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List of Abbreviations

AEA ..... *Affective Embodiment Account*
ATL ..... *anterior temporal lobe*
BOLD ..... *blood-oxygen-level-dependent*
CMT ..... *Conceptual Methaphor Theory*
EEG ..... *electroencephalography*
EPN ..... *early posterior negativity*
ERP ..... *event-related potential*
fMRI ..... *functional magnetic resonance imaging*
IPS ..... *intraparietal sulcus*
LASS ..... *Language and Situated Simulation Theory*
MEG ..... *magnetencephalography*
PET ..... *positron emission tomography*
RT ..... *reaction time*
SEM ..... *standard error of the mean*
TMS ..... *transcranial magnetic stimulation*
WAT ..... *Words as Social Tools Approach*

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Summary

The organization of conceptual knowledge at a functional and neural level in human semantic long-term memory is a matter of intensive debates. While traditional views claim that conceptual knowledge is represented in a unitary system independent of sensorimotor systems in an amodal and symbolic fashion, more recent grounded cognition approaches postulate an essential role of modal brain areas in the representation of concepts, including systems associated with motor, sensory, emotional and introspective processes. While the grounding of concrete concepts (e.g., *hammer*) in modality-specific systems has been documented extensively, the debate gained additional complexity through concepts, which are not directly perceivable, like mental or emotional states, social constellations, scientific theories or abstract ideas, commonly referred to as abstract concepts (e.g., *beauty*). Refined grounded cognition approaches, however, also assume the representation of these abstract concepts to be rooted in modal brain areas in a context-dependent and thus flexible fashion, although supporting empirical evidence is scarce.

The present work aimed to elaborate empirical evidence regarding refined grounded cognition approaches and the representational format of abstract concepts. Therefore, semantic characteristics of abstract concepts and neural activity patterns of their processing were assessed in three studies. In the first study, the semantic content of abstract concepts was investigated using a property generation task. This study provided estimates of the relative contribution of different modal and verbal feature types to the content of abstract concepts and indicated the existence of specific subgroups of abstract concepts including those with a strong reference to vision and action. In the second study, functional magnetic resonance imaging (fMRI) demonstrated dissociable activity in modality-specific motor (pre- and postcentral gyrus) and visual (fusiform and lingual gyrus) brain areas for motor and visual abstract concepts also active during real world movements and object observation. Finally, in two event-related potential (ERP) studies the time course of brain activity during processing of abstract concepts and its dependence on the task was investigated. Results yielded relatively early (as well as later) feature-specific scalp potentials emerging within 200 ms after target onset, thereby indicating rapid access to conceptual information and excluding that differential effects are exclusively based on post-conceptual processes as amodal theories of conceptual representation suggest. By utilizing study tasks with a varying degree of depth (shallow lexical decision task vs. deep conceptual decision task), the two latter studies furthermore confirmed task-dependent brain activity, validating the notion of conceptual flexibility.

Thus, the present results with abstract concepts parallel earlier findings within the domain of concrete concepts and consistently support refined grounded cognition approaches. Even concepts referring to abstract entities are grounded in perception and action in a flexible task-dependent fashion.

Zusammenfassung

Die Organisation von konzeptuellem Wissen im menschlichen semantischen Langzeitgedächtnis auf funktionaler und neuronaler Ebene ist Gegenstand intensiver Debatten. Während traditionelle Theorien behaupten, dass konzeptuelles Wissen in einem einheitlichen, von sensomotorischen Systemen unabhängigen System amodal und symbolisch repräsentiert wird, postulieren neuere Ansätze der Grounded Cognition Theorie eine wesentliche Rolle modaler Hirnareale bei der Konzeptrepräsentation, einschließlich Systemen, die mit motorischen, sensorischen, emotionalen und introspektiven Prozessen assoziiert sind. Während die Verankerung konkreter Konzepte (z.B. *Hammer*) in modalitätsspezifischen Systemen ausführlich dokumentiert ist, gewann die Debatte durch nicht direkt wahrnehmbare Konzepte wie mentale oder emotionale Zustände, soziale Konstellationen, wissenschaftliche Theorien oder abstrakte Ideen, die als abstrakte Konzepte (z.B. *Schönheit*) bezeichnet werden, zusätzlich an Komplexität. Neuere Grounded Cognition Ansätze gehen allerdings davon aus, dass auch die Repräsentation dieser abstrakten Konzepte flexibel in modalen Hirnarealen verankert ist, obwohl entsprechende empirische Belege rar sind.

