Fodor, 2000), specifically for sensory-perceptual and cognitive (at least linguistic) processing levels (but see Sperber, 1994, for an extension beyond these domains).

The modularity hypothesis has a high explanatory value and can accommodate a number of findings. For example, the relationship among given brain structures and cognitive

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[8] The separate processing of these features, as proposed, e.g., in the feature integration theory (Treisman, & Gelade, 1980; Kahneman, Treisman, & Gibbs, 1992), leads to the so-called *binding problem*, the question how processing in distant neural populations or circuits can lead to a united experience.

functions or (double) dissociations of behavioural-brain functions support the modularity hypothesis (Dunn, & Kirsner, 2003). Regarding language, Fodor (1983) pointed out that, for example, comprehension is such a specific function that it is very likely to be informationally encapsulated, i.e., independent of other cognitive domains. This is because lexical comprehension is essentially a many-to-one mapping, that is, a vast number of stimuli, written (in different handwritings or prints) or spoken (in various speeds or emotional states) etc., have to activate one and only one lexical representation (associated with the given word). It is also in line with various areas and sections of the motor system that are functionally separable, at least one can relate different anatomical structures with different functions. In contrast, it is difficult to imagine how a strongly opposing perspective (strict non-modularity) would incorporate findings from the cognitive neuroscience for the whole cognitive system (but see Mesulam, 1990). It appears that some version of modularity is necessary as many findings are difficult to reconcile with a strictly non-modular architecture.

A weaker version of the modularity hypothesis could be seen in some of the recent embodiment frameworks. In these approaches, it is suggested that cognitive functions are rooted in more concrete body control functions, i.e., sensory-perceptual and motor systems (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Wilson, 2002; Clark, 1999). For example, word representations which are symbolic representations involve also neuroanatomic parts of the (sensori)motor system (e.g., Hauk, Johnsrude, & Pulvermüller, 2004; Chwilla, Kolk, & Vissers, 2007; Rüschemeyer, Brass, & Friederici, 2007; Fischer, & Zwaan, 2008; Van Dam, Rueschemeyer, & Bekkering, 2010). Such findings support the view that higher cognitive or symbolic representation, such as language, are partly supported by modality-specific neural systems (Glenberg, & Kaschak, 2002; Rizzolatti, & Arbib, 1998).

It should be noted, however, that strong and weaker versions of the modularity hypothesis lead to fundamental questions; strong versions face contradictory evidence regarding the impenetrability of perceptual functions and weaker versions suffer from reduced explanatory value as they reduce or give up the independence of modules (Stokes, & Bergeron, 2015). Also, theories diverge broadly regarding the degree of embodiment (Clark, 1999; Gentsch, Weber, Synofzik, Vosgerau, & Schütz-Bosbach, 2016). Independent of such criticism, a modular perspective of the cognitive system may contribute to a theoretical fragmentation of psychological phenomena. Various cognitive domains or psychological phenomena are investigated independently and may, consequently, be believed to be also functionally independent and separable. For example, by using a factor analytic approach, Carroll (1993) distinguishes ten cognitive domains with more than a dozen cognitive factors for each of the language and the psychomotor domains.[9] Hence, the unity of psychological phenomena as given in subjective experience may be questioned fundamentally.

One may also see a practical fragmentation of psychological research on an institutional level into a multitude of disciplines devoted to specific psychological fields. Assuming a theoretical independence, such an organisation may also (implicitly) question the unity of the subject matter. However, with recently developed techniques and nowadays conceptual and methodological advances, an integrated approach to understand also the interplay among cognitive domains should be promising.

Unfortunately, there is no straightforward solution in sight at present. Maybe the borders of strong modularity have to be pushed back to sensory processing for structural neuroanatomic reasons (e.g., separate pathways of the sensory modalities). After sensory processing, interactions among cognitive domains may have to be accepted to some extent. For some functions (e.g., executive functions or attention) this seems to be mandatory. However, evidence for independence of some functions such as double dissociations cannot be denied. Finally, there is the principled possibility that the processing configuration is flexible, i.e., task or context dependent. That is, the cognitive processing mechanisms might be adapted to current demands on behaviour.

Two research fields that, obviously, need integration are language comprehension and production. Presumably, theoretical progress does not yet permit a fully integrated theory. There have been some attempts of an integrated view (Price, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Bock, Dell, Chang, & Onishi, 2007; Price, 2010) but mostly an integrated approach was important in neuropsychology as language tests often include reading aloud or word repetition, that is, tasks that involve both comprehension and production (Luzzatti, & De Bleser, 1996; Bormann, & Weiller, 2012; Jarema, Perlak, & Semenza, 2007; Chiarelli, Menichelli, & Semenza, 2006).

Another phenomenon where both comprehension and production are essential is translation (e.g., de Groot, 1992; Green, 1998; Kroll, van Hell, Tokowicz, & Green, 2010). Some models of translation claim an asymmetry between bilingual lexical access (Grosjean, 2000 but see Paulmann, Elston-Güttler, Gunter, & Kotz, 2006) and translation directions (between native, L1, and second language, L2 Kroll, & Stewart, 1994). Accordingly, word translation from L1 to L2 is assumed to be conceptually mediated, i.e., involving lexical meaning representations. In contrast, translation from L2 to L1 is assumed to be mediated by associative links between L2 and L1 word forms. That is, L2 to L1 translation would not activate the meaning representation (or only with a considerable delay). As this hypothesis was based

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[9] Carroll (1993) conceives of the factors as corresponding to real effective functions of the human cognitive system, not as "merely mathematical artifacts" (p. 642) although some factors may be correlated.

on behavioural data (reaction times), more sensitive measures such as ERPs can help to test the semantic processing in both translations directions. To this end, we performed a single word translation study **(Christoffels, Ganushchak, & Koester, 2013)** in which we investigated the temporal unfolding of translation processes by using ERPs. In this study, a similar N400 effect, as a marker of lexical-semantic activation (Van Petten, & Luka, 2006), was found for both translation directions. The latency of the N400 effects did not differ between translation directions either. Thus, it was concluded, as one result, that both translation directions involve conceptual mediation. More generally, this study makes a contribution to the integration of the research fields of language production and comprehension.

Taken together, it is suggested that the human cognitive system and its neural underpinnings are characterised by some correlations between functions and anatomical structures, that is, it shows at least some degree of modularity. At the same time, it has to be acknowledged that not all research fields or cognitive domains are independent even if the current state-of-the-art of science treats them independently; such a situation may rather reflect the current stage of theory development. Hierarchical processing and representations may be found in multiple, if not all, cognitive domains and, thus, provide a connecting principle for understanding and explaining human behaviour. Before discussing some integrative research, the action and the language domains will be discussed.

Chapter 2

Action control

In this chapter I will discuss briefly some aspects of the publications that pertain most closely to action control or, more generally, to human behaviour. Needless to say, human behaviour cannot exhaustively be described as muscle activity. Instead, behaviour is also influenced by cognitive (e.g., goals or anticipations) and even sensory processes (as in sensorimotor control; e.g., Prinz, 1987; Jeannerod, 1985; Rosenbaum et al., 1990; Schack, 1999; Prinz et al., 2013). In **Koester and Schack (2014, p. 595)**, we have suggested a wide characterisation of human behaviour (i.e., *responses*) as ”any reaction of the organism to external or internal events” (see Fig. 2.1; cf. also Janke, & Kallus, 1995; Prinz, 1990). As we pursue an action-centred and (action) effect-related approach (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001; Prinz, 1990; Marken, 1986), we would like to emphasise that behaviour can be seen as manifold responses. Such responses can occur on various levels of body function and may be classified as overt vs. covert responses, although these organisational principles are not completely independent.

Overt and covert responses can be distinguished by the possibility of direct observations of movements by an outside observer. Overt responses involve some form of movement which can range from gross body movements to minor, subtle movements, even inside the body. For example, a response of the cardiovascular system may result in an increased heart rate or blood pressure and, thereby, be observed in a blushing reaction (change in skin colouration). In contrast, covert responses are understood as internal information processing with an emphasis on the psychological system for the present purpose. These covert responses can only indirectly be measured.

As indicated in Figure 2.1, overt and covert responses are supported in parts by the central nervous system (CNS). The CNS activity can further be differentiated into specific (e.g., the motor system) and unspecific nervous subsystems (i.e., attention system). As we are interested in the cognitive system, it is of interest how such CNS activity can be evaluated. Here, we pointed out that not only central measures (e.g., EEG/ERPs, fMRI, near infra-red spectroscopy, transcranial magnetic stimulation, intracortical recording, etc.) are available but peripheral measurements can be equally informative (e.g., responses of the eye—movements, scan paths, changes in pupil size—electromyography, electrocardiogram, electrodermal activity, etc.; **Koester, & Schack, 2014**).

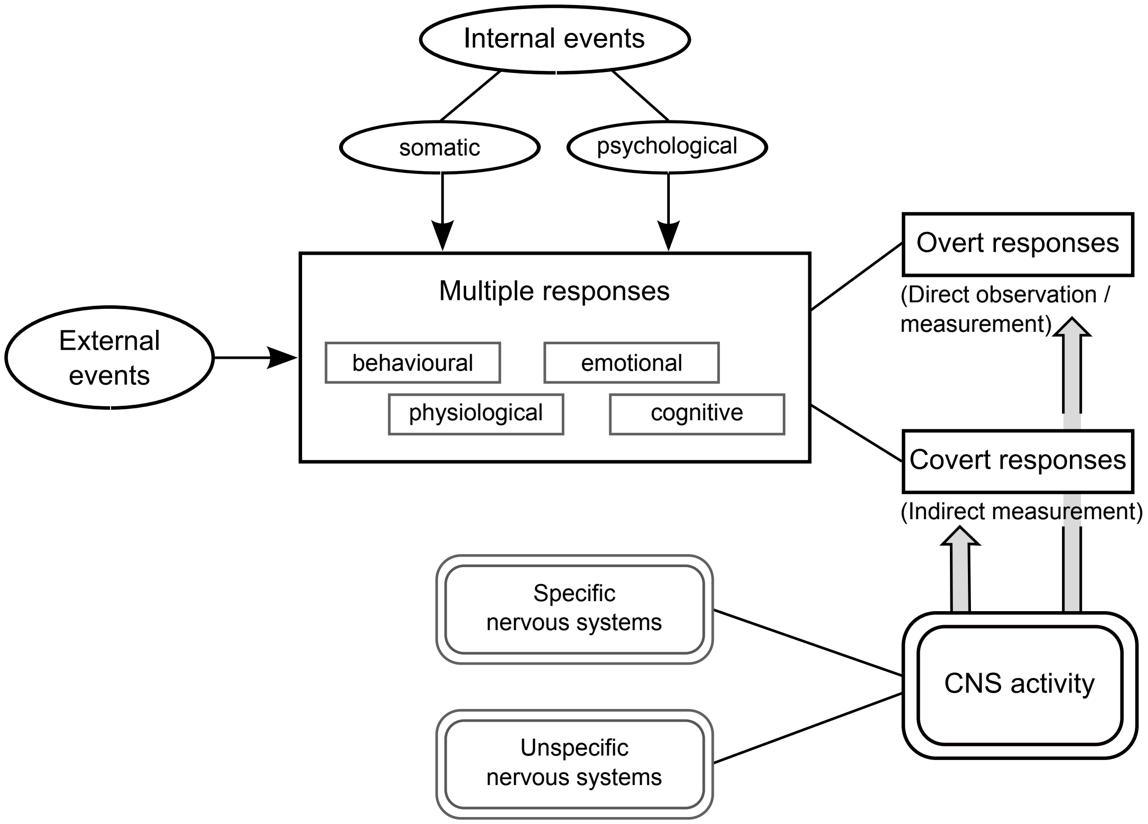

Figure 2.1: Humans can respond in multiple ways (multiple response systems) to external or internal events. Responses can be classified grossly into overt and covert responses which are both partly subserved by the central nervous system (CNS). Within the CNS, specific and unspecific systems can be distinguished.

Another, maybe more common classification of human behaviour is a continuum from automatic, reflex-like to voluntary, intentionally-induced actions (cf. Herwig, & Waszak, 2009). Voluntary movements which are characterised as goal-directed behaviour (Hommel, 2008; Konczak, 2008, for overviews) have been addressed mostly by theories in the tradition of the ideomotor approach in which anticipations of movements effects play a critical role in the initiation and regulation of movement executions. Such cognitive approaches to movement (e.g., Jeannerod, 2006) often contrast with dynamical system approaches which try to explain movements with properties of the body and, to various extent, of the environment, that is, also without internal models (Wolpert, Ghahramani, & Jordan, 1995; Beer, 2000; Ijspeert, Nakanishi, & Schaal, 2002). It should also be noted that cognitive control is not required for all complex movements (e.g., postural control or walking), specifically spinal control and muscle synergies (D'Avella, & Bizzi, 1998; Poppele, & Bosco, 2003; Debicki, & Gribble, 2005). This is to say, the present focus on *cognitive* processes is not intended to de-emphasise other levels such as sensorimotor control (e.g., Kawato, 1999; Todorov, 2004).

There are models that target more specifically the control of movements. For example, *internal motor models* try to explain complex movement by relaying sensory information through some algorithms to motor commands. A reasonable algorithm would then hold not only for one specific movement but for a whole class of movements. Such internal models offer a good explanation for motor learning (cf. Konczak, 2008). Another successful approach is Schmidt's theory of *generalised motor programmes* (GMP) which partly builds on Keele's more concrete motor programmes of muscle activity (Schmidt, 1975; Keele, 1968). Schmidt assumes that only invariant movement parameters are stored and not concrete muscle commands. Hence, one GMP can explain why humans can execute some (learned) movements similarly with different effectors (e.g., writing one's own name). Some of the present work relates to the *cognitive action architecture approach* (CAAA; Schack, 2010; Schack, Schütz, Krause, & Seegelke, 2016) which proposes four level of control and representation for movement control (see Tab. 2.1). A related concept has been suggested by Bernstein in 1947 (cf. Feigenberg, 2014; Bernstein, 1975) assumed an architecture of motor control that ranged across levels from involuntary to voluntary movements.[1]

Table 2.1: *The levels of control and representation in the* cognitive action architecture approach *(CAAA) approach (Schack et al., 2016).*

Code	*Level*	*Main function*	*Content*
IV	Mental control	Regulation	Symbols, Strategies
III	Mental representation	Representation	Basic Action Concepts
II	Sensorimotor representation	Representation	Perceptual representations, Internal models
I	Sensorimotor control	Regulation	Motor primitives, Basic reflexes

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[1] The importance of other principle of action control such as the re-afference principle, effects response selection, movement complexity, Fitts' law, stimulus-response compatibility or response-effect compatibility are acknowledged but are not focussed here.

The CAAA approach is concerned with the representation and the control of (complex) movements, no matter whether the whole body is involved (e.g., in a tennis serve) or only parts of it (e.g., in manual actions). This approach follows the ideomotor approach in that it also assumes bi-directional links between movements and their perceptual effects. In this model, four levels are distinguished; two for mental vs. sensorimotor representations and two for mental vs. sensorimotor control. An overview is given in Table 2.1 (Schack, 2004). Sensorimotor control (level I) refers to reflex-like processes of motor control whereas sensorimotor representation (level II) is concerned with sensory-perceptual information incl. the current of intended body states. The level III (mental representation) houses the cognitive specification for particular movements or classes of movements, and the level of mental control (IV) carries out symbolic or strategic movement planning and execution.

Of particular interest is the movement representation (level III). An optimal movement representation reflects the biomechanical demands and the functional structure of the (complex) movement itself (e.g., a tennis serve) which consists of several and separate movement sub phases (i.e., pre activation, strike & final swing phases Schack, & Mechsner, 2006). A movement representation comprises its constituents, that is, *basic action concepts* (BACs, e.g., bending knee, bending elbow or racket acceleration, etc.) and the relationship among the BACs. In an optimal movement representation, the BACs are grouped together according to their function (often corresponding to sub phase). For example, the BACs *bending knee* and *bending elbow* would be grouped together (with further BACs) to represent the movement sub phase *pre activation* which has the function to generate energy and to prepare the main phase (strike). In contrast, those groups of BACs that contribute to different movement sub phases (i.e., different functions), are kept separated or, in other words, are not associated (the BACs *racket acceleration* & *bending knee* in the example). The BACs themselves are assumed to bind together the sensory/perceptual features (e.g., visual, proprioceptive or vestibular) and the motor features of a given movement part (e.g., motor commands for movements and for stabilisation) for a function of a sub movement. That is, a(n optimal) movement representation is conceived of as a hierarchically organised structure of memory content where the structure of the representation reflects the optimal biomechancial and functional movement structure. These movement representations can be measured objectively with the so-called *structural dimensional analysis—motor* (SDA-M; Schack, 2004).

We have used this method to investigate cognitive aspects of expertise in indoor climbing **(Bläsing, Güldenpenning, Koester, & Schack, 2014)** as a specific form of manual action control. To investigate expertise, novices and athletes (i.e., climbers) were tested in a cross-sectional design. The study employed two methods in an integrative effort to relate processing and representation of grasp-related climbing knowledge. These methods were a classical priming paradigm and the SDA-M, respectively.

The SDA-M consists, in principle, of four analysis steps. First, participants undergo a splitting procedure during which they are presented with all stimuli pairwise. The stimuli are usually the basic action concepts; in our case there were 16 pictures of different climbing holds for four (appropriate) grip types. Participants perform exhaustive pairwise comparisons (i.e., related-unrelated judgements) regarding the similarity of the two BACs. In our study, participants had to indicate whether the two grasping holds require the same grip or not. This splitting procedure yields a distance scaling among BACs. Second, a hierarchical cluster analysis performed to obtain structural relation among BACs, and, third, a factor analysis is use to reveal the dimensions of the cluster structure. In a fourth step the cluster solution for an individual or a group of participants can be tested against a reference structure (e.g., of an expert) or against one another. There is a distance criterion d_{crit} corresponding to the statistical significance level α, below which BACs are interpreted to be associated and to represent a particular movement phase or, in the present case, a particular grip type. Overall, the SDA-M provides psychometric data on the *cognitively* represented structure of complex movements. For further methodological and mathematical details, see Schack (2012).

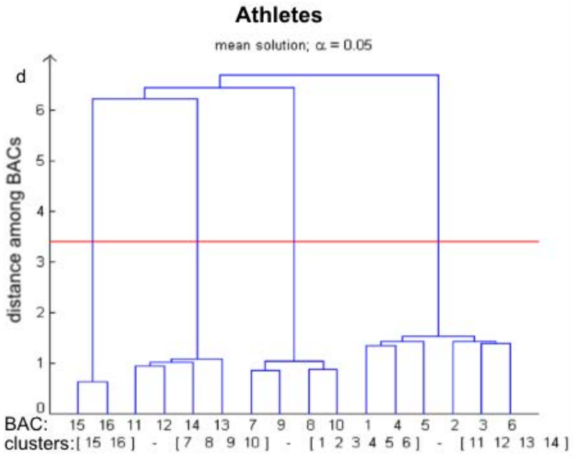

Figure 2.2: Cognitive representations of climbing holds for the athlete group (left panel) and the novice group (right panel) The red, horizontal line indicates the critical values $d_{\text{crit}} = 3.4$.