Ziel der vorliegenden Arbeit war es, die Repräsentationsform abstrakter Konzepte zu untersuchen und neuere Grounded Cognition Ansätze empirisch zu überprüfen. Dafür wurden in drei Studien semantische Merkmale abstrakter Konzepte und neuronale Aktivitätsmuster während deren Verarbeitung untersucht. In der ersten Studie wurde der semantische Inhalt von abstrakten Konzepten mit Hilfe einer Merkmalsgenerieraufgabe untersucht. Diese Studie lieferte Schätzungen zum relativen Beitrag verschiedener modaler und verbaler Merkmalstypen und wies auf die Existenz spezifischer Untergruppen abstrakter Konzepte hin, darunter solche mit einem starken Bezug zu Handlung und Sehen. In der zweiten Studie zeigte die funktionelle Magnetresonanztomographie (fMRI) eine differentielle Aktivität in modalitätsspezifischen motorischen (prä- und postzentraler Gyrus) und visuellen (fusiformer und lingualer Gyrus) Hirnarealen für motorische und visuelle abstrakte Konzepte, die auch bei Bewegungen und Objektbeobachtungen in der realen Welt aktiv sind. Schließlich wurde in zwei Studien mit ereigniskorrelierten Potenzialen (ERP) der zeitliche Verlauf der Hirnaktivität während der Verarbeitung abstrakter Konzepte und dessen Abhängigkeit von der Aufgabe untersucht. Die Ergebnisse ergaben relativ frühe (wie auch spätere) merkmalsspezifische Kopfoberflächenpotentiale, die innerhalb von 200 ms nach Targetpräsentation auftraten, was auf einen schnellen Zugriff auf konzeptuelle Informationen hinweist und ausschließt, dass differentielle Effekte ausschließlich auf postkonzeptuelle Prozesse zurückzuführen sind, wie von amodalen Theorien konzeptueller Repräsentationen angenommen. Durch die Verwendung von Aufgaben mit unterschiedlichen Verarbeitungstiefen (oberflächliche lexikalische Entscheidungsaufgabe vs. tiefe konzeptuelle Entscheidungsaufgabe) bestätigten die beiden letzteren Studien darüber hinaus die aufgabenabhängige Hirnaktivität und validierten die Annahme konzeptueller Flexibilität.

Somit komplementieren die vorliegenden Ergebnisse mit abstrakten Konzepten frühere Befunde im Bereich konkreter Konzepte und stützen konsistent neuere Grounded Cognition Ansätze. Selbst Konzepte, die sich auf abstrakte Entitäten beziehen, sind in Wahrnehmung und Handlung in flexibler und aufgabenabhängiger Weise verankert.

Synopsis

1. Introduction

> *“There is no abstract art. You must always start with something. Afterward you can remove all traces of reality.”*
> (Pablo R. Picasso; translated by Alfred H. Barr, Jr. (1946))

1.1. Concepts and their significance for human cognition

Concepts, which are stored in human long-term memory (Tulving, 1972), are central for important human abilities, such as action planning, problem solving, object recognition, communication and language. They are the basic units of cognition and make up the meaning of words, events and objects on basis of certain features generalizing categorically across exemplars and situations (Humphreys, Riddoch, & Quinlan, 1988; Kiefer & Pulvermüller, 2012; Levelt, Roelofs, & Meyer, 1999; Tulving, 1972). The representation of semantic knowledge is thought to be organized in a categorical fashion (Rosch, 1975) facilitating human cognition and thus making mental activity efficiently working and more predictable (Smith & Medin, 1981). The semiotic triangle (Fig. 1) by Odgen and Richards (1923), which is still valid today despite its age, depicts the relationship between words (names) and their referents and meanings.

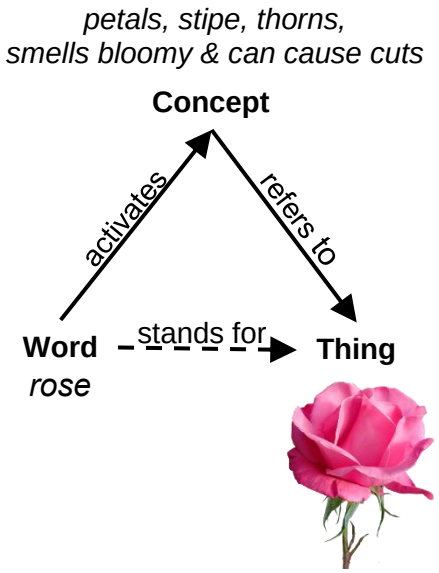

Figure 1. Semiotic triangle (after Odgen & Richards, 1923). Rose picture from https://pixabay.com/de/.

It illustrates that words themselves are not directly associated with specific objects, situations or abstract ideas, which they denote. They are only indirectly related to their referents by activating associated concepts, which, in turn, refer to the denoted entities (Odgen & Richards, 1989). Thus, concepts and not the verbal symbols (i.e. words) constitute meaning in verbal

communication. Note that concepts not only constitute the meaning of physical objects, but also of abstract ideas, in which a clear physical and perceivable referent is missing, as in social constellations, mental or emotional states or scientific theories. These so-called *abstract concepts* pose a challenge to theoretical considerations on conceptual representations due to the high variability of their semantic content and its dependence on different contexts (Barsalou, 2003; Barsalou & Wiemer-Hastings, 2005; Borghi & Binkofski, 2014; Dove, 2016; Hoffman, 2016). Considering the abstract concept *democracy* illustrates the latter considerations: Dependent on the context and the individual, the meaning of *democracy* might be related to a political system, the active participation of the people or the legal equality. Considering the concrete concept *stapler*, in contrast, demonstrates that the meaning of such concepts is much more clear-cut and less ambiguous. Additionally, it is of particular importance in the context of the present dissertation that, compared to concrete concepts, abstract concepts pose a major challenge for those theories assuming a grounding of conceptual knowledge in action and perception as they lack a clear physical referent. In this regard, I will introduce two competing theories of conceptual representation, amodal vs. grounded cognition approaches, in the following sections. Afterwards I will return to the comparison of concrete and abstract concepts.

1.2. Theories of conceptual representation

1.2.1. Amodal approaches

Traditional amodal approaches (Anderson, 1978; Collins & Loftus, 1975; Fodor, 2001; Mahon & Caramazza, 2009; Pylyshyn, 1980) of semantic memory organization, which constituted the dominant opinion in cognitive science for a long time, consider the representational format of concepts to be completely independent of the motor and perceptual systems. Instead, they assume concepts to be represented in an abstract fashion by transforming the original sensorimotor information initially gained through motor interactions and perceptual impressions during concept acquisition into a common symbolic code (Caramazza & Mahon, 2003). Thus, concrete and abstract concepts, like *rose* or *justice*, are both seen to be represented in the same amodal code, detached from the sensory and motor systems. Original experiential information is therefore considered to be extenuated or even to be lost during the transformation process (Anderson, 1978; Caramazza & Mahon, 2003; McClelland & Rogers, 2003). Early semantic network (Collins & Loftus, 1975; Quillian, 1969) and later connectionist network models (Caramazza, Hillis, Rapp, & Romani, 1990; Devlin, Gonnerman, Andersen, & Seidenberg, 1998; McClelland & Rogers, 2003; Tyler & Moss, 2001) are popular representatives of these traditional amodal approaches. While some of these approaches do not specify details about the anatomical seat of conceptual representations (e.g., Collins &

Loftus, 1975), others propose that all forms of conceptual information are represented in so-called amodal semantic hubs in a modality-independent manner (e.g., Visser, Jefferies, & Ralph, 2010). These semantic hubs are assumed anatomically located in heteromodal association cortices, even though the exact number, location and function of semantic hub regions are a matter of intensive ongoing debates (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012). Prefrontal (Devlin, Matthews, & Rushworth, 2003), anterior inferior-temporal (Patterson, Nestor, & Rogers, 2007; Visser et al., 2010), posterior middle temporal (Gold et al., 2006; Hoffman, Pobric, Drakesmith, & Ralph, 2012; Price, 2000) and inferior-parietal cortex (Binder & Desai, 2011) have been considered as cortical seats of amodal semantic hub regions. While older variants of amodal theories (Collins & Loftus, 1975; Quillian, 1969) deny an involvement of modality-specific brain areas during language comprehension and conceptual processing per se, representatives of refined amodal theories (Mahon & Caramazza, 2008) theoretically allow an engagement of modal brain systems. Their involvement, however, is assumed to reflect secondary auxiliary processes, which are not causally engaged in retrieving conceptual information. In their opinion, modality-specific activation reflects an epiphenomenon, based on passive spreading of activation from the amodal conceptual level to the modal input and output levels (Mahon, 2015a, 2015b) or imagery processes (Machery, 2007), after a putatively amodal concept had been accessed.