In our climbing study, we used the SDA-M to evaluate how the cognitive representations of climbing holds are structured, and we applied a visual priming paradigm using holds as primes and grasping postures as targets in order to evaluate the processing of grip representations **(Bläsing et al., 2014)**. The same participants underwent both procedures to ensure comparability. For the cognitive representations, see Figure 2.2; the cluster structure is shown in a tree-like diagrams. All holds are indicated separately on the x-axis (associated with different grips, formally BACs), and the y-axis represents the distance (or similarity) of the BACs. For athletes (Fig. 2.2, left panel), the BACs are represented as four clusters as can be seen from the (four) branches that cross the criterion of a critical distance (d_{crit}). These four clusters of grasps for the athletes correspond correctly to the four grip types[2] used in this study. This result suggests that athletes categorise climbing grasps appropriately and that their cognitive representation of grip types corresponds to a functional organisation.

Novices, in contrast, show a fundamentally different pattern (see Fig. 2.2, right panel). Many BACs (grips) are unordered (i.e., they are apparently not associated with other grips). This is indicated by the BACs' branches crossing the criterion before forming a node with another BAC. For the novice group, three clusters were found. However, these clusters did not represent functional similarity of grips but superficial features of the holds (possibly shape or colour). This result suggests that novices do not represent grasp holds according action functionality. Together with the results from the athletes, it was suggested that the different structures of climbing knowledge reflects the difference in expertise with the subject matter (Hoffmann, 2003). Hence, it may be speculated that experience with objects influences the way how these objects are represented on a cognitive level.

Furthermore, we asked whether such differences in representation would affect behavioural responses **(Bläsing et al., 2014)**. In the priming experiment, we paired not only holds (as primes) and grasping postures (as targets) that were adequate (i.e., congruent) or incongruent but we also included neutral holds which should not interact with the grasping postures. If the class of climbing hold representations do affect activation and selection of grip types (participants had to classify the target picture as crimp grip or sideways pull), athletes should show a response congruency effect, that is, faster processing of congruent vs. incongruent hold-grip pairs. Novices should not show a comparable result pattern or no effect at all. This prediction was actually borne out. Not only did we find a congruency effect for athletes. Moreover, we could show that congruent hold-grip pairs led to facilitation (relative to the neutral condition) and also incongruent hold-grip pairs led to inhibitory processing (again vs. neutral). This priming effect is in accordance with the observation that the perception of (manipulable) objects activates the associated actions (as measured by priming Labeye, Oker, Badard, & Versace, 2008). Novices showed no congruency effect.[3] Taken together, it is suggested that action experience with specific objects structures the cognitive representations according to the action possibilities (SDA-M result), and these functionally structured object representations are used for further action organisation (prim-

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[2] The grip types were: crimp grip, sideways pull, pocket grip and an open grip.

[3] In fact, novices responded faster in the neutral compared to the other conditions.

ing exp.). This interpretation is supported by better recall performance in expert climbers compared to novices for difficult climbing routes that has been suggested to reflect superior formation of motor chunks (Pezzulo, Barca, Bocconi, & Borghi, 2010). Similar to our study, experts seem to have functionally appropriate, cognitive organisation of climbing knowledge.

This finding is interesting for the CAAA approach because it suggests a specification of processing mechanisms within the level of mental representations (III) at least for manual actions. Briefly, for many situations, very fast action planning and execution is optimal (e.g., catching a falling cup). By experience one might reduce the almost infinite number of actions (towards an object) by forming action *categories* or grip *types* in the above example. Hence, relevant objects may upon perception activate appropriate action categories. Such an activation does not solve the problem of selection as more than one action category may be appropriate (or objects may be ambiguous). That is, multiple action categories may be activated to a similar degree. Given the interference effect in our climbing study, one could be tempted to argue that among action categories there is a mutual inhibition in analogy to the well-known mechanism of *lateral inhibition* (Blakemore, Carpenter, & Georgeson, 1970; Blakemore, & Tobin, 1972) which has also been applied to cognitive levels (e.g., Berg, & Schade, 1992; Shallice, 1972; Wheeldon, & Monsell, 1994) and action selection (Shallice, 1972, for a general role of cognitive competition, see Rosenbaum, 2014). That is, more strongly activated action categories (or grip types) would inhibit less activated action categories, thereby speeding up action selection. Lateral inhibition here can be understood as a suppression of competing action categories (i.e., of grip types) and might be considered as a form of reactive inhibition (Johnson, & Proctor, 2004). Along these lines, our results **(Bläsing et al., 2014)** can contribute to theory development (of action control) by specifying *within* level mechanisms and provide evidence for a beneficial combination of methods.

To extend our understanding of action control to underlying, biological possibly causal factors, further methods can provide valuable insight. Manual action, specifically grasping and reaching have been investigated with various neuroscientific methods, incl. animal studies (e.g., Rizzolatti, Camarda, Fogassi, Gentilucci, Luppino, & Matelli, 1988; Jeannerod, Arbib, Rizzolatti, & Sakata, 1995) but the generalisation to humans is not without problems (Castiello, 2005; Husain, & Nachev, 2007). In normal healthy humans, behavioural (e.g., observation or kinematic measurements), neuropsychological approaches and fMRI have been predominantly used. However, understanding the fast processes of action control in healthy humans would greatly benefit from neuroscience methods with high temporal resolution. A recent methodological extension for manual action control was the measurement of ERPs which had been avoided for fear of movement artefacts.

Despite potential movement artefacts, Kirsch and Hennighausen (2010) reported ERP effects for arm movements and Van Schie and Bekkering (2007) for grasp execution. The latter authors reported data for precision grips; in particular, effects in motor potentials over the parietal cortex before grasping an object and over the left frontal cortex before placing the object on the target position. Bozzacchi et al. (2012) investigated also precision grips and analysed the readiness potential (RP). These authors found an earlier RP over parietal areas and a later RP onset over frontal areas. Parietal effects have been suggested to reflect the specification of grip-related information that is further processed in frontal areas (Bozzacchi et al., 2012). While the temporal succession of effects is similar in these two grasping studies, it remains to be shown whether the ERP effects reflect the same functional mechanisms. Recently, the work by Van Schie and Bekkering (2007, grasp-and-place task) was extended to power grips (Westerholz, Schack, & Koester, 2013) and the ERP methodology was also applied to a grasp-and-rotate task (Westerholz, Schack, Schütz, & Koester, 2014) in further grasping experiments.

Notably, grasping actions have been related functionally to other cognitive domains such as (working) memory or attention (see Ch. 4. In line with a hierarchical perspective, grasping is not only influenced by physical variables (e.g., shape, weight, orientation, position, etc., e.g., Castiello, 2005; Desmurget, Prablanc, Arzi, Rossetti, Paulignan, & Urquizar, 1996) but also by cognitive variables (e.g., goals, intentions or anticipations, e.g., Herbort, & Butz, 2010; Kunde, Landgraf, Paelecke, & Kiesel, 2007; Rosenbaum, Marchak, Bames, Vaughan, Siotta, & Jorgensen, 1990) and habitual factors for action control (Herbort, & Butz, 2011; Logan, 2009).

The potential of neuroscience methods (with a further focus on attention) has been outlined specifically for movement and sport science **(Essig, Janelle, Borgo, & Koester, 2014)**. Although attention is critically involved in manual actions such as grasping (Baldauf, & Deubel, 2010; Hesse, & Deubel, 2011) and may have a relevant role in mediating between motor and perceptual processes (Kirsch, 2015), it should be noted that different functions (or movement parts, such as reaching vs. grasping) or different effectors (e.g., eye and its saccades vs. hand) may be differently affected by attentional processes (Deubel, & Schneider, 2003).

Here, I would like to stress again the high potential that neuroscience methods, especially ERPs, bear for movement science and our understanding of action control possibly in combination with other approaches (e.g., expertise approach) or further methods (such as eye movements; **Essig et al., 2014**). Another cognitive domain where ERPs proved particularly valuable is language processing to which I will turn now.

Chapter 3

Language processing

Regarding language processing, some of my work has been devoted to amend our understanding of lexical processes, in particular the processing of compound words which are concatenations of words (free morphemes, to be precise). One prevailing question in language production concerns the status of morphology (i.e., the structure of words); whether it is psychologically real or an epiphenomenon (i.e., emergent from other factors, e.g., semantics and phonology). Structured processing of compounds is less controversial in comprehension but some theoretical positions seem inconsistent, and the present project will be provided new evidence in support of structured rather than holistic auditory comprehension of compounds. Prosodic and orthotactic (letter combinations) information will be suggested to provide cues for adjusting the parsing of compound words.

3.1 Production

As said, some have argued that morphological effects are simply a by-product of semantic and phonological processing (cf. sec. 1.2 Joanisse, & Seidenberg, 1999; Plaut, & Gonnerman, 2000, but see Pinker, & Prince, 1988; Pinker, 1991). This position is mostly promoted by neural network approaches and is also consistent with graded ERP effects of lexical-semantic processing (Morris, Frank, Grainger, & Holcomb, 2007; Gonnerman, Seidenberg, & Andersen, 2007). However, if one compares the brain responses to the very same words in different conditions (e.g., morphologically primed vs. not primed), any effects cannot be due to differently processing of semantic or phonological information.

In **Koester and Schiller (2008)**, we followed this rationale for investigating the morphological processing during overt speech[1] (picture naming, a common task in language

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[1] For other modalities, e.g., writing see Bertram et al. (2015; Damian, Dorjee, & Stadthagen-Gonzalez, 2011; Perret, & Laganaro, 2011).

production research). In this ERP study, we aimed to measure the timing of morphological processing (onset & duration) by means of ERPs. The continuous nature of ERPs is one of their advantages, next to their high temporal resolution. In a previous meta-analytic study of language production (Indefrey, & Levelt, 2004), morphological processing (arising at the stage of word form encoding) should begin around 330 ms after picture presentation; this estimate assumes an average response latency of 600 ms.

To exclude semantic and phonological influences, two methodological measures were taken. Briefly, a long-lag priming paradigms was used in which prime and target stimuli are separated by 7–10 intervening trials. For this paradigm it was shown that neither semantic nor phonological priming effects (nor interference effects) survive such a distance between primes and targets (Feldman, 2000; Zwitserlood et al., 2000). This paradigm has also been used successfully for compound production (Dohmes et al., 2004). As a second measure to control for semantic and phonological effects, three experimental conditions were constructed that varied in their prime-target relations. Primes (compound words, to be read out loud) could be morphologically and semantically related to the targets (pictures), the relation could be morphologically but not semantically related and, finally, the primes and targets could be phonologically related but neither morphologically nor semantically (see Tab. 3.1). These conditions are labelled *transparent*, *opaque* and *form-related*, respectively. There was also an unrelated condition as a baseline.[2] Again, the same targets were used in all conditions and if morphological priming is effective, the following pattern should be found. Regarding the ERPs, the N400 component is expected to be modulated in its amplitude as the N400 shows a sensitivity to morphological processing (McKinnon, Allen, & Osterhout, 2003).

Table 3.1: *The relationships among the experimental conditions and lexical processes in* ***Koester, & Schiller (2008; 2011)****. Ticks represent a positive relationship. Together with the characteristics of the long-lag priming paradigm, the various comparisons permit conclusions about morphological processing; see text.*

	Condition			
Relation	*Transparent*	*Opaque*	*Form-related*	*Unrelated*
Morphological	✓	✓	-	-
Semantic	✓	-	-	-
Phonological	✓	✓	✓	-

If there is true morphological processing one can expect the following effect pattern. *Transparent* and *opaque* conditions should both yield a priming effect relative to the unre-

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[2] Conditions were distributed across two sets of stimuli as it was not possible to construct all conditions within one set.

lated condition as both are morphologically related. Moreover, these two conditions should show a comparable effect because semantic information should not be effective in a long-lag paradigm. In contrast, if any priming effect would reflect semantic processes, the priming effect for *transparent* should be greater than for *opaque* because only *transparent* primes are, in principle, semantically related to the targets. Regarding phonology, the form-related condition (e.g., "trombone" → *bone* as a picture) should *not* yield a priming effect because primes and targets are not morphologically related. Generally, the *transparent* and *opaque* conditions should pattern together, also the *form-related* and the unrelated conditions should pattern together, if only morphology is effective in the long-lag paradigm.

These expectations were confirmed in behavioural and in ERP measures (**N400 Koester, & Schiller, 2008**). The N400 effect for the *transparent* and the *opaque* conditions are reproduced as an example in Figure 3.1 (left panel); the unrelated condition shows a more negative ERP amplitude between 350 and 650 ms than the *transparent* and the *opaque* conditions which do not differ from one another. This pattern of results has a bearing on the psychological reality of morphological processes as these effects cannot be explained by semantic or phonological factors. That is, these support theories of language production that include morphological processing (e.g., Levelt, Roelofs, & Meyer, 1999; Schriefers, Zwitserlood, & Roelofs, 1991; Roelofs, 1998; Schiller, & Costa, 2006; Indefrey, & Levelt, 2004).

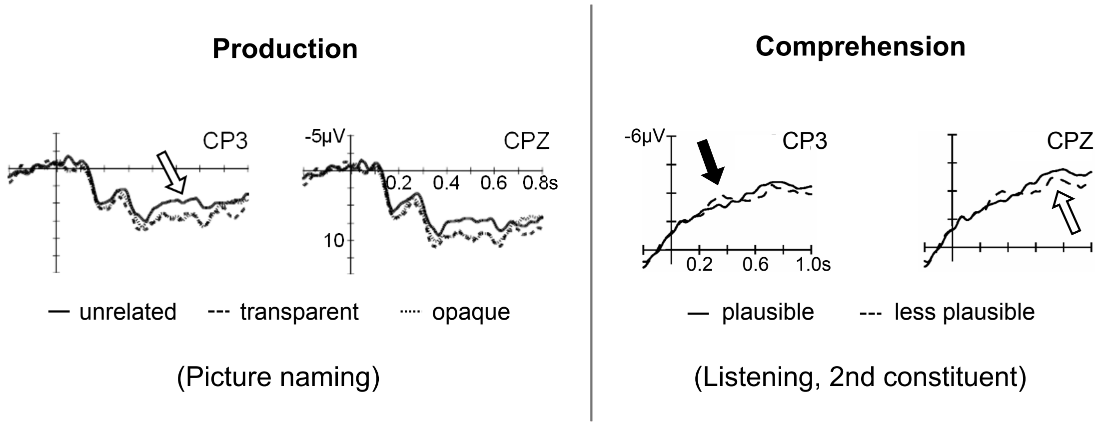

Figure 3.1: Event-related potentials for morphological priming effects during language production (left panel; from **Koester & Schiller, 2008**) and semantic integration (filled arrow) and re-structuring effects (blank arrow) during language comprehension (right panel; from **Koester et al., 2009**).

Regarding the timing of morphological processing (i.e., word form encoding), the onset of the ERP effects matches the estimate by Indefrey and Levelt (2004) closely. The average response latency in our ERP study was 652 ms. Indefrey and Levelt estimated word form encoding to begin around 330 ms after picture onset for an average response latency of 600 ms. If this figure is scaled to a response latency of 650 ms as in our case, word form encoding is expected to begin around 358 ms. This matches nicely with our morphological priming effect between 350 and 650 ms. That is, our results (N400; **Koester, & Schiller, 2008**) confirm the psychological reality of morphological processing and support the temporal estimates for these cognitive processes by Indefrey and Levelt (2004) for language production. More generally, our findings complement (ERP) studies on language production that used delayed or covert speaking (e.g., Jescheniak, Schriefers, Garrett, & Friederici, 2002) or require meta-linguistic decisions (e.g., Schmitt, & Münte, 2000; Van Turennout, Hagoort, & Brown, 1997).

Importantly, the just described study makes a seemingly relevant methodological contribution in showing that reliable ERPs can be analysed even if participants make (non-delayed) movement or, more generally, commit motor reactions. There is hardly any work that combines overt movements with the analysis of ERPs (but see Christoffels, Firk, & Schiller, 2007, from the same lab; Van Schie, & Bekkering, 2007). Interestingly, for spoken language, the source of muscle artefacts can hardly get closer to the brain, and yet reliable ERPs are feasible. To the best of my knowledge, **Koester and Schiller (2008)** report the first cognitive, N400 ERP component for overt movement executions. For a visual impression of the signal-to-noise ratio, compare the ERP waveforms for non-delayed spoken production in Figure 3.1 (left panel) with the ERP waveforms for auditory language comprehension in the same figure (right panel with delayed button-press responses; cf. 3.2).

Whereas ERPs are appropriate to evaluate temporal characteristics of neurocognitive processing, fMRI is more suited to evaluate the spatial aspects of functional neuroanatomy. Using the same experimental approach to morphological processing as just described, we investigated also the functional neuroanatomy of morphology in spoken language production **(Koester, & Schiller, 2011)**. Following the meta-analysis by Indefrey and Levelt (2004), one would expect that morphological priming affects neural activity in the left posterior superior and middle temporal gyri (see also Roelofs, 2008). However, when comparing the *transparent* and the *opaque* conditions with the neural activation for the unrelated condition, both morphologically related condition elicited an increase activation in the left inferior frontal gyrus (LIFG), specifically in Brodmann area (BA) 47; no conclusive effect was seen for the *form-related* condition **(Koester, & Schiller, 2011)**. Although this finding is inconsistent with Indefrey and Levelt (2004), it does corroborate fMRI evidence for derivational processing which also reports an involvement of BA 47 (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Meinzer, Lahiri, Flaisch, Hannemann, & Eulitz, 2009). More generally, our finding is consistent with morphology and morphosyntax being supported by the LIFG (Marangolo, Piras, Galati, & Burani, 2006; Marslen-Wilson, & Tyler, 1998; Tyler, deMornay Davies, Anokhina, Longworth, Randall, & Marslen-Wilson, 2002; Ullman, 2001; Laine, Rinne, Krause, Teräs, & Sipilä, 1999) even though BA 47 is not part of Broca's area proper. Taken together, our contributions to the area of language production support the temporal estimates of morphological processing in language production but the investigation of the functional neuroanatomy calls for further inquiries into the spoken production of structured words.

3.2 Comprehension

Regarding compound comprehension, the structured processing and accordingly the lexical representations, is accepted in many models (i.e., full-parsing & dual-route models). Full-parsing models assume that only morphemes are stored but not the complex words or compounds. Complex words are processed by combining the stored morphemes (e.g., Fiorentino, Naito-Billen, Bost, & Fund-Reznicek, 2014; Taft, 2004; McKinnon et al., 2003; Levelt et al., 1999; Taft, & Forster, 1976). Dual-route models[3] assume a direct processing route and a decompositional route. The direct route processes whole word forms whereas the decompositional route is supposed to retrieve the individual morphemes (e.g., Caramazza, Laudanna, & Romani, 1988; Sandra, 1990; Zwitserlood, 1994; Baayen, Dijkstra, & Schreuder, 1997; Schreuder, Neijt, Van der Weide, & Baayen, 1998, Koester et al., 2004; Fiorentino, & Poeppel, 2007). Only full-listing models assume the storage of whole compounds in addition to the representations of constituents as *separate* words (Butterworth, 1983; Bybee, 1995; Janssen, Bi, & Caramazza, 2008).