1.2.2. Grounded cognition approaches

In contrast to these amodal theories, grounded cognition approaches assume that modality-specific brain systems, which include areas related to perceptual, motor, mental, introspective and emotional processes, are substantially involved in conceptual representation and constitute the meaning of concepts (Barsalou, 2008; Borghi et al., 2017; Ghio, Vaghi, Perani, & Tettamanti, 2016; Herbert et al., 2009; Herbert, Herbert, & Pauli, 2011; Kiefer & Barsalou, 2013; Pulvermüller & Fadiga, 2010). Most importantly, grounded cognition approaches state that these modality-specific brain systems are contributing causally to conceptual processing (Pulvermüller, 2005). The development of these functional neural networks is explained by Hebbian theory (1949), which proposes simultaneous activations of cell assemblies in distinct modal brain areas during concept acquisition as the driving mechanism (Pulvermüller & Fadiga, 2010). Hence, it is assumed that individual experience is strongly involved in shaping conceptual knowledge (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008; Hoenig et al., 2011; Kiefer, Sim, Liebich, Hauk, & Tanaka, 2007; Lyons et al., 2010; Willems, Hagoort, & Casasanto, 2010). Moreover, grounded cognition approaches propose that conceptual processing is highly flexible (Kiefer & Pulvermüller, 2012; Kuhnke, Kiefer, & Hartwigsen, 2020) in the sense of a strong dependence on factors related to bottom-up (e.g., psycholinguistic variables) and to top-down processes such as task demands or situations at hand (Barsalou,

1982). This conceptual flexibility results in situationally variant feature compositions contributing to the concept (Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Popp, Trumpp, & Kiefer, 2019a; Pulvermüller, 2018; van Dam, van Dijk, Bekkering, & Rueschemeyer, 2012). For instance, task-related conceptual flexibility is mechanistically explained with help of cortical control processes, which result from feedback loops adjusting excitation or inhibition processes in modal brain systems. Differential task-dependent brain activity is seen as a result of attentional shifts toward or away from sensory and motor features (Pulvermüller, 2018).

Note that the terms *grounded cognition* and *embodied cognition* are often used synonymously, even though they are related to somewhat different grounding mechanisms (Barsalou, 2010). According to Kiefer and Barsalou (2013, p. 382) the term *embodied cognition* "*is overly narrow and conveys the inaccurate assumptions that the body dominates cognition and that cognition always depends on the body*." The term *grounded cognition*, in contrast, refers to a wider scope of grounding mechanisms including grounding through the modalities, introspections, emotional states, situations and the physical and social environment (Barsalou, 2008, 2010; Kiefer & Barsalou, 2013; Kiefer & Harpaintner, 2020). For the purpose of this dissertation, I use the term *grounded cognition* as suggested by Kiefer and Barsalou (2013) in order to cover a broad spectrum of cognitive grounding mechanisms through manifold forms of experiential information and in order to avoid immoderate focus on the body.

1.2.3. Hybrid approaches

Since hybrid frameworks (Fernandino et al., 2016a; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016b; Garagnani & Pulvermüller, 2016; Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020; Muraki, Cortese, Protzner, & Pexman, 2020a; Patterson et al., 2007; Popp et al., 2019a; Simmons & Barsalou, 2003; Wang, Men, Gao, Caramazza, & Bi, 2020), which synthesize important assumptions of amodal and grounded cognition theories, are reconcilable with a broad range of empirical evidence, these approaches recently gained popularity in the scientific community. These sometimes called *hub-and-spokes models* propose an interplay between modality-specific, multimodal and amodal conceptual hub regions (Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020; Patterson et al., 2007). Whereas modality-specific and multimodal brain areas are thought to serve conceptual feature representation (*spokes*), amodal conceptual *hubs* in heteromodal association cortices are supposed to provide the basis for integrational processes and general semantic binding. These frameworks furthermore propose that conceptual processing is organized in a hierarchical fashion, starting in lower-level modality-specific brain regions continuing over adjacent cross-modality convergence zones and ending in higher-level amodal hub areas, the latter serving as storage of non-physical semantic information unified across different modalities (Patterson & Ralph, 2016; Ralph, Jefferies, Patterson, & Rogers, 2017). Besides other anatomical regions (e.g., inferior

parietal cortex; Binder, 2016), the anterior temporal lobe (ATL) is often considered the most likely candidate for a hub region (Ralph, 2014; Ralph et al., 2017). Conceptual flexibility is seen as a result of task-dependent modulation of brain activity within this processing hierarchy (Kemmerer, 2015a; Kiefer & Harpaintner, 2020; Kuhnke et al., 2020; Popp et al., 2019a).

1.3. Representation of concrete concepts

Previous findings on the representational format of concepts mainly derive from investigations dealing with the processing of concrete concepts, in which the characterization of the semantic content is more clear-cut as compared to abstract concepts (Barsalou & Wiemer-Hastings, 2005), as the former are associated with a lower complexity and meaning variability (Borghi & Binkofski, 2014; see also section 1.4.1.). Furthermore, the investigation of concrete concepts is more feasible, because their classification into differential taxonomies as well as into categories within these taxonomies (e.g., animals, tools) is less ambiguous (Rosch, 1975).

1.3.1. Evidence for amodal conceptual hubs

Several neuropsychological studies favor the assumption of amodal theories that the representational format of (concrete) concepts is independent of the sensorimotor systems and relies on amodal conceptual hubs. One line of evidence comes from studies reporting dissociations between retained conceptual knowledge and impaired corresponding perceptional or action-related processes: Patients with impaired skilled tool use often still show retained knowledge about manipulable objects (Buxbaum & Saffran, 2002; Garcea, Dombovy, & Mahon, 2013; Negri et al., 2007; Papeo, Negri, Zadini, & Rumiati, 2010; Rosci, Chiesa, Laiacona, & Capitani, 2003), and patients with impaired color perception do not necessarily show impairments in object-color knowledge (Shuren, Brott, Schefft, & Houston, 1996), and vice versa (Luzzatti & Davidoff, 1994; Miceli et al., 2001; Stasenko, Garcea, Dombovy, & Mahon, 2014). Another line of evidence comes from studies investigating conceptual processing in patients with Semantic Dementia, a neurodegenerative disease leading to temporal lobe atrophy, more precisely in the temporal pole and its vicinity (Patterson et al., 2007; Rogers et al., 2004). This brain damage is associated with the loss of a broad range of conceptual knowledge, not differentiating between feature types (e.g., visual, motor-related,…) or conceptual categories (e.g., animals, tools,…), what led to the conclusion that the temporal pole is one neural seat of amodal semantic hub regions (Patterson et al., 2007; Visser et al., 2010). Studies making use of the transcranial magnetic stimulation (TMS) replicated the functional relevance of anterior inferior-temporal cortex in healthy participants by showing that TMS application to these areas leads to poorer performances in semantic tasks using pictures or words as stimuli (Pobric, Jefferies, & Ralph, 2010). Functional magnetic resonance imaging (fMRI) studies (Devlin et al., 2000; Rogers et al., 2006) and studies investigating conceptual

processing in congenitally blind participants (Bedny, Caramazza, Pascual-Leone, & Saxe, 2012) further indicated an essential contribution of the anterior temporal cortex in semantic processing. Besides the temporal pole, meta-analyses of neuroimaging studies (fMRI; positron emission tomography [PET]) in healthy participants indicated the functional importance of other possible amodal hub regions such as inferior parietal, posterior middle temporal and medial prefrontal areas, which show neural activity independent of the respective feature content or taxonomic category (Binder, 2016; Binder, Desai, Graves, & Conant, 2009).

1.3.2. Evidence for modality-specific conceptual systems

However, opposing results have also been reported speaking in favor of grounded cognition approaches by demonstrating the involvement of differential brain regions in conceptual processing in a modality-dependent fashion (for reviews see Kiefer & Barsalou, 2013; Kiefer & Harpaintner, 2020; Kiefer & Pulvermüller, 2012; Meteyard et al., 2012; Mkrtychian et al., 2019; Pulvermüller & Fadiga, 2010). Neuroimaging studies in healthy volunteers indicated an involvement of sensorimotor brain regions across a broad range of modalities and conceptual tasks (e.g., Hoenig et al., 2008; Martin, Wiggs, Ungerleider, & Haxby, 1996; Simmons, Martin, & Barsalou, 2005). Several fMRI studies demonstrated a contribution of brain areas related to vision (Simmons et al., 2007), hearing (Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008), action (Hauk, Johnsrude, & Pulvermüller, 2004) and the gustatory (Simmons et al., 2005) and olfactory (Gonzalez et al., 2006) senses during the processing of concepts with a corresponding feature dominance. Note that a theory-driven experimental two-step approach led to the most conclusive findings with regard to the representational format of concrete concepts (Kiefer & Harpaintner, 2020): In a first step, property listings or feature ratings are used in order to determine their semantic content and in order to further select specific subsets of concrete concepts, which are characterized by the dominance of certain modal conceptual features (e.g., *hammer* as a concrete concept with dominant motor-related features). In the second step, specific subsets of concrete concepts containing several exemplars with similar a priori determined sensorimotor feature compositions are presented to volunteers while recording behavioral and/or neurophysiological data.