In order to understand a compound, that is, to create a semantic representation, one has to take into account the structure of the compound (unless it is represented in itself, e.g., for very frequent compounds). In German, the last constituent determines the semantic category of the whole compound and is, therefore, crucial for understanding. (It is called the *head*.) Given that the head has a central role in defining the compound's meaning, it seems possible that the comprehension system (*parser*) waits for this critical constituent by using, for example, prosodic cues in the auditory modality (see also below). This idea has been proposed with strong empirical support from a number of behavioural experiments (cross-modal priming Isel, Gunter, & Friederici, 2003). That is, the parser is assumed to change its processing configuration upon detecting a (spoken) compound word and to wait with the semantic integration (i.e., composition of meaning) until the head is perceived. Specifically, Isel et al.,

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[3] As related position is taken by multiple route models which are a recent theoretical contribution that assumes that all reliable morphological cues are used for parsing (Kuperman, Schreuder, Bertram, & Baayen, 2008; Marelli, & Luzzatti, 2012).

(2003) reported no semantic activation of non-head constituents before the head constituent was heard. In control experiments, it was shown that this was not an artefact of the specific stimuli; when the non-head constituents were changed in prosody to indicate single nouns (non-compounds), semantic activation was obtained.

In order to test this claim regarding the time course of semantic processing in auditory compound comprehension, we resorted to a continuous, possibly more sensitive measure (ERPs). In two studies, we tested for semantic processing *before* the head was presented, that is, while a non-head constituent was still being presented **(Koester, Holle, & Gunter, 2009; Holle, Gunter, & Koester, 2010)**.

First, we tested for lexical-semantic access of initial constituents which should be delayed according to the account by Isel et al. (2003). To this end, compounds were constructed that could contain pseudomorphemic foil constituents (e.g., "Patose.schlot," *patose chimney) either in the first or in the second constituent position. Foil constituents were created from nouns that were appropriate in the according compound position. All foils adhered to German phonological rules and were matched closely to their (word) counterparts. Participants had to listen for understanding and perform a semantic judgement task (comparison to subsequently presented visual test words). If lexical-semantic access is indeed postponed until the head is available, the ERPs for initial foil constituents should not differ from initial noun constituents. In contrast, if lexical-semantic processing is an incremental process, an N400 effect was expected. Indeed, such an N400 effect was found (500–700 ms after stimulus onset; **Holle et al., 2010**). Importantly, the initial constituents (c1) had an average duration of 701 ms. (All c1s were composed of three syllables.) Therefore, the N400 effect began before the head was presented, and it was concluded that lexical-semantic processing is not delay until the head is perceived. Rather, it seems that lexical-semantic access takes place incrementally.

Second, another attempt to understand auditory compound comprehension made use of three-constituent compounds **(Koester et al., 2009)** which are not investigated very often (e.g., Inhoff, Radach, & Heller, 2000). In this study, we were interested in semantic integration among constituents, that is, compositional processes (cf. Bai, Bornkessel-Schlesewsky, Wang, Hung, Schlesewsky, & Burkhardt, 2008). These are logically necessary if the stimulus has been decomposed. The question was whether such composition is delayed for compounds (Isel et al., 2003) or whether is an incremental process (Pratarelli, 1995; Koester et al., 2004). To address this question, we constructed three-constituent compound for which the second constituent (c2) was more or less plausible given the first. For this plausibility manipulation, independent participants generated c2s in response to c1s. Implausible c2s were not produced by any of these participants. The plausibility of the third constituent was manipulated in the same way with new, independent participants for the rating. Again, in the experiment proper, participants listened for understanding and performed a semantic judgement task. The critical comparison concerned the plausibility effect *during* the c2. If lexical-semantic processing is delayed, no effect is expected. However, if lexical-semantic processing is incremental in nature, an N400 effect can be expected which could arise from the increased semantic integration difficulty for less plausible constituents (c2; e.g., De Long et al., 2005 Van den Brink, Brown, & Hagoort, 2006). The ERPs showed a clear amplitude modulation by plausibility (see Fig. 3.1, right panel). Less plausible c2s elicited a greater N400 with a left-hemispheric dominance between 300 and 500 ms after c2 onset. Again, the head constituent (c3) began on average 370 ms after c2. That is, the N440 effect was traced before c3 was presented. Hence, the lexical-semantic integration of c1 and c2 did not depend on the availability of the head constituents, and it was concluded that lexical-semantic integration of compounds (composition) proceeds incrementally in the auditory modality.

Furthermore, the plausibility manipulation of c2 in our study elicited a further ERP effect, namely an increased P600 for less plausible c2s (600–900 ms after c2 onset; cf. Kolk, & Chwilla, 2007; Kuperberg, 2007). This P600 effect takes place during c3 (see Fig. 3.1, right panel). Although more speculative, it is conceivable that this P600 effect reflects the re-analysis of the compound structure. If the parser expects initially a two-constituent compound with an A-B structure, B would carry the head role, and a restructuring would be required when a head constituent is detected. That is, the A-B structure would have to be changed into AB-C, where B would change its role from a head to a modifier constituent. Such a re-analysis may be more resource-demanding for less plausible compound constituents, in line with an increased P600 amplitude (Hagoort, Brown, & Groothusen, 1993; Osterhout, & Holcomb, 1992; Friederici, Hahne, & Mecklinger, 1996). This interpretation is also consistent with the observation that there was not P600 effect for c3. As c3 was always the head constituent, no re-analysis was required and, accordingly, no P600 effect would be expected. Overall, these results **(Koester et al., 2009; Holle et al., 2010)**, clearly suggest that auditory compound comprehension proceeds incrementally and follows hierarchical morphological structures (Downing, 1977; Fabb, 2001).

3.2.1 Parsing cues

Here, it can only be speculated why Isel et al. (2003) did not find semantic activation of initial compound constituents (see above). As said, initial compound constituents and single nouns (non-compounded) differ in prosody, for example in duration and mean fundamental frequency (Vogel, & Raimy, 2002; Isel et al., 2003) and contour of the fundamental frequency (Koester et al., 2004; Farnetani, Torsello, & Cosi, 1988). Since compound constituents are shorter than single nouns, processing time may become a critical factor for building up semantic activation (Zwitserlood, & Schriefers, 1995); shorter durations (for a compound prosody) might not provide enough processing time for full semantic activation.

Finally, two factors should be mentioned that affect the comprehension of compound words; one for listening and one for reading. Prosody has been shown to differ for words that are produced as part of a compound or as a single word. If people are sensitive to these differences, prosodic cues can be used to change the processing configuration of the parser (Isel et al., 2003; Koester et al., 2004). That is, prosody might be an assistive cue because it is not available in reading (or only implicitly) that could be used to control the processing of word structure and, thus, increase processing flexibility.

Again ERPs were used to test whether the brain's response changes quantitatively or qualitatively when processing the same words once with a compound prosody and once with a single noun prosody **(Koester, 2014)**. To this end, participants listened to determiner + nouns constructions and made number agreement judgements and occasionally semantic judgements for these constructions. Importantly, the critical nouns (1/3 of all stimuli) carried in 50 % of the cases a compound prosody and in 50 % a single nouns prosody. These critical nouns were always followed by white noise that was actually created from an according head constituent (but this noise constituent was never intelligible). The ERPs were analysed only for these nouns. To avoid strategic responses, the experiment contained filler items; 1/3 were single nouns and 1/3 were two-constituent compounds. Neither of the filler nouns contained any noise. Hence, the processing of the critical stimuli (determiner + noun + noise) should not be biased towards a(n implicit) single noun or compound interpretation.

The results show a clear qualitative change in the brain response. For the single noun prosody, number violations[4] elicited a left-anterior negativity (LAN, 650–750 ms after noun onset; **Koester, 2014**) as it is known for morphosyntactic violations (e.g., Barber, & Carreiras, 2005; Deutsch, & Bentin, 2001; Gunter, Friederici, & Schriefers, 2000). In contrast, for the compound prosody, number violations yielded a right-anterior negativity that was delayed by about 600 ms. That is, the processing of number information was not only slowed down by the compound prosody but it led also to a distinct scalp topography of the associated ERP effect. Hence, it was concluded that prosody is an effective cue to compound processing and that the parsing configuration is flexible in that it is changed when a compound prosody

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[4] The violation paradigm is a standard methodological procedure to test for the temporal processing of specific types of information. Violations are assumed to disturb the relevant brain processes and, thereby, to strengthen the associated brain response.

is detected. This is generally, in line with the assumption of flexible dual-route mechanisms for the processing of morphologically complex words.

The second factor that may influence the structural processing of compounds relates to the visual modality. In a word reading study (compounds), the role of orthotactic, that is, letter combinations (*bigrams*) was investigated (**Lemhöfer et al., 2011**; Libben, 1994; Rastle, Davis, & New, 2004, for derivations). The question was whether or not people use such orthotactic information. That is, if letter *combinations* are used for parsing compounds, one should find an effect of the legality of the two letters forming the morpheme boundary. For example, the bigram ”sb” does not occur within (Dutch) morphemes. Hence, we asked whether such ”illegal” bigrams would facilitate compound processing as they may mark the morpheme boundary or make it more salient. For example, the compound ”fiet*s.b*el” (bicycle bell) should be easier to process than ”roo*m.i*js” (ice cream) assuming that ”sb” but not ”mi” marks the boundary (”mi” does occur within Dutch morphemes). Participants performed a lexical decision task on these stimuli (incl. filler items).

The main result was that the bigram legality of the morpheme boundary affected compound processing as reflected in reaction times. When the orthotactic cues was present (i.e., an illegal bigram such as ”sb”), participants were faster (751 ms) compared with compounds that contained no such cue (777 ms). Further analyses showed that this effect was only present for long compounds (more than nine letters) in accordance with previous studies in Finnish (Bertram, Pollatsek, & Hyönä, 2004; Bertram, & Hyönä, 2012, but see Inhoff et al., 2000). As the orthotactic cue was also effective in non-native speakers of Dutch (see **Lemhöfer et al., 2011** for details), it can be assumed that the orthotactic cue is generally used and its usage may be reduced with language proficiency. Native speakers may represent short compounds indeed holistically. This study points out that not all compounds are processed in the same way in reading; at least long compounds are decomposed and, presumably, are processed according to their hierarchical morphological structure.

In conclusion, the work described in this chapter suggests that compound structure affects processing which is in accordance with full-parsing and dual-route models. That is, brain responses and behavioural measures reflect the structured processing of compound words which speaks to the psychological reality of morphology. Especially, the production studies strongly argue for true morphological processing in the cognitive system. For the comprehension domain, there is evidence for specific processing cues in the auditory and in the visual modality. These cues seem to affect the way of parsing compounds. That is, the parser configuration appears to be variable or to consist of more than one way of processing which is in favour of dual-route models. Generally, it is argued that lexical processing at least compounding is structured according to hierarchical rules (i.e., morphology) in the production and in the comprehension domain.

Chapter 4

Domain interactions

The relations among different cognitive domains have been discussed for a long time, especially perception, language and action (Whorf, 1963; Greenwald, 1970; MacKay, 1987; Schütz-Bosbach, & Prinz, 2007), but the conceptions of scientific accounts of the cognitive system incl. the relationship among domains vary broadly (e.g., Clark, 1999; Gentsch et al., 2016). In contrast to Piaget, Vygotsky assumed that language plays an important role during development as a driving force, less as a consequence of thinking (Vygotsky, 1971; Duncan, 1995). Vygotsky understood language (*inner speech*) as a tool for cognitive development. Such a perspective implies an mutual influence of action and language processes. Of course, language plays not only a role for the acquisition of an appropriate behavioural repertoire but language also helps for the acquisition of conceptual knowledge. Language helps to sharpen concepts by forming categories (i.e., using the same words for similar but non-identical objects) and to communicate about objects or events (e.g., Hoffmann, 1986). Potentially, language fulfils a mediating or, maybe better, coordinating function in organising perceived objects and appropriate actions (and according concepts, e.g., MacKay, 1987) during development; vice versa neurocognitive language processing is shaped by experience (Pierce, Chen, Delcenserie, Genesee, & Klein, 2015). Needless to say, language cannot be the sole organising factor regarding the cognitive development (see Prinz, 2013, for the importance of social factors). Besides the domains of motivation, volition, learning, and memory, etc., executive functions play an important role (Norman, 1980; Goschke, 2008). In an action context, for example, goal setting, (task) planning are important as well as attention, prediction, and action monitoring which require, furthermore, working memory. This is not meant as an exhaustive list but should demonstrate that multiple domain interactions are necessary for understanding human behaviour.

In section 1.3 (p. 17), I have pointed out that during translation, language comprehension and production necessarily interact **(Christoffels et al., 2013)**. But even if language is regarded as *one* domain, it does not only need input from other domains during translation (e.g., from executive functions; Green, 1998) but also in situations where the relevance of language input may vary. That is, language comprehension may be influenced by the task or depth of processing (Chwilla, Brown, & Hagoort, 1995; Craik, & Lockhart, 1972); similar to monitoring processes in language production (Schiller, & Meyer, 2003).

The prediction of upcoming words is a potential mechanism that could affect processing in situations where language is or is not relevant (Wicha, Bates, Moreno, & Kutas, 2003; Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005; DeLong, Urbach, & Kutas, 2005). If prediction as a "higher" cognitive process (Bubic, Von Cramon, & Schubotz, 2010) is used to control language processing, especially early comprehension stages, one would need to consider the possibility that language comprehension is not informationally encapsulated. To answer this question, we tested whether specific (spoken) words in sentences (as picture descriptions) would be predicted if the language input is or is not relevant to the participant's task **(Schiller, Horemans, Ganushchak, & Koester, 2009)**.

Using ERPs, we found quantitative but also qualitative processing differences in the ERP signature. When language was irrelevant to the task, participants showed mainly an N400 effect if the specific words did not match the pictorial content. In contrast, when the language was relevant, we found not only a relatively increased N400 effect which indicates deeper semantic processing but also a very early, additionally occurring phonological mismatch negativity (PMN). The PMN is known to reflect a mismatch between a perceived and an expected phoneme (or at least a deviating phonological onset of a word; Connolly, Byrne, & Dywan, 1995; Conolly, & Phillips, 1994). Such a prediction of upcoming words may be achieved by means of the language production system (Pickering, & Garrod, 2007), but our results suggest that such prediction may be context or task dependent (cf. also Rueschemeyer, Lindemann, van Rooij, van Dam, & Bekkering, 2010, for effects of *intentions* on language processing). This finding **(Schiller et al., 2009)** represents evidence for the influence of a non-linguistic (maybe domain general) cognitive process, namely prediction, on early language comprehension and may, therefore, be difficult to reconcile with informational encapsulation of language. Rather, the results are suggestive of a functional interaction between executive functions such as prediction and language processing. That is, neurophysiological language processing seems to be task or context dependent.

Another form of domain interaction between language and non-linguistic sequence processing would be the sharing of (neural) processing resources for according tasks. Admittedly, domain interactions or sharing of common resources is difficult to differentiate empirically at present. Keeping this issue in mind, we investigated the visual perception of non-linguistic events (novel, visual shapes with varying colours & shapes) that followed two types of rules again using ERPs **(Koester, & Prinz, 2007)**. There was a hierarchical rule (e.g., for sequences of shapes) and a non-hierarchical, category-restriction rule (e.g., for colours, but shape and colour were counterbalanced across participants and did not themselves affect the main results).

The results are not straightforward. While we found a qualitatively different ERP response for hierarchical rule violations (exclusively a P300 modulation) and for category-restriction violations (P200 and P300 modulation), it was not the case that we obtained ERP components that are typically found in sentence violation paradigms for semantic or structural violations (i.e., N400 or LAN/P600). The results suggest that hierarchical rule and category restriction information is processed separately and that the processing of such sequence rules depends differently on short-term and long-term memory resources (because the rule had to be stored). The category-restriction violations are thought to draw on short-term memory resources because these rules change among stimulus sequences. Also, these violations were easy to process which coincided with an early ERP effect (a P200 modulation). In contrast, hierarchical rule violations are interpreted to draw on long-term memory resources as they would not change among sequences (in rough analogy to linguistic, syntactic rules). As the processing of such hierarchical rule violations was more difficult, we suggested that the associated P300 reflects access to long-term memory. Generally, the results are in line with a cognitive architecture that differentiates hierarchically organised sequence rules from non-hierarchical sequence rules and may, precautiously, suggest a hierarchical distinction among processing levels (Velichkovsky, 1993).

More interestingly, an fMRI study using the same non-linguistic stimuli yielded evidence for shared neural resources when processing such hierarchically organised, non-linguistic event sequences **(Bahlmann, Schubotz, Mueller, Koester, & Friederici, 2009)**. These non-linguistic stimuli which can hardly be verbalised were used to construct hierarchical sequences (hierarchical dependency rule) and non-hierarchical sequences (adjacent dependency rule, comparable to the category-restriction rule in **Koester, & Prinz, 2007**). One main result in this fMRI study was an increased activity in the pre-SMA[1] for processing of the hierarchical dependency rule compared with the category-restriction rule. The pre-SMA is known to be involved in sequencing or sequence chunking but not in motor aspects (Kennerley, Sakai, & Rushworth, 2004; Isoda, & Tanji, 2004) or temporal adjustment

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[1] Pre-SMA: pre-supplementary motor area

(Schwartze, Rothermich, & Kotz, 2012). More importantly, we found a similar, increased activation in Brodmann area (BA) 44 for the hierarchical dependency rule, and BA 44 is well-known to be involved in language processing (e.g., Miceli, Turriziani, Caltagirone, Capasso, Tomaiuolo, & Caramazza, 2002; Nishitani, Schürmann, Amunts, & Hari, 2004; Heim, Eickhoff, Friederici, & Amunts, 2009; Sahin, Pinker, Cash, Schomer, & Halgren, 2009). In fact, it is part of Broca's area. Given that the sequence events were not verbalised, one can assume that BA 44 provides neural resources to both non-linguistic sequence processing and to language processing, as is already known. Hence, non-linguistic sequence and language processing seem to share partly neural resources, that is, there might be a domain general processor for the perception of visual sequences (see Koechlin, & Jubault, 2006, for action sequences) and language (*parser*; cf. also Greenfield, Nelson, & Saltzman, 1972; Fiebach, & Schubotz, 2006). We have to await further research to relate the BA 44 and pre-SMA activity more closely to the ERP results of our sequence processing (Koester, & Prinz, 2007).

Conceivably, there might be computational resources in the neurocognitive system that is used by multiple domains (e.g., sequence perception, action planning or language processing), although this is speculative at present (Vergauwe, Barrouillet, & Camos, 2010). For example, attention can be seen as a domain general cognitive function (Johnson, & Proctor, 2004). Regarding action, task, and language, a functional relation during ontogenetic development has been discussed (see above; Vygotsky, 1971; Pierce et al., 2015). For manual actions, for example grasping, a mutual influence has been reported on different levels such as articulation/phonetics (e.g., Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Gentilucci, 2003; Vainio, Schulman, Tiippana, & Vainio, 2013) or conceptual processing (e.g., Glenberg, & Kaschak, 2002; Glover, Rosenbaum, Graham, & Dixon, 2004; Lindemann, Stenneken, van Schie, & Bekkering, 2006). A potential explanation of such a functional relation is often seen in a phylogenetic co-evolution of the manual and the vocal control systems (e.g., Steklis, & Harnad, 1976; Corballis, 1991; Rizzolatti, & Arbib, 1998; Klix, 1999; Gentilucci, & Corballis, 2006, for review). While there are more studies that suggest a functional interaction between the action and the language domain, other cognitive domains may also influence action (planning or control) because the whole cognitive system seems to contribute to behavioural optimisation (e.g., Norman, 1980; Creem, & Proffitt, 2001). Memory is another central domain for action control which has been recognised already by ancient Greek philosophers and physicians (see Introduction).