Making use of this two-step approach, event-related potential (ERP) studies were able to parallel neuroimaging results by demonstrating that the processing of concrete concepts, which were characterized by differential dominant features, was associated with differential ERPs with distinct topographies. For instance, concrete concepts with dominant motor features consistently elicited ERPs that were more positive over the fronto-central scalp, while concepts with dominant visual features were frequently associated with more positive ERPs over occipital and parietal scalp regions suggesting that these ERPs in response to different subsets of concrete concepts are generated in different modal brain areas (Kiefer, 2001, 2005;

Proverbio, Del Zotto, & Zani, 2007). Because of their high temporal resolution in the range of milliseconds, ERP studies were furthermore able to demonstrate that differential modality-specific ERPs begin to emerge at about 150 ms after target onset (Hauk & Pulvermüller, 2004; Hoenig et al., 2008; Kiefer, Sim, Helbig, & Graf, 2011). These results were complemented by experiments based on the magnetencephalography (MEG), also featuring an excellent temporal resolution, demonstrating differential feature-specific effects in a similar time range (Klepp et al., 2014; Niccolai, Klepp, van Dijk, Schnitzler, & Biermann-Ruben, 2020; Niccolai et al., 2014). Such a rapid emergence of modality-specific ERP/MEG effects (between 150 and 300 ms) most likely reflects early lexico-semantic processes in conceptual processing, instead of later post-conceptual processes such as semantic elaboration, imagery or spreading of activation as predicted by amodal approaches (Mahon & Caramazza, 2008). Note that complete visual word recognition is finished at about 150 ms after word onset (Pulvermüller, Shtyrov, & Ilmoniemi, 2005b), and imagery processes require full access to a concept (Kosslyn, 1994). Thus, ERP effects emerging immediately after 150 ms are assumed to imply semantic access and not imagery.

Several studies illustrated the dependence of modality-specific brain activity on the task at hand during conceptual processing, thereby supporting the notion of conceptual flexibility of grounded cognition approaches (Hoenig et al., 2008; Muraki, Sidhu, & Pexman, 2020b; Popp et al., 2019a; van Dam et al., 2012). Shallow lexical decision tasks, in which task performance is independent of the retrieval of conceptual knowledge but is instantiated through associative links, led to relatively weak differential effects or even to their absence (Kuhnke et al., 2020). In contrast, deep conceptual decision tasks, in which retrieval of conceptual knowledge is obligatory for task performance (Simmons, Hamann, Harenski, Hu, & Barsalou, 2008), led to pronounced modality-specific effects (Papeo, Vallesi, Isaja, & Rumiati, 2009; Popp et al., 2019a; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008), demonstrating that conceptual processing is flexible and dependent on the requested task demands (see Cao, Klepp, Schnitzler, Gross, & Biermann-Ruben, 2016; Klepp et al., 2017; Niccolai, Klepp, Indefrey, Schnitzler, & Biermann-Ruben, 2017 for further evidence regarding the association between depth of semantic processing and presence of effects). While it is mandatory in a deep conceptual decision task (e.g., determining the semantic relatedness of two words) to retrieve conceptual information, it is not in case of visual word recognition in a shallow lexical decision task (e.g., word vs. pseudoword decision), which primarily demands retrieval of lexical information. Retrieval of conceptual information in the latter case is thought to be instantiated auxiliary (Dilkina, McClelland, & Plaut, 2010).

As neuroimaging and neurophysiological studies only provide correlational information, they are not sufficient to prove functional relevance of sensorimotor systems in conceptual processing. To do so, methods making causal conclusions possible, such as TMS or

behavioral interference/facilitation paradigms or investigations of brain-damaged patients, are inevitable. Already available data obtained with help of these methods demonstrated the functional relevance of visual (Vermeulen, Corneille, & Niedenthal, 2008), auditory (Bonner & Grossman, 2012; Cao et al., 2016; Trumpp, Kliese, Hoenig, Haarmeier, & Kiefer, 2013a) and action (Bak, O'Donovan, Xuereb, Boniface, & Hodges, 2001; Cotelli et al., 2006; Daniele, Giustolisi, Silveri, Colosimo, & Gainotti, 1994; Helbig, Steinwender, Graf, & Kiefer, 2010; Neininger & Pulvermüller, 2001, 2003; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005a) information in the processing of concrete concepts (action information was even found to be somatotopically represented in some of these studies: Klepp, Niccolai, Buccino, Schnitzler, & Biermann-Ruben, 2015; Klepp et al., 2017; Klepp, van Dijk, Niccolai, Schnitzler, & Biermann-Ruben, 2019; Niccolai et al., 2017; Pulvermüller et al., 2005a).