Recently, it was shown that working memory (WM) and grasping are not fully independent (Weigelt, Rosenbaum, Huelshorst, & Schack, 2009). In a dual-task paradigm, participants opened a series of drawers and had to memorise the content of each drawer (one letter per drawer). In subsequent recall, these authors found only a primacy effect but no recency effect under various conditions. As the recency effect is typically interpreted to reflect working memory, Weigelt et al. (2009) concluded that the concurrent action task required working memory resources that were consequently not available for the letter recall task. While Logan and Fischman (2011, 2015) argued that this disappearance of the recency effect was basically a dual-task effect (*basic concurrence costs,* as they call it), it was shown that action planning (for grasping) shares processing resources in a specific way (interference with visuo-spatial but not verbal WM) whereas re-planning shares unspecific WM resources (interference for both, visuo-spatial and verbal WM Spiegel, Koester, & Schack, 2013). In this study, participants had to grasp a sphere and plan either a leftward or a rightward movement. Before executing the placement, a visual stimulus had to be memorised and, on indication, the placement movement was executed and the memorised stimuli had to be recalled. Furthermore, Spiegel, Koester, Weigelt and Schack (2012) provided evidence that such a grasping-WM interference cost (for re-planning) arises during movement planning, not during the control phase, i.e., when executing the grasping movement.

Using a very similar design, it was further shown that also attention is affected by grasp planning (Spiegel, Koester, & Schack, 2014). This study did not attempt to explain attention in itself; for more complete models of (visual) attention see, for example, Itti and Koch (2001), Desimone and Duncan (1995), or Schneider (2013). Spiegel et al. (2014) were more concerned with the specific processing during grasping and found that movement planning influenced the allocation of attention. That is, when participants planned a leftward (or rightward) placement movement with their hand, more attentional resources were allocated to the left visual field (right visual field, respectively) as stimuli within the according visual field were better encoded and later recalled in contrast to the opposite visual field. This effect was expected as it was already known that selecting a movement target position results in a spatial attention shift towards the target position (e.g., Collins, Heed, & Röder, 2010; Deubel, Schneider, & Paprotta, 1998). Note, that such functional relations may differ for various effectors. For example, in eye-tracking studies using also a dual-task paradigm (perceptual judgements & motor planning) it was shown that saccades are necessarily preceded by attention shifts to the target position whereas this is different for manual movements (reaching Deubel, & Schneider, 2003). For immediate reaching, attention is shifted to the target position but for delayed reaching this is not mandatory (Schneider, & Deubel, 2002, for review).

However, in Spiegel et al.'s (2014) study, there was no specific effect of the allocation of attentional resources on the movement re-planning. Specifically, the cue for movement execution was presented visually either in the left or in the right visual field but this position was irrelevant (as in a Simon task). Although such a stimulus should draw the attentional focus towards the position of occurrence, the side of this visual cue did not interact with the movement re-planning costs. That is, movement planning and spatial attention seem not to influence one another in both directions. Clearly, the relationship between movement planning and spatial attention is not trivial. Both processes may not share the same cognitive resources because the influence should be bi-directional in such a case. Alternatively, one may have to distinguish movement planning from changing a already specified plan (i.e., re-planning; Quinn, & Sherwood, 1983). The latter possibility would be in accordance with the results by Spiegel et al., (2013) where dual-task costs for additional grasp executions were specific for visuo-spatial WM but re-planning costs were the same for verbal and visua-spatial WM. For the present work, it is noted that also WM and (spatial) attention have been shown to interact with the action domain in intricate and yet not fully understood ways.

Finally, there is some evidence available regarding the interaction of the language and the action domain. Similarities between action sequences and sentence structures have been proposed (Greenfield et al., 72; Olmstead, Viswanathan, Aicher, & Fowler, 2009; Pastra, & Aloimonos, 2012) and functional interactions have been reported (e.g., Boulenger, Roy, Paulignan, Deprez, Jeannerod, & Nazir, 2006; Boulenger, Silber, Roy, Paulignan, Jeannerod, & Nazir, 2008; Fischer, & Zwaan, 2008; Rueschemeyer, Lindemann, van Elk, & Bekkering, 2009, for review). For example, Hickok (2012) applied recently the re-afference principle, known from the domain of motor control (von Holst, & Mittelstädt, 1950), to language production, specifically to phonological encoding and articulation. For neurophysiological aspects, it is noted that ERPs can are beneficial to such questions because many language processes and also many movements critically depend on precise timing and are usually very fast **(cf. Essig et al., 2014)**. That is, ERPs can help to investigate the timing, duration and succession of particular cognitive processes (Kutas, & Van Petten, 1994).

Specifically, Amsel and colleagues reported an ERP study in which they investigated the processing of action-related (graspability) and conceptual information (semantics: living vs. non-living) during word reading (Amsel, Urbach, & Kutas, 2013). For this study, Amsel et al. (2013) used a go/no-go paradigm in order to evaluate when graspability and conceptual information is processed. That is, whether these information are processed at the same time or in which order these information become available. The results suggest that conceptual information (available after 150–200 ms) are processed well before graspability information (available after 340 ms). That is, it is estimated to take about 190 ms more to access graspability information than conceptual information in this reading task. Importantly, the task may have emphasised the semantic evaluation, and the task did not require any complex movement which was also noted by Amsel et al. (2013).

Concerning this issue, we contribute some preliminary data on the functional interaction of conceptual/semantic noun information and (uni-manual) grasping behaviour (**Koester, & Schack, in press**). In a go/no-go paradigm (based on lexical decisions), participants executed either precision or power grips on objects of various sizes but with an equal weight and surface. Grasping was performed in response to nouns (go trials; pseudo words represented no-go trials) which referred to small (e.g., ”raisin”) or larger objects (e.g., ”apple”) in critical trials. Grip executions and word reading were fully crossed as factors so that grip execution (small vs. larger corresponding to precision and power grips) and conceptual noun information (small vs. large; implicit object size) could be congruent or incongruent. The important question was whether and, if so, when an interaction would occur. If conceptual information has priority over action-related information (*graspability*) as suggested by Amsel et al.'s (2013) results, an interaction should only occur after about 340 ms after word onset. However, if the behavioural *task* requirements do affect processing, action-related information may gain priority and an interaction could be expected as early as 150–200 ms given the availability of conceptual information according to Amsel et al. (2013).

The results show an early interaction of *grip execution* and *conceptual noun information* between 100 and 200 ms after word onset. In addition, there was an N400 effect for *conceptual noun information* between 500 and 650 ms (**Koester, & Schack, in press**). The preliminary finding of this early interaction argues for a context- or task-dependent processing configuration as also discussed as a possibility by Amsel et al. (2013). Notably, the word stimuli in our study were nouns, not verbs which means that they do not directly refer to actions as in the studies of Boulenger et al. (2006, 2008). Furthermore, the nouns were spatially less related to the action object than in other studies that suggest a semantic influence on kinematic features of grasping (Glover, Rosenbaum, Graham, & Dixon, 2004) where the words were printed on the objects that had to be grasped. At present, it can only be speculated whether action affordances are an inherent part of *lexical* representations (i.e., of nouns) in analogy to the suggestion that action affordances are an integral part of object representations (Tucker, & Ellis, 2001, 2004). After all, our finding (**Koester, & Schack, in press**) is in line with a functional interaction of the action and the language domain, at least for lexical representations.

In this chapter, I have discussed some recent (and selected) evidence that points towards an interaction among cognitive domains. Yet, the results do not suggest that the whole cognitive system is fully interactive. Even in this selected presentation, it was found that some domains or functions may not influence each other, for example, the influence of spatial attention on grasping re-planning appears to be small if there should be an influence at all

(Spiegel et al., 2014). The reviewed work suggests that a task or the context impacts the neurophysiological processing of language, presumably via prediction as a cognitive mechanism. The visual processing of event sequences seems to share some (neural) processing resources (BA 44) with an often found language network. Also, uni manual grasping interacts neurophysiologically very early with language processing and also with further domains such as WM and attention. That is, the evidence from our described work points towards interactive cognitive processes at least for visual (sequence) perception, language and action.

Overall, the present findings contrast with the strict idea of informational encapsulation of perceptual-cognitive domains (e.g., Fodor, 1983; Sperber, 1994). A common structural processing has been proposed, more specifically, for action and language (e.g., Pulvermüller, 2005, 2014; Moro, 2014; Guerra-Filho, & Aloimonos, 2012) but such conceptions are still being discussed (Fodor, 2000; Boeckx, & Fujita, 2014). At least, the evidence presented here indicates some interactions among cognitive domains, that is, shared use of resources or exchange of information. Together with the general, neuroanatomical distinction of sensory and motor systems (incl. various modalities), the present evidence favours a weak modularity that allows for various interactions among the (neuro)cognitive modules.

Summary & conclusions

The topic of the present work is the human neurocognitive system and my aim was to contribute some evidence to further our understanding of it by testing for interactions or sharing of resources among cognitive domains. To this end, several methods were employed and various variables analysed. Following an action-centred and modular approach to the cognitive system in accordance with the ideomotor framework (e.g., Prinz, 1987, 1997; Hommel et al., 2001; Hoffmann, 1993; Schack, & Ritter, 2009), I pursued the hypotheses that there are functional interactions among (some) cognitive domains and that hierarchical processing might be characteristic of multiple (if not all) domains (Norman, 1980; Velichkovsky, 1993).

To test these hypotheses, various neurocognitive approaches were used. Event-related potentials and fMRI were used to evaluate temporal and spatial aspects of neurocognitive (brain) processes. Additionally, behavioural and cognitive measures were employed to assess the structure of cognitive representations and behavioural relevance of the processes and representations. The present work makes some contributions to action and language research incl. a methodological advance, visual sequence processing and interactions among these domains (or sharing of resources).

Regarding action research, an overview was provided with a classification of various forms of responses (or response systems) into overt and covert responses which may be brought about by specific or unspecific parts of the nervous system (cf. Fig. 2.1, p. 20). The benefits of neurocognitive methods for action research in general and movement sciences more specifically has been pointed out, for example, in recording peripheral or central measures of cognitive processing **(Koester, & Schack, 2014; Essig et al., 2014)**. Consequently, one contribution of our work is the demonstration of reliable measurement of ERPs (and cognitive ERP components, i.e., N400 effects) during movement execution (speaking, translating, & grasping + reading; **Koester, & Schiller, 2008; Christoffels et al., 2013; Koester & Schack, in press**; cf. Ganushchak, Christoffels, & Schiller, 2011, for a language production review). Although, the EEG signal has sometimes been measured during movements, it should be stressed that now also ERPs which are smaller by a magnitude than the EEG signal, can be used to investigate action control.

In the domain of language, six studies were reported within this project regarding lexical processing, that is morphology, in the field of comprehension (auditory & visual) and production (speaking). For production, the estimated time course of morphological processing (Indefrey, & Levelt, 2004) was confirmed by ERP measurements (about 350 ms after picture onset for a mean response latency of about 650 ms) but the according functional neuroanatomical correlate could not be substantiated **(Koester, & Schiller, 2008, 2011)**. In fact, morphological processing seems to be associated with BA 47 rather than temporal areas. Some of these findings presumably have encouraged further investigations showing that morphological priming is temporally robust and can work also across languages (e.g., Verdonschot, Middelburg, Lensink, & Schiller, 2012; Kaczer, Timmer, Bavassi, & Schiller, 2015).

For morphological processing (decomposition), prosody and orthotactic information (bigram frequency) could be shown to be reliable and effective cues **(Lemhöfer et al., 2011; Koester, 2014)**. These cues are proposed to facilitate the distinction of compound from non-compound words and to detect the constituent boundaries for structured interpretation according to the constituents' roles. Given the evidence that compound words are decomposed, composition is required (i.e., semantic integration) to arrive at the whole compound's meaning. Accordingly, it has been shown that semantic composition proceeds incrementally. This is the case for lexical-semantic access as well as for lexical-semantic constituent integration **(Koester et al., 2009; Holle et al., 2010)**. These studies support theories that assume multiple routes of (lexical) processing and point towards flexible processing mechanisms (e.g., Arcara, Marelli, Buodo, & Mondini, 2014; Hagoort, 2008). In contrast, they are difficult to reconcile with a delayed access account (Isel et al., 2003).

Regarding perception, specifically visual processing of event sequences, we investigated the processing of hierarchical sequences that consisted of novel visual stimuli that could not be verbalised. Here, the neural processing was investigated by comparing two types of rules, a hierarchically structured and a local (non-hierarchical) rule **(Koester, & Prinz, 2007)**. The ERPs point towards qualitatively distinct processing of local rule information and hierarchical rule knowledge. Interestingly, in a related fMRI study, BA 44 (part of Broca's area) has been implicated in processing hierarchical compared with non-hierarchical rules suggesting some shared neural resource for non-linguistic sequence processing (in visual perception; **Bahlmann et al., 2009**) because BA 44 has been associated with language processing (e.g., Miceli et al., 2002; Nishitani et al., 2004; Heim et al., 2009; Sahin et al., 2009).

The present findings are generally in line with a hierarchical processing conception as has been discussed previously for action control (motor system & long-term actions such as, for example, obtaining a driving licence; cf. Heckhausen, 1991; Velichkovsky, 1993; Schack, 2010) and language. For example, climbing knowledge of athletes is cognitively represented in a hierarchically structured manner, and their behavioural performance (priming effects) support a cognitive organisation according to *functional* features which are superordinate to (visual) surface features **(Bläsing et al., 2014**, cf. Pezzulo et al., 2010). Similarly, the hierarchical structure of compound words—at least distinguishing head and modifier roles—is generally accepted in linguistics and supported by the empirical data reported in Chapter 3. Importantly, our translation work also supports a hierarchical architecture of the language domain. Single word translation would be a prime candidate for serial (or associative) processing because word forms from one language could be ”translated” by simple associative links to word forms from the other language, that is, without involving any ”higher” level of processing.[2] In contrast, our findings indicate that even single word translation shows neurophysiological signs of semantic mediation, that is, implying meaning representations which are superordinate to word form representations **(Christoffels et al., 2013)**. Therefore, it is argued that the above-mentioned findings are in line with hierarchically structured representations and processing at least in the investigated domains. Such a hierarchical architecture within cognitive domains does not invalidate all serial processing mechanisms (e.g., S-R associations) but they may be more appropriate for an explanation of behaviour in relatively simple situations (Velichkovsky, 1993).

Although there is good evidence for the assumption that the cognitive system is functionally subdivided, that is, it contains in parts cognitive modules, the present work also shows that there are (some) interactions among (some) domains. In the present project, I have presented neurophysiological evidence for an influence of one executive function, namely prediction on the manner and intensity of language comprehension. If spoken language is irrelevant for a person, there still seems to be semantic processing, presumably in the sense of shallow processing (Craik, & Lockhart, 1972), and we reported an N400 effect for such irrelevant semantic incongruencies between pictures and sentences **(Schiller et al., 2009)**. In contrast, if the spoken language is task-relevant, the N400 effect became larger, that is, semantic processing is deeper, but there is also an additional, very early PMN effect that is suggestive of predictive processes. Hence, language processing changed also qualitatively, presumably by *predicting* upcoming words which is not a linguistic processes. Similarly, language related neural resources (BA 44) have been found in the service of (hierarchical)

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[2] Such associative links would very likely not work for sentences, but see Elman (1991) and Weckerly and Elman (1992).

sequence processing (in addition to pre-SMA; **Bahlmann et al., 2009**; Koechlin, & Jubault, 2006). This finding suggests that sequence processing and language share partially neural resources which is considered equivalent to a functional interaction between domains. At present, it is not clear yet whether or not this BA 44 activation could be related to predictive processing (i.e., prediction of goals, Bubic et al., 2010; Schubotz, 2007, 2010). Finally, we reported also an early neurophysiological interaction between motor control (grasping) and language processing (single word reading; **Koester, & Schack, in press**). For re-cent investigations of common processing mechanisms in language production and action, see de Zubicaray, Hartsuiker, and Acheson (2014). The above-mentioned studies are taken to support the claim of functional interactions among (some) cognitive modules and, thus, underline the need to further investigate the integrated architecture of the human cognitive system.

In sum, the current work provides neurocognitive evidence, next to a methodological contribution, for the domains of *action control*, *language processing* and (visual) sequence *perception*. The results are consistent with the claim that within these domains cognitive processes can be characterised by hierarchical structures. Furthermore, the results point towards functional interactions among these cognitive domains. In this sense, the present project contributes to a better understanding of the characteristic features of an architecture of the cognitive system.

Not quite surprisingly, this project has also limitations. Certainly, one cannot generalise the findings from the presently investigated domains to all other cognitive domains. That is, more research should be devoted to testing other domains and potential relationships. Also, the absence of an influence in a given study (e.g., no influence of spatial attention on re-planning costs in grasping; Spiegel et al., 2014), may reflect the independence of given domains or be due to a small effect size, that is, an effect might simply be undetected. Moreover, the direction of influence between domains may be uni- or bi-directional. Also, it would be interesting to learn where domains do *not* interact, that is an informational boundary (reminiscent of encapsulation). As said, if there are hierarchical principles of organisation in the cognitive domains, it does not rule out other non-hierarchical processing as in associations. Finally, I believe that it has to be accepted at present that we do not fully understand the relations between neurophysiological responses and cognitive functions. Even some well-research neurophysiological responses are not fully understood. For example, the N400 was thought to uniformly reflect semantic processing effort (beginning with Kutas, & Hillyard, 1980; Kutas, & Federmeier, 2011). But, over the last 40 or so years, the N400 has been found responsive to various cognitive processes. Currently, it is seriously discussed whether the N400 is actually fractionated into multiple sub functions (e.g., Lau, Phillips, & Poeppel, 2008; Pylkkänen, & Marantz, 2003).

Future research efforts in this field may benefit from the combined employment of new experimental techniques and the use of (more) realistic settings. The suggestion of method combination has the potential to contribute to answers to *new* research questions, rather than investigating the same phenomenon from another perspective, that is, by using another method. For example, using ERPs and fMRI to investigate morphological priming helped to tie a specific processing time course to a particular neural substrate for testing a neurocognitive model of language production. Ideally, the methods could be applied simultaneously which becomes more and more feasible. Eye-tracking is also a very promising tool that can be combined with the EEG/ERP methodology, not only for movement sciences, as pointed out in **Essig et al., (2014)**. Eye movements can also be recorded during movement execution in realistic settings (Foerster, Carbone, Koesling, & Schneider, 2011, 2012; Wascher, Heppner, & Hoffmann, 2014, for ERP measurements in realistic action contexts) and can be combined with many established experimental paradigms (e.g., the visual world paradigm; Knoeferle, Habets, Crocker, & Münte, 2008; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995).

In line with the ideomotor perspective, the cognitive system is conceived of as organising behaviour (here, with a focus on voluntary actions), that is, generation of sequences of motor actions or linguistic (communicative) utterances in an optimal or at least efficient way. Distinguishable cognitive domains are acknowledged. That is, even some early scientific localisations such as a cortical motor area by Fritsch and Hitzig, visual processing in the occipital lobe (by Munk; Oeser, 2002; Shiraev, 2015), or Broca's and Wernicke's *localisations* of language functions are still valid.[3] Although distinguishable domains are akin to the concept of processing modules, some functional and neurophysiological interactions among domains must be accepted. Here, the organisation of complex behaviour, that is, the function of the cognitive system, is suggested to follow hierarchical principles in representing and processing information in the sense of generative (i.e., creative) operations (Boeckx, & Fujita, 2014).

In closing, and keeping in mind the above-mentioned limitations, one may say that the function of cognitive processes (which can be conceived of as computations; cf. Miller et al., 1960; Bandura, 1965; Fodor, 1983; 2000) is to generate sequences (for acting, speaking, or predicting upcoming events) by applying hierarchical rules. Such rules but not serial associations mechanisms can explain long-distance dependencies (within action chains or

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[3] The precise language *functions* of Broca's and Wernicke's areas are still debated but not their involvement in language processing.

sentences). Our current research findings do not contradict the hypothesis that hierarchical representations and processing are a common principle of the human cognitive domains and their neurophysiological underpinnings.

References

Amsel, B. D., Urbach, T. P., & Kutas, M. (2013). Alive and grasping: Stable and rapid semantic access to an object category but not object graspability. *NeuroImage*, *77*, 1–13.

Arcara, G., Marelli, M., Buodo, G., & Mondini, S. (2014). Compound headedness in the mental lexicon: An event-related potential study. *Cognitive Neuropsychology*, *31*, 164–183.

Aristoteles (1947). *Über die Seele [De Anima, translated by P. Gohlke].* Paderborn: Ferdinand Schöningh.

Baayen, R. H., Dijkstra, T., & Schreuder, R. (1997). Singulars and plurals in Dutch: evidence for a parallel dual-route model. *Journal of Memory and Language*, *37*, 94–117.

Bahlmann, J., Schubotz, R. I., Mueller, J. L., Koester, D., & Friederici, A. D. (2009). Neural circuits of hierarchical visuo-spatial sequence processing. *Brain Research*, *1298*, 161–170.

Bai, C., Bornkessel-Schlesewsky, I., Wang, L., Hung, Y.-C., Schlesewsky, M., & Burkhardt, P. (2008). Semantic composition engenders an N400: evidence from Chinese compounds. *NeuroReport*, *19*, 695–699.

Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. Minireview. *Vision Research*, *50*, 999–1013.

Bandura, A. (1965). Vicarious processes: A case of no-trial learning. *Advances in Experimental Social Psychology*, *2*, 1–55.

Barber, H., & Carreiras, M. (2005). Grammatical Gender and Number Agreement in Spanish: An ERP Comparison. *Journal of Cognitive Neuroscience*, *17*, 137–153.

Beer, R. D. (2000). Dynamical approaches to cognitive science. *Trends in Cognitive Sciences*, *4*, 91–99.

Berg, T., & Schade, U. (1992). The role of inhibition in a spreading-activation model of language production. I. The psycholinguistic perspective. *Journal of Psycholinguistic Research*, *21*, 405–434.

Berger, H. (1929). Über das Elektroenkephalogramm des Menschen. *Archiv Psychatrischer Nervenkrankheiten*, *87*, 527–570.

Bernstein, N. (1967). *The Co-ordination and Regulation of Movements*. Oxford: Pergamon.

Bernstein, N. A. (1975). *Bewegungsphysiologie*. Leipzig: J. A. Barth.

Bertram, R., & Hyönä, J. (2012). The role of Hyphens at the constituent boundary in compound word identification. Facilitative for long, detrimental for short compound words. *Experimental Psychology*, *60*, 157–163.

Bertram, R., Pollatsek, A., & Hyönä, J. (2004). Morphological parsing and the use of segmentation cues in reading finnish compounds. *Journal of Memory and Language*, *51*, 325–345.

Bertram, R., Tønnessen, F. E., Strömqvist, S., Hyönä, J., & Niemi, P. (2015). Cascaded processing in writting compound word production. *Frontiers in Human Neuroscience*, *9*, 207.

Blakemore, C., Carpenter, R. H. S., & Georgeson, M. A. (1970). Lateral inhibition between orientation detectors in the human visual system. *Nature*, *228*, 37–39.

Blakemore, C., & Tobin, E. A. (1972). Lateral inhibition between orientation detectors in the cat's visual system. *Experimental Brain Research*, *15*, 439–440.

Bläsing, B. E., Güldenpenning, I., Koester, D., & Schack, T. (2014). Expertise affects representation structure and categorical activation of grasp postures in climbing. *FrontierPsy*, *5*, 1008.

Bock, K., Dell, G. S., Chang, F., & Onishi, K. H. (2007). Persistent structural priming from language comprehension to language production. *Cognition*, *104*, 437–458.

Boeckx, C. A., & Fujita, K. (2014). Syntax, action, comparative cognitive science, and Darwinian thinking. *Frontiers in Psychology*, *5*, 1–2.

Bormann, T., & Weiller, C. (2012). "Are there lexicons?" A study of lexical and semantic processing in word-meaning deafness suggests "yes". *Cortex*, *48*, 294–307.

Boulenger, V., Roy, A. C., Paulignan, Y., Deprez, V., Jeannerod, M., & Nazir, T. A. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience*, *18*, 1607–1615.

Boulenger, V., Silber, B., Roy, A., Paulignan, Y., Jeannerod, M., & Nazir, T. (2008). Subliminal display of action words interferes with motor planning: A combined eeg and kinematic study. *Journal of Physiology-Paris*, *102*, 130–136.

Bozic, M., Marslen-Wilson, W. D., Stamatakis, E. A., Davis, M. H., & Tyler, L. K. (2007). Differentiating morphology, form, and meaning: neural correlates of morphological complexity. *Journal of Cognitive Neuroscience*, *19*, 1464–1475.

Bozzacchi, C., Giusti, M. A., Pitzalis, S., Spinelli, D., & Di Russo, F. (2012). Awareness affects motor planning for goal-oriented actions. *Biological Psychology*, *89*, 503–514.

Van den Brink, D., Brown, C. M., & Hagoort, P. (2006). The cascaded nature of lexical selection and integration in auditory sentence processing. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *32*, 364–372.

Broca, P. (1861). Remarqus sur le siége de la faculté du langage articulé, suivies d'une observation d'aphemie (perte de la parole). *Bulletin de la Société Anatomique*, *6*, 330–357.

Bubic, A., Von Cramon, D. Y., & Schubotz, R. I. (2010). Prediction, cognition and the brain. *Frontiers in Human Neuroscience*, *4*, 25.

Butterworth, B. (1983). Lexical Representation. In B. Butterworth (ed.), *Language production Vol. 2* (pp. 257–294). London: Academic Press.

Bybee, J. (1995). Regular Morphology and the Lexicon. *Language and Cognitive Processes*, *10*, 425–455.

Caramazza, A., Laudanna, A., & Romani, C. (1988). Lexical access and inflectional morphology. *Cognition*, *28*, 297–332.

Carroll, J. B. (1993). *Human cognitive abilities : A survey of factor-analytic studies*. Cambridge: Cambridge University Press.

Castiello, U. (2005). The neuroscience of grasping. *Nature Reviews Neuroscience*, *6*, 726–736.

Chiarelli, V., Menichelli, A., & Semenza, C. (2006). Retrieval of compound words in picture naming. A study in Alzheimer's disease and in aphasia. *Brain and Language*, *99*, 214–215.

Chomsky, N. (1959). A review of B. F. Skinner's Verbal Behavior. *Language*, *35*, 26–58.

Christoffels, I., Ganushchak, L., & Koester, D. (2013). Language conflict in translation: An ERP study of translation production. *European Journal of Cognitive Psychology*, *25*, 646–664.

Christoffels, I. K., Firk, C., & Schiller, N. O. (2007). Bilingual language control: An event-related brain potential study. *Brain Research*, *1147*, 192–208.

Chwilla, D. J., Brown, C. M., & Hagoort, P. (1995). The N400 as a function of the level of processing. *Psychophysiology*, *32*, 274–285.

Chwilla, D. J., Kolk, H. H. J., & Vissers, C. T. W. M. (2007). Immediate integration of novel meanings: N400 support for an embodied view of language comprehension. *Brain Research*, *1183*, 109–123.

Clark, A. (1999). An embodied cognitive science? *Trends in Cognitive Sciences*, *3*, 345–351.

Clarke, E., & Dewhurst, K. (1973). *Die Funktionen des Gehirns. Lokalisationstheorien von der Antike bis zur Gegenwart*. München: Heinz Moos.

Clifton Jr., C., Ferreira, F., Henderson, J. M., Inhoff, A. W., Liversedge, S. P., Reichle, E. D., & Schotter, E. R. (2016). Eye movements in reading and information processing: Keith Rayer's 40 year legacy. *Journal of Memory and Language*, *86*, 1–19.

Collins, T., Heed, T., & Röder, B. (2010). Visual target selection and motor planning define attentional enhancement at perceptual processing stages. *Frontiers in Human Neuroscience*, *4*, 14.

Coltheart, M. (1999). Modularity and cognition. *Trends in Cognitive Sciences*, *3*, 115–120.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*, 204–256.

Connolly, J. F., Byrne, J. M., & Dywan, C. A. (1995). Assessing adult receptive vocabulary with event-related potentials: an investigation of cross-modal and cross-form priming. *Journal of Clinical and Experimental Neuropsychology*, *17*, 548–565.

Conolly, J. F., & Phillips, N. A. (1994). Event-related potential components reflect phonological and semantic processing of the terminal word of spoken sentences. *Journal of Cognitive Neuroscience*, *6*, 256–266.

Corballis, M. C. (1991). *The Lopsided Ape. Evolution of the Generative Mind.* New York: Oxford University Press.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: a framework for memory research. *Journal of Verbal Learning & Verbal Behavior*, *11*, 671–684.

Creem, S. H., & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary interaction between cognition and action. *Journal of Experimental Psychology: Human Perception & Performance*, *27*, 218–228.

Culicover, P. W., & Jackendoff, R. (2005). *Simpler Syntax.* Oxford: Oxford University Press.

Damian, M., Dorjee, D., & Stadthagen-Gonzalez, H. (2011). Long-Term Repetition Priming in Spoken and Written Word Production: Evidence for a Contribution of Phonology to Handwriting. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *37*, 813–826.

D'Avella, A., & Bizzi, E. (1998). Low dimensionality of supraspinally induced force fields. *Proceedings of the National Academy of Sciences USA*, *95*, 7711–7714.

Debicki, D. B., & Gribble, P. L. (2005). Persistence of inter-joint coupling during single-joint elbow flexions after shoulder fixation. *Experimental Brain Research*, *163*, 252–257.

DeLong, K. A., Urbach, T. P., & Kutas, M. (2005). Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nature Neuroscience*, *8*, 1117–1121.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222.

Desmurget, M., Prablanc, C., Arzi, M., Rossetti, Y., Paulignan, Y., & Urquizar, C. (1996). Integrated control of hand transport and orientation during prehension movements. *Experimental Brain Research*, *110*, 265–278.

Deubel, H., & Schneider, W. X. (2003). Delayed saccades, but not delayed manual aiming movement, require visual attention shifts. *Annals of the New York Academy of Sciences* (pp. 289–296).

Deubel, H., Schneider, W. X., & Paprotta, I. (1998). Selective dorsal and ventral processing: evidence for a common attentional mechanism in reaching and perception. *Visual Cognition*, *5*, 81–107.

Deutsch, A., & Bentin, S. (2001). Syntactic and semantic factors in processing gender agreement in Hebrew: Evidence from ERPs and eye movements. *Journal of Memory and Language*, *45*, 200–224.

Dohmes, P., Zwitserlood, P., & Bölte, J. (2004). The impact of semantic transparency of morphologically complex words on picture naming. *Brain and Language*, *90*, 203–212.

Downing, P. (1977). On the creation and use of English compound nouns. *Language*, *53*, 810–842.

Dronkers, N. F., Plaisant, O., Iba-Zizen, M. T., & Cabanis, E. A. (2007). Paul Broca's historic cases: high resolution MR imaging of the brains of Leborgne and Lelong. *Brain*, *130*, 1432–1441.

Duncan, R. M. (1995). Piaget and Vygotsky revisited: Dialogue or assimilation? *Developmental Review*, *15*, 458–472.

Dunn, J. C., & Kirsner, K. (2003). What can we infer from double dissociations? *Cortex*, *39*, 1–7.

Elman, J. L. (1991). Distributed representations, simple recurrent networks, and grammatical structure. *Machine Learning*, *7*, 195–225.

Essig, K., Janelle, C., Borgo, F., & Koester, D. (2014). Attention and neurocognition. In A. G. Papaioannou, & D. Hackfort (eds.), *Fundamental concepts in sport and exercise psychology. International Society of Sport Psychology (ISSP)* (pp. 253–271). London: Routledge.

Fabb, N. (2001). Compounding. In A. Spencer, & A. M. Zwicky (eds.), *The Handbook of Morphology* (pp. 66–83). Oxford: Blackwell.

Farnetani, E., Torsello, C. T., & Cosi, P. (1988). English compound versus non-compound noun phrases in discourse: An acoustic and perceptual study. *Language and Speech*, *31*, 157–180.

Feigenberg, J. M. (2014). *Nikolai Bernstein. From Reflex to the Model of the Future*. Münster: LIT.

Feldman, L. B. (2000). Are Morphological Effects Distinguishable From the Effects of Shared Meaning and Shared Form? *Journal of Experimental Psychology: Learning, Memory & Cognition*, *26*, 1431–1444.

Fiebach, C. J., & Schubotz, R. I. (2006). Dynamic anticipatory processing of hierarchical sequential events: a common role for Broca's area and ventral premotor cortex across domains? *Cortex*, *42*, 499–502.

Fiorentino, R., Naito-Billen, Y., Bost, J., & Fund-Reznicek, E. (2014). Electrophysiological evidence for the morpheme-based combinatoric processing of English compounds. *Cognitive Neuropsychology*, *31*, 123–146.

Fiorentino, R., & Poeppel, D. (2007). Compound words and structure in the lexicon. *Language and Cognitive Processes*, *22*, 953–1000.

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *The Quarterly Journal of Experimental Psychology*, *61*, 825–850.

Fischler, I., Bloom, P. A., Childers, D. G., Roucos, S. E., & Perry, N. W. (1983). Brain Potentials Related to Stages of Sentence Verification. *Psychophysiology*, *20*, 400–409.

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT Press.

Fodor, J. A. (2000). *The Mind Doesn't Work That Way: The Scope and Limits of Computational Psychology*. Cambridge: MIT Press.

Foerster, R. M., Carbone, E., Koesling, H., & Schneider, W. X. (2011). Saccadic eye movements in a high-speed bimanual stacking task: Changes of attentional control during learning and automatization. *Journal of Vision*, *11*, 1–16.

Foerster, R. M., Carbone, E., Koesling, H., & Schneider, W. X. (2012). Saccadic eye movements in the dark while performing an automatized sequential high-speed sensorimotor task. *Journal of Vision*, *12*, 1–15.

Friederici, A. D. (1995). The Time Course of Syntactic Activation during Language Processing: A Model Based on Neuropsychological and Neurophysiological Data. *Brain and Language*, *50*, 259–281.

Friederici, A. D., Hahne, A., & Mecklinger, A. (1996). Temporal Structure of Syntactic Parsing: Early and Late Event-Related Brain Potential Effects. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *22*, 1219–1248.

Ganushchak, L., Christoffels, I., & Schiller, N. O. (2011). The use of electroencephalography (eeg) in language production research: A review. *Frontiers in Psychology*, *2*, 208.

Gentilucci, M. (2003). Short communication. Grasp observation influences speech producation. *European Journal of Neuroscience*, *17*, 179–184.

Gentilucci, M., Benuzzi, F., Bertolani, L., Daprati, E., & Gangitano, M. (2000). Language and motor control. *Experimental Brain Research*, *133*, 468–490.

Gentilucci, M., & Corballis, M. C. (2006). From manual gesture to speech: a gradual transition. *Neuroscience and Biobehavioral Reviews*, *30*, 949–960.

Gentsch, A., Weber, A., Synofzik, M., Vosgerau, G., & Schütz-Bosbach, S. (2016). Towards a common framework of grounded action cognition: Relating motor control, perception and cognition. *Cognition*, *146*, 81–89.

Gergely, G., Bekkering, H., & Király, I. (2002). Rational imitation in preverbal infants. *Nature*, *415*, 755.

Gigerenzer, G., & Brighton, H. (2009). Homo heuristicus: Why biased minds make better inferences. *Topics in Cognitive Science*, *1*, 107–143.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*, 558–565.

Glover, S., Rosenbaum, D. A., Graham, J., & Dixon, P. (2004). Grasping the meaning of words. *Experimental Brain Research*, *154*, 103–108.

Gonnerman, L. M., Seidenberg, M. S., & Andersen, E. S. (2007). Graded semantic and phonological similarity effects in priming: evidence for a distributed connectionist approach to morphology. *Journal of Experimental Psychology: General*, *136*, 323–345.

Goschke, T. (2008). Volition und kognitive Kontrolle. In J. Müsseler (ed.), *Allgemeine Psychologie* (pp. 230–293). Berlin: Spektrum.

Grafton, S. T., Aziz-Zadeh, L., & Ivry, R. B. (2009). Relative hierarchies and the representation of action. In M. S. Gazzaniga (ed.), *The cognitive neuroscience* (pp. 641–652). Cambridge, MA: MIT Press.

Green, D. W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, *1*, 67–81.

Greenfield, P. M., Nelson, K., & Saltzman, E. (1972). The development of rulebound strategies for manipulating seriated cups: A parallel between action and grammar. *Cognitive Psychology*, *3*, 291–310.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: with special reference to the ideo-motor mechanism. *Psychological Review*, *77*, 73–99.

de Groot, A. M. B. (1992). Determinants of word translation. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *18*, 1001–1018.

Grosjean, F. (2000). The bilingual's language modes. In J. L. Nicol (ed.), *One mind, two languages: bilingual language processing* (pp. 1–22). Oxford: Blackwell.

Gross, C. G. (2007). The discovery of motor cortex and its background. *Journal of the History of the Neurosciences*, *16*, 320–331. PMID: 17620195.

Guerra-Filho, G., & Aloimonos, Y. (2012). The syntax of human actions and interactions. *Journal of Neurolinguistics*, *25*, 500–514.

Gunter, T. C., Friederici, A. D., & Schriefers, H. (2000). Syntactic Gender and Semantic Expectancy: ERPs Reveal Early Autonomy and Late Interaction. *Journal of Cognitive Neuroscience*, *12*, 556–568.

Hagoort, P. (2008). The fractionation of spoken language understanding by measuring electrical and magnetic brain signals. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences*, *363*, 1055–1069.

Hagoort, P., Brown, C., & Groothusen, J. (1993). The Syntactic Positive Shift (SPS) as an ERP Measure of Syntactic Processing. *Language and Cognitive Processes*, *8*, 439–483.

Hagoort, P., Brown, C. M., & Osterhout, L. (1999). The neurocognition of syntactic processing. In C. M. Brown, & P. Hagoort (eds.), *The Neurocognition of Language* (pp. 273–316). Oxford: Oxford University Press.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron*, *41*, 301–307.

Heckhausen, H. (1991). *Motivation and action*. Springer.

Heim, S., Eickhoff, S., Friederici, A., & Amunts, K. (2009). Left cytoarchitectonic area 44 supports selection in the mental lexicon during language production. *Brain Structure and Function*, *213*, 441–456.