1.3.3. Evidence for hybrid approaches

As indicated above, findings on the processing of concrete concepts are heterogeneous. The reasons for these inconsistent results remain open: On the one hand, mixed findings might be the result of different task demands, with some of these tasks requiring relatively superficial processing of verbal associations only, while other tasks demand deep access to modality-specific information (see also the Language and Situated Simulation Theory of Barsalou, Santos, Simmons, & Wilson-Mendenhall, 2008). On the other hand, mixed results might speak in favor of hybrid approaches (Fernandino et al., 2016a; Fernandino et al., 2016b; Garagnani & Pulvermüller, 2016; Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020; Muraki et al., 2020a; Patterson et al., 2007; Popp et al., 2019a; Simmons & Barsalou, 2003; Wang et al., 2020), which assume an interaction between modality-specific, multimodal and amodal hub regions. This hypothesized interplay might explain why some neuropsychological studies favor assumptions of amodal approaches by suggesting that conceptual knowledge is represented in single amodal hubs (Patterson et al., 2007; Rogers et al., 2004), while other studies in patients with brain injuries emphasize the importance of modality-specific brain regions for conceptual processing (Bak et al., 2001; Cotelli et al., 2006; Daniele et al., 1994; Neininger & Pulvermüller, 2001, 2003). It is likely that deficits in one region (e.g., modality-specific brain area) can be compensated for by other areas (e.g., amodal semantic hub regions), which in principle stabilizes conceptual processing. Because the semantic content of (concrete) concepts relies on a variety of types of modal information (e.g., Lynott & Connell, 2013), it might even be possible that intact modal regions compensate malfunctions in other modal regions.

Evidence favoring hybrid approaches was delivered by neuroimaging studies (Kuhnke et al., 2020; Popp, Trumpp, Sim, & Kiefer, 2019b) by demonstrating that processing of concepts with certain dominant features (e.g., action or acoustic features) was not only

associated with an enhanced blood-oxygen-level-dependent (BOLD) signal in corresponding modality-specific brain regions but also in regions, which were frequently identified as higher-level, multimodal and amodal regions. Interestingly, in accordance with the notion of flexible conceptual representations, Kuhnke et al. (2020) also showed that neural activity in both modality-specific and multimodal areas were dependent on the task at hand and related task-relevant conceptual features. Flexibility in conceptual representations was furthermore indicated by a recent fMRI study (Chiou & Ralph, 2019), which suggested that the ATL dynamically modulates flexible long-range networks including differential modal cortical regions, further validating assumptions of hybrid hub-and-spokes models (Patterson et al., 2007; Patterson & Ralph, 2016; Ralph et al., 2017).

1.4. Representation of abstract concepts

1.4.1. Definition of abstract concepts

While the grounding of concrete concepts in the sensory and motor systems has been extensively investigated, the representation of abstract concepts, including scientific theories and abstract ideas, has just recently become subject of intensive research. A clear-cut distinction between concrete and abstract concepts, such as *justice*, *beauty* and *democracy*, is difficult to this day. There are different views with regard to the characteristics distinguishing the two types of concepts. Furthermore, there is a fundamental debate whether *abstract* and *concrete* represent two independent, completely dichotomous concept categories, or whether they reflect the endpoints of a much more complex continuum (Wiemer-Hastings, Krug, & Xu, 2001).

The classic definition, which also serves as a working definition for this dissertation, states that abstract concepts, in contrast to concrete concepts, refer to entities with which a direct interaction in the real environment is not possible (Barsalou & Wiemer-Hastings, 2005). They lack characteristic physical properties, such as shapes, colors and structures (Wiemer-Hastings et al., 2001). Abstract concepts therefore represent content that is not directly perceivable with our senses. At the same time, it is not possible to interact directly with an abstract concept in an action-related manner (Casasanto, 2009). Hence, a natural dichotomy is assumed here. Borghi and Binkofski (2014) specify additional main characteristics with regard to abstract concepts including complexity and meaning variability. Abstract concepts are more complex than concrete concepts, since they often represent complicated configurations of mental and physical events (Barsalou, 2003). Furthermore, the meaning of abstract concepts is highly ambiguous in comparison to the meaning of concrete concepts, because abstract concepts extensively depend on individual experiences and do often apply to a broad range of situations (Barsalou & Wiemer-Hastings, 2005). Note, however, that this dichotomous view (concrete vs. abstract) is questionable (Barsalou, Dutriaux, & Scheepers,

2018) as recent studies suggested a complex continuum instead (Wiemer-Hastings et al., 2001).

Due to the characteristics just mentioned, all approaches of conceptual representation face new challenges with regard to their theoretical framework. Because abstract concepts apply to very heterogeneous situations, theoretical approaches have to deal with highly flexible conceptual representations. Furthermore, especially grounded cognition approaches have to deal with the question, how concepts without a perceivable referent, which can be acted upon, could be rooted in the sensorimotor systems (Dove, 2009, 2016). The mere existence of abstract concepts led some researchers to conclude that grounded cognition theories are quite naturally falsified (Dove, 2009).