Herbart, J. F. (1968/1850). *Psychologie als Wissenschaft, neu gegründet auf Erfahrung, Metaphysik und Mathematik. Zweiter, analytischer Teil.* Amsterdam: E. J. Bonset.

Herbort, O., & Butz, M. (2010). Planning and control of hand orientation in grasping movements. *Experimental Brain Research*, *202*, 867–878.

Herbort, O., & Butz, M. (2011). Habitual and goal-directed factors in (everyday) object handling. *Experimental Brain Research*, *213*, 371–382.

Herwig, A., & Waszak, F. (2009). Intention and attention in ideomotor learning. *The Quarterly Journal of Experimental Psychology*, *62*, 219–227.

Hesse, C., & Deubel, H. (2011). Efficient grasping requires attentional resources. *Vision Research*, *51*, 1223–1231.

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews Neuroscience*, *13*, 135–145.

Hoffmann, J. (1986). *Die Welt der Begriffe. Psychologische Untersuchungen zur Organisation der menschlichen Wissens*. Berlin: VEB Deutscher Verlag der Wissenschaft.

Hoffmann, J. (1993). *Vorhersage und Erkenntnis*. Göttingen: Hogrefe.

Hoffmann, J. (2003). Anticipatory behavioral control. In M. Butz, O. Sigaud, & P. Gerards (eds.), *Anticipatory Behavior in Adaptive Learning Systems* (pp. 44–65). Heidelberg: Springer.

Hoffmann, J., Butz, M. V., Herbort, O., Kiesel, A., & Lenhard, A. (2007). Spekulationen zur Struktur ideo-motorischer Beziehungen. *Zeitschrift für Sportpsychologie*, *14*, 95–103.

Holle, H., Gunter, T. C., & Koester, D. (2010). The time course of lexical access in morphologically complex words. *NeuroReport*, *21*, 319–323.

von Holst, E., & Mittelstädt, H. (1950). Das Reafferenzprinzip (Wechselwirkungen zwischen Zentralnervensystem und Peripherie). *Naturwissenschaften*, *37*, 464–476.

Hommel, B. (2008). Handlungsplanung und -ausführung. In J. Müsseler (ed.), *Allgemeine Psychologie* (pp. 684–783). Berlin: Spektrum.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, *24*, 849–937.

Husain, M., & Nachev, P. (2007). Space and the parietal cortex. *Trends in Cognitive Sciences*, *11*, 30–36.

Ijspeert, A. J., Nakanishi, J., & Schaal, S. (2002). Movement imitation with nonlinear dynamical systems in humanoid robots. In *Proceedings 2002 IEEE International Conference on Robotics and Automation*, Vol. 2 (pp. 1398–1403).

Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*, 101–144.

Inhoff, A. W., Radach, R., & Heller, D. (2000). Complex compounds in German: Interword spaces facilitate segmentation but hinder assignment of meaning. *Journal of Memory and Language*, *42*, 23–50.

Isel, F., Gunter, T. C., & Friederici, A. D. (2003). Prosody-assisted head-driven access to spoken German compounds. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *29*, 277–288.

Isoda, M., & Tanji, J. (2004). Participation of the primate presupplementary motor area in sequencing multiple saccades. *Journal of Neurophysiology*, *92*, 653–659.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience*, *2*, 194–203.

James, W. (1890). *The Principles of Psychology*. New York: Holt.

Janke, W., & Kallus, K. W. (1995). Reaktivität. In M. Amelang (ed.), *Enzyklopädie der Psychologie (Ser. 8),* Differentielle Psychologie und Personlichkeitsforschung (Bd. 2), Verhaltens- und Leistungsunterschiede (pp. 1–89). Göttingen: Hogrefe.

Janssen, N., Bi, Y., & Caramazza, A. (2008). A tale of two frequencies: Determining the speed of lexical access for Mandarin Chinese and English compounds. *Language and Cognitive Processes*, *23*, 1191–1223.

Jarema, G., Perlak, D., & Semenza, C. (2007). The processing of compounds in bilingual aphasia. *Brain and Language*, *103*, 22–23.

Jeannerod, M. (1985). *The brain machine: the development of neurophysiological thought*. Cambridge, MA: Harvard University Press.

Jeannerod, M. (2006). *Motor Cognition*. New York: Oxford University Press.

Jeannerod, M., Arbib, M., Rizzolatti, G., & Sakata, H. (1995). Grasping objects: the cortical mechanisms of visuomotor transformation. *Trends in Neuroscience*, *18*, 314–320.

Jescheniak, J. D., Schriefers, H., Garrett, M. F., & Friederici, A. D. (2002). Exploring the activation of semantic and phonological codes during speech planning with event-related brain potentials. *Journal of Cognitive Neuroscience*, *14*, 951–964.

Joanisse, M. F., & Seidenberg, M. S. (1999). Impairments in verb morphology after brain injury: A connectionist model. *Proceedings of the National Academy of Sciences USA*, *96*, 7592–7597.

Johnson, A., & Proctor, R. W. (2004). *Attention: Theory and Practice*. Sage.

Kaczer, L., Timmer, K., Bavassi, L., & Schiller, N. O. (2015). Distinct morphological processing of recently learned compound words: an ERP study. *Brain Research*, *1629*, 309–317.

Kahneman, D. (2011). *Thinking Fast and Slow*. London: Penguin.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment Under Uncertainty: Heuristics and Biases*. Cambridge: Cambridge University Press.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*, 175–219.

Kanfer, F. H., & Phillips, J. S. (1970). *Learning foundations of behavior therapy*. Series in psychology. New York: Wiley.

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, *9*, 718–727.

Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, *70*, 387–403.

Kennerley, S. W., Sakai, K., & Rushworth, M. F. S. (2004). Organization of action sequences and the role of pre-SMA. *Journal of Neurophysiology*, *91*, 978–993.

Kirsch, W. (2015). Impact of action planning on spatial perception: attention matters. *Acta Psychologica*, *156*, 22–31.

Kirsch, W., & Hennighausen, E. (2010). ERP correlates of linear hand movements: Distance dependent changes. *Clinical Neurophysiology*, *121*, 1285–1292.

Klix, F. (1999). Am Anfang war die Hand. In M. Wehr, & M. Weinmann (eds.), *Die Hand - Werkzeug des Geistes* (pp. 227–246). Berlin: Spektrum.

Knoeferle, P., Habets, B., Crocker, M. W., & Münte, T. F. (2008). Visual scenes trigger immediate syntactic reanalysis: Evidence from ERPs during situated spoken comprehension. *Cerebral Cortex*, *18*, 789–795.

Koechlin, E., & Jubault, T. (2006). Broca's Area and the Hierarchical Organization of Human Behavior. *Neuron*, *50*, 963–974.

Koester, D. (2014). Manual action. *Cognitive Processing*, *15*, S16–17.

Koester, D., Gunter, T. C., Wagner, S., & Friederici, A. D. (2004). Morphosyntax, Prosody, and Linking Elements: The Auditory Processing of German Nominal Compounds. *Journal of Cognitive Neuroscience*, *16*, 1647–1668.

Koester, D., Holle, H., & Gunter, T. C. (2009). Electrophysiological evidence for incremental lexical-semantic integration in auditory compound comprehension. *Neuropsychologia*, *47*, 1854–1864.

Koester, D., & Prinz, W. (2007). Capturing regularities in event sequences: Evidence for two mechanisms. *Brain Research*, *1180*, 59–77.

Koester, D., & Schack, T. (under review). Action priority? Early neurophysiological interaction of conceptual and motor representations.

Koester, D., & Schack, T. (2014). Response. In R. C. Eklund, & G. Tenenbaum (eds.), *Encyclopedia of Sport and Exercise Psychology* (pp. 596–599). Sage: Thousand Oaks.

Koester, D., & Schiller, N. O. (2008). Morphological priming in overt language production: Electrophysiological evidence from Dutch. *NeuroImage*, *42*, 1622–1630.

Koester, D., & Schiller, N. O. (2011). The functional neuroanatomy of morphology in language production. *NeuroImage*, *55*, 732–741.

Kolk, H., & Chwilla, D. (2007). Late positivities in unusual situations. *Brain and Language*, *100*, 257–261.

Konczak, J. (2008). Motorische Kontrolle. In J. Müsseler (ed.), *Allgemeine Psychologie* (pp. 739–766). Berlin: Spektrum.

Kroll, J. F., van Hell, J. G., Tokowicz, N., & Green, D. W. (2010). The revised hierarchical model: A critical review and assessment. *Bilingualism: Language and Cognition*, *13*, 373–381.

Kroll, J. F., & Stewart, E. (1994). Category Interference in Translation and Picture Naming: Evidence for Asymetric Connections between Bilingual Memory Representatins. *Journal of Memory and Language*, *33*, 149–174.

Kunde, W., Landgraf, F., Paelecke, M., & Kiesel, A. (2007). Dorsal and ventral processing under dual-task conditions. *Psychological Science*, *18*, 100–104.

Kuperberg, G. R. (2007). Neural mechanisms of language comprehension: Challenges to syntax. *Brain Research*, *1146*, 23–49.

Kuperman, V., Schreuder, R., Bertram, R., & Baayen, R. H. (2008). Reading polymorphemic Dutch compounds: Toward a multiple route model of lexical processing. *Journal of Experimental Psychology: Human Perception & Performance*, *35*, 876–895.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, *62*, 621–647.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, *207*, 203–205.

Kutas, M., & Van Petten, C. K. (1994). Psycholinguistics Electrified: Event-Related Brain Potential Investigations. In M. A. Gernsbacher (ed.), *Handbook of Psycholinguistics* (pp. 83–143). San Diego: Academic Press.

Labeye, E., Oker, A., Badard, G., & Versace, R. (2008). Activation and integration of motor components in a short-term priming paradigm. *Acta Psychologica*, *129*, 108–111.

Laine, M., Rinne, J. O., Krause, B. J., Teräs, M., & Sipilä, H. (1999). Left hemisphere activation during processing of morphologically complex word forms in adults. *Neuroscience Letters*, *271*, 85–88.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (ed.), *Cerebral Mechanisms in Behavior* (reprinted 1967). (pp. 112–147). New York: Hafner.

Lau, E. F., Phillips, C., & Poeppel, D. (2008). A cortical network for semantics: (de)constructing the N400. *Nature Reviews Neuroscience*, *9*, 920–933.

Lemhöfer, K., Koester, D., & Schreuder, R. (2011). When bicycle pump is harder to read than bicycle bell: effects of parsing cues in first and second language compound reading. *Psychonomic Bulletin & Review*, *18*, 364–370.

Levelt, W. J. M. (1989). *Speaking: From Intention to Articulation*. Cambridge, MA: MIT Press.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*, 1–75.

Libben, G. (1994). How is Morphological Decomposition Achieved? *Language and Cognitive Processes*, *9*, 369–391.

Lindemann, O., Stenneken, P., van Schie, H. T., & Bekkering, H. (2006). Semantic activation in action planning. *Journal of Experimental Psychology: Human Perception & Performance*, *32*, 633–643.

Llinás, R. (2001). *The I of the Vortex*. Cambridge: MIT Press.

Logan, G. D. (2009). The role of memory in the control of action. In E. Morsella, J. Bargh, & P. Gollwitzer (eds.), *Oxford handbook of human action* (pp. 427–441). Oxford: Oxford Univ. Press.

Logan, S. W., & Fischman, M. G. (2011). The relationship between end-state comfort effects and memory performance in serial and free recall. *Acta Psychologica*, *137*, 292–299.

Logan, S. W., & Fischman, M. G. (2015). The death of recency: Relationship between end-state comfort and serial position effects in serial recall: Logan and Fischman (2011) revisited. *Human Movement Science*, *44*, 11–21.

Lotze, H. (1966/1852). *Medicinische Psychologie oder Physiologie der Seele*. Leipzig: Weidmann.

Lurija, A. R. (1970). *Die höheren kortikalen Funktionen und ihre Störung bei örtlicher Hirnschädigung*. Berlin: Deutscher Verlag der Wissenschaften.

Luzzatti, C., & De Bleser, R. (1996). Morphological Processing in Italian Agrammatic Speakers: Eight Experiments in Lexical Morphology. *Brain and Language*, *54*, 26–74.

MacKay, D. G. (1987). *The Organization of Perception and Action*. New York: Springer.

MacNeilage, P. F., & MacNeilage, L. A. (1973). Central processes controlling speech production during sleep and waking. In F. J. McGuigan, & R. A. Schoonover (eds.), *The psychophysiology of thinking* (pp. 417–440). New York: Academic Press.

Marangolo, P., Piras, F., Galati, G., & Burani, C. (2006). Functional anatomy of derivational morphology. *Cortex*, *42*, 1093–1106.

Marelli, M., & Luzzatti, C. (2012). Frequency effects in the processing of Italian nominal compounds: Modulation of headedness and semantic transparency. *Journal of Memory and Language*, *66*, 644–664.

Marken, R. S. (1986). Perceptual organization of behavior: A hierarchical control model of coordinated action. *Journal of Experimental Psychology: Human Perception and Performance*, *12*, 267–276.

Marslen-Wilson, W., & Tyler, L. K. (1998). Rules, representations, and the english past tense. *Trends in Cognitive Sciences*, *2*, 428–435.

Marslen-Wilson, W. D. (2001). Access to lexical representations: Cross-linguistic issues. *Language and Cognitive Processes*, *16*, 699–708.

Marslen-Wilson, W. D., & Welsh, A. (1978). Processing interactions during word-recognition in continuous speech. *Cognitive Psychology*, *10*, 29–63.

McClelland, J. L., & Patterson, K. (2002). Rule or connections in past-tense inflections: what does the evidence rule out? *Trends in Cognitive Sciences*, *6*, 465–472.

McClelland, J. L., Rumelhart, D. E., & the PDP research group (1986). *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* Vol. 2: Psychological and Biological Models. Cambridge, MA: MIT Press.

McKinnon, R., Allen, M., & Osterhout, L. (2003). Morphological decomposition involving non-productive morphemes: ERP evidence. *NeuroReport*, *14*, 883–886.

Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature*, *414*, 69–73.

Meinzer, M., Lahiri, A., Flaisch, T., Hannemann, R., & Eulitz, C. (2009). Opaque for the reader but transparent for the brain: Neural signatures of morphological complexity. *Neuropsychologia*, *47*, 1964–1971.

Mesulam, M.-M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology*, *28*, 597–613.

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, *48*, 788–804.

Miceli, G., Turriziani, P., Caltagirone, C., Capasso, R., Tomaiuolo, F., & Caramazza, A. (2002). The neural correlates of grammatical gender: an fMRI investigation. *Journal of Cognitive Neuroscience*, *14*, 618–628.

Miller, G. A. (2003). The cognitive revolution: a historical perspective. *Trends in Cognitive Sciences*, *7*, 141–144.

Miller, G. A., Galanter, E., & Pribram, K. (1960). *Plans and the structure of behavior*. New York: Holt.

Moro, A. (2014). On the similarity between syntax and actions. *Trends in Cognitive Sciences*, *18*, 109–110.

Morris, J., Frank, T., Grainger, J., & Holcomb, P. J. (2007). Semantic transparency and masked morphological priming: an ERP investigation. *Psychophysiology*, *44*, 506–521.

Morton, J. (1969). Interaction of information in word recognition. *Psychological Review*, *76*, 165–178.

Nishitani, N., Schürmann, M., Amunts, K., & Hari, R. (2004). Broca's Region: From Action to Language. *Physiology*, *20*, 60–69.

Nitsch, J. R. (2000). Handlungstheoretische Grundlagen der Sportpsychologie. In H. Gabler, J. R. Nitsch, & R. Singer (eds.), *Einführung in die Sportpsychologie Teil 1: Grundthemen* (pp. 43–164). Schorndorf: Karl Hofmann.

Norman, D. A. (1980). Twelve issues for cognitive science. *Cognitive Science*, *4*, 1–32.

Oeser, E. (2002). *Geschichte der Hirnforschung: Von der Antike bis zur Gegenwart*. Darmstadt: Wissenschaftliche Buchgesellschaft.

Oeser, E., & Seitelberger, F. (1989). From brain pathology to neurophilosophy. In F. C. Rose (ed.), *Neuroscience across the centuries* (pp. 7–21). London: Smith-Gordon.

Olmstead, A. J., Viswanathan, N., Aicher, K. A., & Fowler, C. A. (2009). Sentence comprehension affects the dynamics of bimanual coordination: Implications for embodied cognition. *The Quarterly Journal of Experimental Psychology*, *62*, 2409–2417.

Osterhout, L., & Holcomb, P. J. (1992). Event-Related Brain Potentials Elicited by Syntactic Anomaly. *Journal of Memory and Language*, *31*, 785–806.

Pastra, K., & Aloimonos, Y. (2012). The minimalist grammar of action. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences*, *367*, 103–117.

Patterson, K., & Shewell, C. (1987). Speak and spell: Dissociations and word-class effects. In M. Coltheart, S. G., & J. R. (eds.), *The cognitive neuropsychology of language* (pp. 273–294). London: Erlbaum.

Paulmann, S., Elston-Güttler, K. E., Gunter, T. C., & Kotz, S. A. (2006). Is bilingual lexical access influenced by language context? *NeuroReport*, *17*, 727–731.

Perret, C., & Laganaro, M. (2011). Comparison of electrophysiological correlates of writing and speaking: A topographic ERP analysis. *Brain Topography*, *24*, 19–29.

Pezzulo, G., Barca, L., Bocconi, A. L., & Borghi, A. M. (2010). When affordances climb into your mind: Advantages of motor simulation in a memory task perfomed by novice and expert rock climbers. *Brain and Cognition*, *73*, 68–73.

Pickering, M. J., & Garrod, S. (2007). Do people use language production to make predictions during comprehension? *Trends in Cognitive Sciences*, *11*, 105–110.

Pierce, L. J., Chen, J.-K., Delcenserie, A., Genesee, F., & Klein, D. (2015). Past experience shapes ongoing neural patterns for language. *Nature Communications*, *6*, 10073. doi: 10.1038/ncomms10073.

Pinker, S. (1991). Rules of Language. *Science*, *253*, 530–535.

Pinker, S., & Prince, A. (1988). On language and connectionism: Analysis of a parallel distributed processing model of language acquisition. *Cognition*, *28*, 73–193.

Pinker, S., & Ullman, M. (2002). The past and future of the past tense. *Trends in Cognitive Sciences*, *6*, 456–463.

Plaut, D. C., & Gonnerman, L. M. (2000). Are non-semantic morphological effects incompatible with a distributed connectionist approach to lexical processing? *Language and Cognitive Processes*, *15*, 445–485.

Poppele, R., & Bosco, G. (2003). Sophisticated spinal contributions to motor control. *Trends in Neuroscience*, *26*, 269–276.

Pratarelli, M. E. (1995). Modulation of semantic processing using word length and complexity: an ERP study. *International Journal of Psychophysioloy*, *19*, 233–246.

Pribram, K. H. (1971). *Languages of the brain: experimental paradoxes and principles in neuropsychology*. Englewood Cliffs, NJ: Prentice-Hall.

Price, C. J. (1998). The functional anatomy of word comprehension and production. *Trends in Cognitive Sciences*, *2*, 281–288.

Price, C. J. (2010). The anatomy of language: a review of 100 fMRI studies published in 2009. *Annals of the New York Academy of Sciences*, *1191*, 62–88.

Prinz, W. (1987). Ideo-motor action. In H. Heuer, & A. F. Sanders (eds.), *Perspectives on Perception and Action* (pp. 47–76). Erlbaum, NJ: Hillsdale.

Prinz, W. (1990). A common coding approach to perception and action. In O. Neumann, & W. Prinz (eds.), *Relationships Between Perception and Action* (pp. 167–201). Berlin: Springer.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*, 129–154.

Prinz, W. (2013). *Selbst im Spiegel: Die soziale Konstuktion von Subjektivität*. Berlin: Suhrkamp.

Prinz, W., Beisert, M., & Herwig, A. (2013). *Action Science: Foundations of an Emerging Discipline*. Cambridge: MIT Press.

Pritzel, M., Brand, M., & Markowitsch, H. J. (2003). *Gehirn und Verhalten: Ein Grundkurs der physiologischen Psychologie*. Heidelberg: Spektrum.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience*, *6*, 576–582.

Pulvermüller, F. (2014). The syntax of action. *Trends in Cognitive Sciences*, *18*, 219–220.

Putscher, M. (1972). *Geschichte der medizinischen Abbildung [Bnd. II]: Von 1600 bis zur Gegenwart*. München: Heinz Moos Verlag.

Pylkkänen, L., & Marantz, A. (2003). Tracking the time course of word recognition with MEG. *Trends in Cognitive Sciences*, *7*, 187–189.

Quinn, J. T., & Sherwood, D. E. (1983). Time requirements of changes in program and parameter variables in rapid ongoing movements. *Journal of Motor Behavior*, *15*, 163–178.

Rastle, K., Davis, M. H., & New, B. (2004). The broth in my brother's brothel: Morpho-orthographic segmentation in visual word recognition. *Psychonomic Bulletin & Review*, *11*, 1090–1098.

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neuroscience*, *21*, 188–193.

Rizzolatti, G., Camarda, R., Fogassi, L., Gentilucci, M., Luppino, G., & Matelli, M. (1988). Functional organization of inferior area 6 in the macaque monkey. *Experimental Brain Research*, *71*, 491–507.

Roelofs, A. (1998). Rightward incrementality in encoding simple phrasal forms in speech production: verb-particle combinations. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *24*, 904–921.

Roelofs, A. (2008). Attention to spoken word planning: chronometric and neuroimaging evidence. *Language and Linguistics Compass*, *2/3*, 389–405.

Rosenbaum, D., Marchak, F., Bames, H., Vaughan, J., Siotta, J., & Jorgensen, M. (1990). Contraints for action selection: Overhand versus underhand grips. In M. Jeannerod (ed.), *Attention and performance XIII* (pp. 321–342). Hillsdale, NJ: Erlbaum.

Rosenbaum, D. A. (2005). The Cinderella of psychology: the neglect of motor control in the science of mental life and behavior. *American Psychologist*, *60*, 308–317.

Rosenbaum, D. A. (2014). *It's a Jungle in There: How Competition and Cooperation in the Brain Shape the Mind.* Oxford: Oxford University Press.

Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control. *Human Movement Science*, *11*, 61–69.

Rüschemeyer, S.-A., Brass, M., & Friederici, A. D. (2007). Comprehending prehending: Neural correlates of processing verbs with motor stems. *Journal of Cognitive Neuroscience*, *19*, 855–865.

Rubinov, M. (2015). Neural networks in the future of neuroscience research. *Nature Reviews Neuroscience*, *16*, 767. doi: 10.1038/nrn4042.

Rueschemeyer, S.-A., Lindemann, O., van Elk, M., & Bekkering, H. (2009). Embodied cognition: The interplay between automatic resonance and selection-for-action mechanisms. *European Journal of Social Psychology*, *39*, 1180–1187.

Rueschemeyer, S.-A., Lindemann, O., van Rooij, D., van Dam, W., & Bekkering, H. (2010). Effects of intentional motor actions on embodied language processing. *Experimental Psychology*, *57*, 260–266.

Rumelhart, D. E., McClelland, J. L., & the PDP research group (1986). *Parallel Distributed Processing: Explorations in the Microstructure of Cognition* Vol. 1: Foundations. Cambridge, MA: MIT Press.

Sahin, N. T., Pinker, S., Cash, S. S., Schomer, D., & Halgren, E. (2009). Sequential processing of lexical, grammatical, and phonological information within Broca's area. *Science*, *326*, 445–449.

Sandra, D. (1990). On the representation and processing of compound words: automatic access to constituent morphemes does not occur. *The Quarterly Journal of Experimental Psychology*, *42A*, 529–567.

Schachner, A., & Carey, S. (2013). Reasoning about 'irrational' actions: When intentional movements cannot be explained, the movements themselves are seen as the goal. *Cognition*, *129*, 309–327.

Schack, T. (1999). Mentale Strukturen im motorischen Lernprozeß - Zugänge zur kognitiven Architektur motorischen Könnens. In J. Krug, & C. Hartmann (eds.), *Praxisorientierte Bewegungslehre als angewandte Sportmotorik; Sport und Wissenschaft* (pp. 142–150). Sankt Augustin: Academia.

Schack, T. (2004). The cognitive architecture of complex movement. *International Journal of Sport and Exercise Psychology; Special Issue Part II: The Construction of Action - New Perspectives in Movement Science*, *2*, 403–438.

Schack, T. (2010). *Die kognitive Architektur menschlicher Bewegung – innovative Zugänge für Psychologie, Sportwissenschaft und Robotik*. Meyer & Meyer.

Schack, T. (2012). Measuring Mental Representation. In G. Tenenbaum, R. C. Eklund, & A. Kamata (eds.), *Measurement in Sport and Exercise Psychology* (pp. 203–214). Champaign (IL): Human Kinetics.

Schack, T., & Mechsner, F. (2006). Representation of motor skills in human long-term memory. *Neuroscience Letters*, *391*, 77–81.

Schack, T., & Ritter, H. (2009). The cognitive nature of action – functional links between cognitive psychology, movement science, and robotics. In J. G. J. Markus Raab, & H. R. Heekeren (eds.), *Mind and Motion: The Bidirectional Link between Thought and Action*, Vol. 174 of *Progress in Brain Research* (pp. 231–250). Elsevier.

Schack, T., & Ritter, H. (2013). Representation and learning in motor action - bridges between experimental research and cognitive robotics. *New Ideas in Psychology*, *31*, 258–269.

Schack, T., Schütz, C., Krause, A. F., & Seegelke, C. (2016). Representation and anticipation in motor action. In M. Nadin (ed.), *Anticipation Across Disciplines*, Vol. 29 of *Cognitive Systems Monographs* (pp. 203–215). Springer.

Schiller, N., Horemans, I., Ganushchak, L., & Koester, D. (2009). Event-related brain potentials during the monitoring of speech errors. *NeuroImage*, *44*, 520–530.

Schiller, N. O., & Costa, A. (2006). Different selection principles of freestanding and bound morphemes in language production. *Journal of experimental psychology: Learning, memory, and cognition*, *32*, 1201–1207.

Schiller, N. O., & Meyer, A. S. (2003). *Phonetics and Phonology in Language Comprehension and Production. Differences and Similarities*. Berlin: Mouton de Gruyter.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, *82*, 225–260.

Schmitt, B. M., & Münte, T. F.and Kutas, M. (2000). Electrophysiological estimates of the time course of semantic and phonological encoding during implicit picture naming. *Psychophysiology*, *37*, 473–484.

Schneider, W., & Deubel, H. (2002). Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: A review of recent findings and new evidence from stimulus-driven saccade control. In W. Prinz, & B. Hommel (eds.), *Attention and Performance XIX: Common Mechanisms in Perception and Action* (pp. 609–627). Oxford: Oxford University Press.

Schneider, W. X. (2013). Selective visual processing across competition episodes: A theory of task-driven visual attention and working memory. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences*, *368*, 1–13.

Schreuder, R., Neijt, A., Van der Weide, F., & Baayen, R. H. (1998). Regular Plurals in Dutch Compounds: Linking Graphemes or Morphemes? *Language and Cognitive Processes*, *13*, 551–573.

Schriefers, H., Zwitserlood, P., & Roelofs, A. (1991). The identification of morphologically complex spoken words: continuous processing or decomposition? *Journal of Memory and Language*, *30*, 26–47.

Schütz-Bosbach, S., & Prinz, W. (2007). Perceptual resonance: action-induced modulation of perception. *Trends in Cognitive Sciences*, *11*, 349–355.

Schubotz, R. I. (2007). Prediction of external events with our motor system: towards a new framework. *Trends in Cognitive Sciences*, *11*, 211–218.

Schubotz, R. I. (2010). Wie wir unser motorisches System nutzen, um Ereignisse vorherzusagen. *Zeitschrift für Sportpsychologie* (pp. 109–119).

Schwartze, M., Rothermich, K., & Kotz, S. A. (2012). Functional dissociation of pre-SMA and SMA-proper in temporal processing. *NeuroImage*, *60*, 290–298.

Shallice, T. (1972). Dual functions of consciousness. *Psychological Review*, *79*, 383–393.

Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary Ideomotor Theory. *Psychological Bulletin*, *136*, 943–974.

Shiraev, E. (2015). *A history of psychology: a global perspective*. Los Angeles: Sage.

Skinner, B. F. (1957). *Verbal Behavior*. The century psychology series. New York: Appleton-Century-Crofts.

Sperber, D. (1994). The modularity of thought and the epidemiology of representations. In L. A. Hirschfeld, & S. A. Gelman (eds.), *Mapping the mind: domain specificity in cognition and culture* (pp. 39–67). New York, NY: Cambridge University Press.

Spiegel, M. A., Koester, D., & Schack, T. (2013). The Functional Role of Working Memory in the (Re-)Planning and Execution of Grasping Movements. *Journal of Experimental Psychology: Human Perception & Performance*, *39*, 1326–1339.

Spiegel, M. A., Koester, D., & Schack, T. (2014). Movement planning and attentional control of visuospatial working memory: evidence from a grasp-to-place task. *Psychological Research*, *78*, 494–505.

Spiegel, M. A., Koester, D., Weigelt, M., & Schack, T. (2012). The costs of changing an intended action: Movement planning, but not execution, interferes with verbal working memory. *Neuroscience Letters*, *509*, 82–86.

Steklis, H. D., & Harnad, S. (1976). From hand to mouth: Some cirtical stages in the evolution of language. In S. Harnad, H. D. Steklis, & J. B. Lancaster (eds.), *Origins and Evolution of Language and Speech* (pp. 445–455). New York Academy of Sciences.

Stokes, D., & Bergeron, V. (2015). Modular architectures and informational encapsulation: a dilemma. *European Journal for Philosophy of Science*, *5*, 315–338.

Taft, M. (2004). Morphological decomposition and the reverse base frequency effect. *The Quarterly Journal of Experimental Psychology*, *57A*, 745–765.

Taft, M., & Forster, K. I. (1976). Lexical storage and retrieval of polymorphemic and polysyllabic words. *Journal of Verbal Learning & Verbal Behavior*, *15*, 607–620.

Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, *268*, 1632–1643.

Todorov, E. (2004). Optimality principles in sensorimotor control. *Nature Neuroscience*, *7*, 907–915.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136.

Trepel, M. (2012). *Neuroanatomie: Struktur und Funktion*. München: Elsevier.

Tucker, M., & Ellis, R. (2001). The potentiation of grasp types during visual object categorization. *Visual Cognition*, *8*, 769–800.

Tucker, M., & Ellis, R. (2004). Action priming by briefly presented objects. *Acta Psychologica*, *116*, 185–203.

Tyler, L. K., deMornay Davies, P., Anokhina, R., Longworth, C., Randall, B., & Marslen-Wilson, W. D. (2002). Dissociations in processing past tense morphology: neuropathology and behavioral studies. *Journal of Cognitive Neuroscience*, *14*, 79–94.

Ullman, M. T. (2001). A neurocognitive perspective on language: The declarative/procedural model. *Nature Reviews Neuroscience*, *2*, 717–726.

Vainio, L., Schulman, M., Tiippana, K., & Vainio, M. (2013). Effect of syllalble articulation on precision and power grip performance. *PLOS ONE*, *8*, e53061.

Van Berkum, J. J. A., Brown, C. M., Zwitserlood, P., Kooijman, V., & Hagoort, P. (2005). Anticipating upcoming words in discourse: Evidence from ERPs and reading times. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *31*, 443–467.

Van Dam, W. O., Rueschemeyer, S.-A., & Bekkering, H. (2010). How specifically are action verbs represented in the neural motor system: An fmri study. *NeuroImage*, *53*, 1318–1325.

Van Petten, C., & Luka, B. J. (2006). Neural localization of semantic context effects in electromagnetic and hemodynamic studies. *Brain and Language*, *97*, 279–293.

Van Schie, H., & Bekkering, H. (2007). Neural mechanisms underlying immediate and final action goals in object use reflected by slow wave brain potentials. *Brain Research*, *1148*, 183–197.

Van Turennout, M., Hagoort, P., & Brown, C. M. (1997). Electrophysiological evidence on the time course of semantic and phonological processes in speech production. *Journal of Experimental Psychology: Learning, Memory & Cognition*, *23*, 787–806.

Velichkovsky, B. (1993). Die vertikale Dimension der kognitiven Prozesse. In H. Hildebrandt, & E. Scheerer (eds.), *Interdiziplinäre Perspektiven der Kognitionsforschung* (pp. 207–222). Frankfurt/M.: Peter Lang.

Verdonschot, R. G., Middelburg, R., Lensink, S. E., & Schiller, N. O. (2012). Morphological priming survives a language switch. *Cognition*, *124*, 343–349.

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, *21*, 384–390.

Vogel, I., & Raimy, E. (2002). The acquisition of compound vs. phrasal stress: the role of prosodic constituents. *Journal of Child Language*, *29*, 225–250.

Vygotsky, L. S. (1971). *Thought and Language*. Cambridge, MA: MIT Press.

Walach, H. (2013). *Psychologie: Wissenschaftstheorie, philosophische Grundlagen und Geschichte; ein Lehrbuch*. Stuttgart: Kohlhammer.

Wascher, E., Heppner, H., & Hoffmann, S. (2014). Towards the measurement of event-related EEG activity in real-life working environments. *International Journal of Psychophysioloy*, *91*, 3–9.

Weckerly, J., & Elman, J. L. (1992). A PDP approach to processing center-embedded sentences. In *Proceedings of the fourteenth annual conference of the Cognitive Science Society* (pp. 414–419).

Weigelt, M., Rosenbaum, D. A., Huelshorst, S., & Schack, T. (2009). Moving and memorizing: Motor planning modulates the recency effect in serial and free recall. *Acta Psychologica*, *132*, 68–79.

Wernicke, C. (1874). *Der aphasische Symptomencomplex: eine psychologische Studie auf anatomischer Basis*. Breslau: Max Cohn & Weigert.

Westerholz, J., Schack, T., & Koester, D. (2013). Event-related brain potentials for goal-related power grips. *PLOS ONE*, *8*, e68501.

Westerholz, J., Schack, T., Schütz, C., & Koester, D. (2014). Habitual vs Non-Habitual manual actions: An ERP study on overt movement execution. *PLOS ONE*, *9*, e93116.

Wheeldon, L. R., & Monsell, S. (1994). Inhibition of spoken word production by priming a semantic competitor. *Journal of Memory and Language*, *33*, 332–356.

Whiten, A., Flynn, E., Lee, B., & Lee, T. (2006). Imitation of hierarchical action structure by young children. *Developmental Science*, *9*, 574–582.

Whorf, B. L. (1963). *Sprache—Denken—Wirklichkeit: Beiträge zur Metalinguistik und Sprachphilosophie*. Reinbek bei Hamburg: Rowohlt.

Wicha, N. Y. Y., Bates, E. A., Moreno, E. M., & Kutas, M. (2003). Potato not Pope: human brain potentials to gender expectation and agreement in Spanish spoken sentences. *Neuroscience Letters*, *346*, 165–168.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625–636.

Wohlschläger, A., Gattis, M., & Bekkering, H. (2003). Action generation and action perception in imitation: an instance of the ideomotor principle. *Philosophical Transactions of the Royal Society of London. Series B, Biological sciences*, *358*, 501–515.

Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, *269*, 1880–1882.

Yuste, R. (2015a). From the neuron doctrine to neural networks. *Nature Reviews Neuroscience*, *16*, 487–497.

Yuste, R. (2015b). On testing neural network models. *Nature Reviews Neuroscience*, *16*, 767. doi: 10.1038/nrn4043.

de Zubicaray, G. I., Hartsuiker, R. J., & Acheson, D. (2014). Mind what you say—general and specific mechanisms for monitoring in speech production. *Frontiers in Human Neuroscience*, *8*, 514.

Zwitserlood, P. (1994). The role of semantic transparency in the processing and representation of Dutch compounds. *Language and Cognitive Processes*, *9*, 341–368.

Zwitserlood, P., Bölte, J., & Dohmes, P. (2000). Morphological effects on speech production: Evidence from picture naming. *Language and Cognitive Processes*, *15*, 563–591.

Zwitserlood, P., & Schriefers, H. (1995). Effects of sensory information and processing time in spoken-word recognition. *Language and Cognitive Processes*, *10*, 121–136.

Part II

Appendix

Appendix A

Publication list

List of publications *(Kumulus)* for the *schriftliche Habilitationsleistung*.

Note: *IF*–2 yr. journal impact factor; *No.cit*–number of citations according to Thompson Reuters (accessed 30 November 2015)

No.	*Reference*	*IF*	*No.cit*
1	**Koester, D.** & Schack, T. (2014). Response. In: R. C. Eklund & G. Tenenbaum (Eds.), *Encyclopedia of Sport and Exercise Psychology,* (pp. 596–599). Thousand Oaks: Sage. doi: 10.4135/9781483332222.n231		
2	Bläsing, B., Güldenpenning, I., **Koester, D.**, & Schack, T. (2014). Expertise affects representation structure and categorical activation of grasp postures in climbing. *Frontiers in Psychology, 5,* 1008. doi: 10.3389/fpsyg.2014.01008	2.800	1
3	Essig, K., Janelle, C., Borgo, F., & **Koester, D.** (2014). Attention and Neurocognition. In: A. Papaioannou & D. Hackfort (Eds.), *Routledge Companion to Sport and Exercise Psychology: Global Perspectives and Fundamental Concepts,* (pp. 253–271). London: Routledge. doi: 10.4324/9781315880198.ch17		
4	**Koester, D.**, & Schiller, N. O. (2008). Morphological Priming in Language Production: Electrophysiological Evidence from Dutch. *NeuroImage, 42*, 1622–1630. doi: 10.1016/j.neuroimage.2008.06.043	5.694	52
5	**Koester, D.**, & Schiller, N. O. (2011). The functional neuroanatomy of morphology in language production. *NeuroImage, 55*, 732–741. doi: 10.1016/j.neuroimage.2010.11.044	5.932	10

6	**Koester, D.**, Holle, H., & Gunter, T. C. (2009). Electrophysiological evidence for incremental lexical-semantic integration in auditory compound comprehension. *Neuropsychologia, 47*, 1854–1864. doi: 10.1016/j.neuropsychologia.2009.02.027	4.345	14
7	Holle, H., Gunter, T. C., & **Koester, D.** (2010). The time course of lexical access in morphologically complex words. *NeuroReport, 21*, 319–323. doi: 10.1097/WNR.0b013e328335b3e0	1.822	5
8	**Koester, D.** (2014). Prosody in parsing morphologically complex words: Neurophysiological evidence. *Cognitive Neuropsychology, 31*, 147–163. doi: 10.1080/02643294.2013.857649	1.517	1
9	Lemhöfer, K., **Koester, D.**, & Schreuder, R. (2011). When *bicycle pump* is harder to read than *bicycle bell*: Effects of parsing cues in first and second language compound reading. *Psychonomic Bulletin & Review, 18*, 364–370. doi: 10.3758/s13423-010-0044-y	2.283	11
10	Christoffels, I. K., Ganushchak, L., & **Koester, D.** (2013). Language conflict in translation: An ERP study of translation production. *Journal of Cognitive Psychology, 25*, 646–664. doi: 10.1080/20445911.2013.821127	1.090	2
11	Schiller, N. O., Horemans, I., Ganushchak, L., & **Koester, D.** (2009). Event-related brain potentials during the monitoring of speech errors. *NeuroImage, 44*, 520–530. doi: 10.1016/j.neuroimage.2008.09.019	5.739	13
12	**Koester, D.**, & Prinz, W. (2007). Capturing regularities in event sequences: Evidence for two mechanisms. *Brain Research, 1180,* 59–77. doi: 10.1016/j.brainres.2007.08.056	2.641	9
13	Bahlmann, J., Schubotz, R. I., Mueller, J. L., **Koester, D.**, & Friederici, A. D. (2009). Neural circuits of hierarchical visuo-spatial sequence processing. *Brain Research, 1298,* 161–170. doi: 10.1016/j.brainres.2009.08.017	2.463	41
14	**Koester, D.**, & Schack, T. (in press). Action priority: Early neurophysiological interaction of conceptual and motor representations. *PLOS ONE.*		
	Average (IF):	3.264	
	Sum (No.cit):		159

Appendix B

Abstracts of the Kumulus contributions

1) **Koester, D.** & Schack, T. (2014). Response. In: R. C. Eklund & G. Tenenbaum (Eds.), *Encyclopedia of Sport and Exercise Psychology,* (pp. 596–599). Thousand Oaks: Sage.

Abstract

All animals must act in their environment in order to survive. They must also react to changes in the environment, for example, when threats or beneficial opportunities arise. Responses are defined as any reation of the organism to external or internal events. Responses can pertain to one or more levels of body function ranging from cognition, behavior, and physiology to endocrine and biochemical reactions. The overall purpose of human and animal responses is optimal adaptation to environmental demands.

In sports, humans develop an hone sophisticated, explicit systems of action and reaction, often with the sole purpose of competing with one another. ...

DOI: 10.4135/9781483332222.n231 (http://dx.doi.org/10.4135/9781483332222.n231)

2) Bläsing, B., Güldenpenning, I., **Koester, D.**, & Schack, T. (2014). Expertise affects representation structure and categorical activation of grasp postures in climbing. *Frontiers in Psychology, 5,* 1008.

Abstract

In indoor rock climbing, the perception of object properties and the adequate execution of grasping actions highly determine climbers performance. In two consecutive experiments, effects of climbing expertise on the cognitive activation of grasping actions following the presentation of climbing holds was investigated. Experiment 1 evaluated the representation of climbing holds in the long-term memory of climbers and non-climbers with the help of a psychometric measurement method. Within a hierarchical splitting procedure subjects had to decide about the similarity of required grasping postures. For the group of climbers, representation structures corresponded clearly to four grip types. In the group of non-climbers, representation structures differed more strongly than in climbers and did not clearly refer to grip types. To learn about categorical knowledge activation in Experiment 2, a priming paradigm was applied. Images of hands in grasping postures were presented as targets and images of congruent, neutral, or incongruent climbing holds were used as primes. Only in climbers, reaction times were shorter and error rates were smaller for the congruent condition than for the incongruent condition. The neutral condition resulted in intermediate performance. The findings suggest that perception of climbing holds activates the commonly associated grasping postures in climbers but not in non-climbers. The findings of this study give evidence that the categorization of visually perceived objects is fundamentally influenced by the cognitive-motor potential for interaction, which depends on the observers experience and expertise. Thus, motor expertise not only facilitates precise action perception, but also benefits the perception of action-relevant objects.

DOI: 10.3389/fpsyg.2014.01008 (http://dx.doi.org/10.3389/fpsyg.2014.01008)

Full text: (http://journal.frontiersin.org/article/10.3389/fpsyg.2014.01008/full

3) Essig, K., Janelle, C., Borgo, F., & **Koester, D.** (2014). Attention and Neurocognition. In: A. Papaioannou & D. Hackfort (Eds.), *Routledge Companion to Sport and Exercise Psychology: Global Perspectives and Fundamental Concepts,* (pp. 253–271). London: Routledge.

Abstract

Attention plays a central role in action and movement control and refers to the processing of relevant and suppression or irrelevant information. Following the theoretical background, we describe spatial and temporal brain bases for attentional control. These provide the neural underpinnings for cognitive aspects of attention such as '*what*' (object identity) and '*where*' (object location) information. The next section describes different forms of attentional focus in the context of various sport situations that are differently reliant on attentional width and direction for effective information processing. These processes have been deeply investigated by eye-tracking methods, often emphasizing visual search. Visual search strategies reflect the temporal focusing and extraction of context relevant information depending on bottom-up and top-down processes. Visual search is often used within the expertise approach. In this approach the gaze patterns of athletes of different skill levels are compared to relative non-experts to determine the cognitive processes underlying optimal and non-optimal (motor) performances. The chapter concludes with aspects of distraction and other attentional problems.

DOI: 10.4324/9781315880198.ch17 (http://dx.doi.org/10.4324/9781315880198.ch17)

4) **Koester, D.**, & Schiller, N. O. (2008). Morphological Priming in Language Production: Electrophysiological Evidence from Dutch. *NeuroImage, 42*, 1622–1630.

Abstract

The present study investigated morphological priming in Dutch and its time course in overt speech production using a long-lag priming paradigm. Prime words were compounds that were morphologically related to a picture name (e.g., the word jaszak, ’coat pocket’ was used for a picture of a coat; Dutch: jas) or form-related monomorphemic words (e.g., jasmijn, ’jasmine’). The morphologically related compounds could be semantically transparent (e.g.; eksternest, ’magpie nest’) or opaque (e.g. eksteroog, lit. ’magpie eye’, ’corn’, for a picture of a magpie, Dutch: ekster). Behavioral and event-related potential (ERP) data were collected in two sessions. The production of morphologically related and complex words facilitated subsequent picture naming and elicited a reduced N400 compared with unrelated prime words. The effects did not differ for transparent and opaque relations. Mere form overlap between a prime word and a target picture name did not affect picture naming. These results extend previous findings from German to another language and demonstrate the feasibility of measuring cognitive ERP components during overt speech. Furthermore, the results suggest that morphological priming in language production cannot be reduced to semantic and phonological processing. The time course of these priming effects as reflected in the ERP measure is in accordance with a meta-analytic temporal estimate of morphological encoding in speaking [Indefrey, P., & Levelt, W.J.M. (2004). The spatial and temporal signatures of word production components. Cognition, 92, 101–144.] suggesting that morphological relations are encoded at the word form level.

DOI: 10.1016/j.neuroimage.2008.06.043 (http://dx.doi.org/10.1016/j.neuroimage.2008.06.043)

5) **Koester, D.**, & Schiller, N. O. (2011). The functional neuroanatomy of morphology in language production. *NeuroImage, 55*, 732–741.

Abstract

The present study investigated the neural correlates of morphological priming in overt Dutch language production using a long-lag priming paradigm. Compound words were read out loud as primes that were morphologically related to picture names (e.g., the word jaszak, 'coat pocket' was used for a picture of a coat; Dutch: jas), or primes were form-related, but not morphologically related monomorphemic words (e.g., jasmijn, 'jasmine'). The morphologically related compounds could be semantically transparent (e.g., eksternest, 'magpie nest') or opaque (e.g., eksteroog, lit. 'magpie eye,' 'corn,' for a picture of a magpie, Dutch: ekster). These four priming conditions were complemented by two matched, unrelated conditions. The production of morphologically related, complex words but not the production of form-related words facilitated subsequent picture naming. Also, morphologically related but not form-related words led to a neural priming effect in the left inferior frontal gyrus (LIFG). The effects did not differ for transparent and opaque relations. The results point to a functional role of LIFG in morphological information processing during language production contrary to previous meta-analytic findings. Specifically, morphological priming effects in language production seem to be independent from semantic overlap. However, further research should confirm the independence of morphological and phonological factors. It is suggested that LIFG subserves word form encoding in language production.

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6) **Koester, D.**, Holle, H., & Gunter, T. C. (2009). Electrophysiological evidence for incremental lexical-semantic integration in auditory compound comprehension. *Neuropsychologia, 47*, 1854–1864.

Abstract

The present study investigated the time-course of semantic integration in auditory compound word processing. Compounding is a productive mechanism of word formation that is used frequently in many languages. Specifically, we examined whether semantic integration is incremental or is delayed until the head, the last constituent in German, is available. Stimuli were compounds consisting of three nouns, and the semantic plausibility of the second and the third constituent was manipulated independently (high vs. low). Participants' task was to listen to the compounds and evaluate them semantically. Event-related brain potentials in response to the head constituents showed an increased N400 for less plausible head constituents, reflecting the lexical-semantic integration of all three compound constituents. In response to the second (less plausible) constituents, an increased N400 with a central-left scalp distribution was observed followed by a parietal positivity. The occurrence of this N400 effect during the presentation of the second constituents suggests that the initial two non-head constituents are immediately integrated. The subsequent positivity might be an instance of a P600 and is suggested to reflect the structural change of the initially constructed compound structure. The results suggest that lexical-semantic integration of compound constituents is an incremental process and, thus, challenge a recent proposal on the time-course of semantic processing in auditory compound comprehension.

DOI: 10.1016/j.neuropsychologia.2009.02.027
(http://dx.doi.org/10.1016/j.neuropsychologia.2009.02.027)

7) Holle, H., Gunter, T. C., & **Koester, D.** (2010). The time course of lexical access in morphologically complex words. *NeuroReport, 21*, 319–323.

Abstract

Compounding, the concatenation of words (e.g., ’dishwasher’), is an important mechanism across many languages. This study investigated whether access of initial compound constituents occurs immediately or, alternatively, whether it is delayed until the last constituent (i.e., the head). Electroencephalogram was measured as participants listened to German two-constituent compounds. Both the initial as well as the following head constituent could consist of either a word or a nonword, resulting in four experimental conditions. Results showed a larger N400 for initial nonword constituents, suggesting that lexical access was attempted before the head. Thus, this study provides direct evidence that lexical access of transparent compound constituents in German occurs.

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(http://dx.doi.org/10.1097/WNR.0b013e328335b3e0)

8) **Koester, D.** (2014). Prosody in parsing morphologically complex words: Neurophysiological evidence. *Cognitive Neuropsychology, 31*, 147–163.

Abstract

Little is known about the neurophysiological correlates of lexical prosody in the comprehension of compound words, i.e., morphologically complex words. Here, it is investigated whether lexical prosody influences the decomposition of spoken compound words. In order to explore the neurophysiological correlates (event-related potentials, ERP) of a compound prosody, German native speakers had to judge the number agreement between numerals and nouns which did or did not agree in 50% of the cases. Importantly, the nouns carried either a compound or non-compound (single noun) prosody. The compound prosody led to increased reaction times (RTs) and reduced judgement accuracy. Critically, number violations for words with a compound prosody elicited an increased ERP negativity that was delayed by about 600 ms relative to a left-anterior negativity elicited by number violations for a single noun prosody. The ERP effect for the compound prosody preceded the according behavioural response by about 200 ms, and the ERP peak latency effect correlated with the RT effect. These findings suggest that the ERP effect for the compound prosody could be functionally related to the accurate judgement performance for the compound prosody. The results suggest, more generally, that prosody plays a critical role in auditory compound comprehension and morphological processing.

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9) Lemhöfer, K., **Koester, D.**, & Schreuder, R. (2011). When *bicycle pump* is harder to read than *bicycle bell*: Effects of parsing cues in first and second language compound reading. *Psychonomic Bulletin & Review, 18*, 364–370.

Abstract

Reading and understanding morphologically complex words can sometimes be a particular challenge to non native speakers. For example, compound words consist of multiple free morphemes, oftentimes without explicit marking of the morpheme boundaries. In a lexical decision task, we investigated compound reading in native and non native speakers of Dutch. The compounds differed in that the letter bigram that formed the morpheme boundary could or could not occur within a Dutch morpheme, thus providing an orthotactic cue as to the position of the morpheme boundary. Native and non native speakers responded faster to compounds that contained such an orthotactic cue. Additional analyses showed that although native speakers used this cue for long, but not for short compounds, no such word length modulation was observed for non native speakers. It is suggested that orthotactic parsing cues are used during compound reading and possibly even more so in non native speakers.

DOI: 10.3758/s13423-010-0044-y (http://dx.doi.org/10.3758/s13423-010-0044-y)

10) Christoffels, I. K., Ganushchak, L., & **Koester, D.** (2013). Language conflict in translation: An ERP study of translation production. *Journal of Cognitive Psychology, 25*, 646–664.

Abstract

Although most bilinguals can translate with relative ease, the underlying neuro-cognitive processes are poorly understood. Using event-related brain potentials (ERPs) we investigated the temporal course of word translation. Participants translated words from and to their first (L1, Dutch) and second (L2, English) language while ERPs were recorded. Interlingual homographs (IHs) were included to introduce language conflict. IHs share orthographic form but have different meanings in L1 and L2 (e.g., ”room” in Dutch refers to CREAM). Results showed that the brain distinguished between translation directions as early as 200 ms after word presentation: the P2 amplitudes were more positive in the L1→L2 translation direction. The N400 was also modulated by translation direction, with more negative amplitudes in the L2→L1 translation direction. Furthermore, the IHs were translated more slowly, induced more errors, and elicited more negative N400 amplitudes than control words. In a naming experiment, participants read aloud the same words in L1 or L2 while ERPs were recorded. Results showed no effect of either IHs or language, suggesting that task schemas may be crucially related to language control in translation. Furthermore, translation appears to involve conceptual processing in both translation directions, and the task goal appears to influence how words are processed.

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11) Schiller, N. O., Horemans, I., Ganushchak, L., & **Koester, D.** (2009). Event-related brain potentials during the monitoring of speech errors. *NeuroImage, 44*, 520–530.

Abstract

When we perceive speech, our goal is to extract the meaning of the verbal message which includes semantic processing. However, how deeply do we process speech in different situations? In two experiments, native Dutch participants heard spoken sentences describing simultaneously presented pictures. Sentences either correctly described the pictures or contained an anomalous final word (i.e., a semantically or phonologically incongruent word). In the first experiment, spoken sentences were task-irrelevant and both anomalous conditions elicited similar centro-parietal N400s that were larger in amplitude than the N400 for the correct condition. In the second experiment, we ensured that participants processed the same stimuli semantically. In an early time window, we found similar phonological mismatch negativities for both anomalous conditions compared to the correct condition. These negativities were followed by an N400 that was larger for semantic than phonological errors. Together, these data suggest that we process speech semantically, even if the speech is task-irrelevant. Once listeners allocate more cognitive resources to the processing of speech, we suggest that they make predictions for upcoming words, presumably by means of the production system and an internal monitoring loop, to facilitate lexical processing of the perceived speech.

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12) **Koester, D.**, & Prinz, W. (2007). Capturing regularities in event sequences: Evidence for two mechanisms. *Brain Research, 1180,* 59–77.

Abstract

The processing of regular event sequences was investigated by presenting categorical visual events in sequences that followed a rule system and a category restriction. Participants' task was to detect deviations of the rule or category restriction (single deviants) or both (double deviants). In Experiment 1, participants detected double deviants faster and more accurately than single deviants. This result is compatible with statistical facilitation, i.e., with distinct information processing in two channels. Experiment 2 used the same paradigm but did not require an immediate behavioural response to deviants. Here, event-related brain potentials revealed a redundant deviance effect in the P3 component (i.e., shorter latency and larger amplitude for double deviants compared with either single deviant). Category restriction deviants additionally led to an increased P2 amplitude. It is suggested that rule and category restriction information is processed separately at central levels, and that two central stages can be distinguished in the processing of categorical visual sequence events that make different use of short-term and long-term memory resources.

DOI: 10.1016/j.brainres.2007.08.056 (http://dx.doi.org/10.1016/j.brainres.2007.08.056)

13) Bahlmann, J., Schubotz, R. I., Mueller, J. L., **Koester, D.**, & Friederici, A. D. (2009). Neural circuits of hierarchical visuo-spatial sequence processing. *Brain Research, 1298,* 161–170.

Abstract

Sequence processing has been investigated in a number of studies using serial reaction time tasks or simple artificial grammar tasks. Little, however, is known about higher-order sequence processing entailing the hierarchical organization of events. Here, we manipulated the regularities within sequentially occurring, non-linguistic visual symbols by applying two types of prediction rules. In one rule (the adjacent dependency rule), the sequences consisted of alternating items from two different categories. In the second rule (the hierarchical dependency rule), a hierarchical structure was generated using the same set of item types. Thus, predictions about non-adjacent elements were required for the latter rule. Functional magnetic resonance imaging (fMRI) was used to investigate the neural correlates of the application of the two prediction rules. We found that the hierarchical dependency rule correlated with activity in the pre-supplementary motor area and the head of the caudate nucleus. In addition, in a hypothesis-driven ROI analysis in Broca's area (BA 44), we found a significantly higher hemodynamic response to the hierarchical dependency rule than to the adjacent dependency rule. These results suggest that this neural network supports hierarchical sequencing, possibly contributing to the integration of sequential elements into higher-order structural events. Importantly, the findings suggest that Broca's area is also engaged in hierarchical sequencing in domains other than language.

DOI: 10.1016/j.brainres.2009.08.017 (http://dx.doi.org/10.1016/j.brainres.2009.08.017)

14) **Koester, D.**, & Schack, T. (in press). Action priority: Early neurophysiological interaction of conceptual and motor representations. *PLOS ONE.*

Abstract

Handling our everyday life, we often react manually to verbal requests or instruction, but the functional interrelations of motor control and language are not fully understood yet, especially their neurophysiological basis. Here, we investigated whether specific motor representations for grip types interact neurophysiologically with conceptual information, that is, when reading nouns. Participants performed lexical decisions and, for words, executed a grasp-and-lift task on objects of different sizes involving precision or power grips while the electroencephalogram was recorded. Nouns could denote objects that require either a precision or a power grip and could, thus, be (in)congruent with the performed grasp. In a control block, participants pointed at the objects instead of grasping them. The main result revealed an event-related potential (ERP) interaction of grip type and conceptual information which was not present for pointing. Incongruent compared to congruent conditions elicited an increased positivity (100 – 200 ms after noun onset). Grip type effects were obtained in response-locked analyses of the grasping ERPs (100 – 300 ms at left anterior electrodes). These findings attest that grip type and conceptual information are functionally related when planning a grasping action but such an interaction could not be detected for pointing. Generally, the results suggest that control of behaviour can be modulated by task demands; conceptual noun information (i.e., associated action knowledge) may gain processing priority if the task requires a complex motor response.

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Koester, D., & Schack, T. (2016). Data from: Action priority: Early neurophysiological interaction of conceptual and motor representations. Bielefeld University.

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