1.4.2. Representational dualism

In fact, the missing clear physical referent in abstract concepts has been interpreted as a proof of the existence of verbal symbolic representations in addition to visual imagery representations (Paivio, 1986). This view dates back to the influential Dual Coding Theory of Paivio (1986), who assumes that two systems are responsible for the encoding of concrete and abstract words. It states that the representation of abstract concepts relies on a verbal-symbolic system only, while concrete concepts are represented through both, a verbal-symbolic and a visual imagery code, thus holding a dualistic representational view. This representational dualism is promoted by the fact that a huge amount of empirical evidence, as reviewed above, indicates an (causal) involvement of the sensorimotor brain systems in the representation of concrete concept knowledge. At the same time, amodal or verbal representations are often considered to exclusively code the meaning of abstract concepts. However, this dualistic view renders it difficult to set up an integrated mechanistic model allowing an explanation for the representational format of both concept classes (Kiefer & Harpaintner, 2020).

Early behavioral studies adopted this dualistic view by contrasting abstract concepts as an undifferentiated conceptual category with concrete concepts. A core result of these early studies is the so-called *concreteness effect*, which describes a processing advantage for words referring to concrete concepts as compared to words referring to abstract concepts. This effect has been explained by the hypothesized dual coding of concrete concepts (visual imagery and verbal-symbolic), whereas abstract concepts are assumed to rely on a single code (verbal-symbolic) only. It is supposed that the imageability of abstract concepts relies on mediations through associated concrete words (e.g., *justice* through *court* and *judge*) leading to merely indirect imageability of abstract concept meaning and subsequently to adverse effects in their processing (Borghi & Binkofski, 2014). For instance, in contrast to abstract concepts, concrete ones were found to be recognized (Fliessbach, Weis, Klaver, Elger, & Weber, 2006; Marschark

& Paivio, 1977) and learnt (Mestres-Misse, Munte, & Rodriguez-Fornells, 2014) faster, remembered better (James, 1975; Schwanenflugel, Akin, & Luh, 1992) and acquired earlier (Kroll & Merves, 1986). Note, however, that the Contextual Availability Theory (Schwanenflugel, Harnishfeger, & Stowe, 1988) argues that the processing advantage for concrete concepts is due to the fact that abstract concepts are relatively weakly related to a large number of contexts, while concrete concepts are relatively strongly associated to a low number of contexts. Hence, the availability of contextual information, e.g., situational information, is reduced in abstract and enhanced in concrete concepts, especially when words are presented in isolation. It is worth mentioning, like in case of the Dual Coding Theory (Paivio, 1986), the validity of the Contextual Availability Theory (Schwanenflugel et al., 1988) has been recently questioned (see Borghi & Binkofski, 2014). After controlling for confounding variables such as context availability and imageability ratings, Kousta et al. (2011) even reported a processing advantage for abstract concepts compared to concrete concepts in a lexical decision task. This effect was explained by higher degrees of affective associations in abstract words emphasizing the significant role of emotional information in abstract concept representation.

Previous neuroscientific evidence with regard to the unique relation of abstract concepts to the verbal brain systems is mixed. In line with the notion of the Dual Coding Theory that abstract concepts predominantly rely on the verbal system, their processing was found to be associated with an enhanced activity in left anterior and middle temporal regions, areas typically involved in language processes. The processing of concrete concepts, in contrast, was related to an increased brain activity within the visual system (Desai, Binder, Conant, Mano, & Seidenberg, 2011; Sakreida et al., 2013). However, other neuroimaging studies observed an increased BOLD-signal in sensory and motor brain areas for both abstract and concrete concepts (Pexman, Hargreaves, Edwards, Henry, & Goodyear, 2007). One study (Kiehl et al., 1999) even found that the processing of abstract concepts was associated with a greater engagement of modal areas in the right hemisphere, clearly opposing considerations made by the Dual Coding Theory (Paivio, 1986). Combining data of several fMRI and PET studies, a meta-analysis (Wang, Conder, Blitzer, & Shinkareva, 2010) indicated that the processing of abstract concepts is predominantly associated with greater recruitment of left temporal (middle and superior temporal gyrus), and left inferior frontal language regions (inferior frontal gyrus). Concrete concepts, in contrast, were found to be related to an increased activity in fusiform, posterior cingulate and parahippocampal gyrus as well as in left precuneus, important parts of the human perceptual system. The majority of previous findings thus indicates that abstract concepts predominantly rely on left hemispheric language regions proposing a high relevance of verbal information for this conceptual class (Dove, 2014). However, existing empirical evidence is highly inconsistent indicating that abstract concepts

do not exclusively depend on the verbal system. This assumption is supported by an fMRI study (Wang et al., 2018), which found dissociable neural correlates for both linguistic contextual and semantic feature information of abstract concepts in the classical language system but also in a distributed network including modal regions, respectively (Montefinese, 2019).

Several electrophysiological studies comparing the processing of abstract vs. concrete concepts found the so-called *N400 concreteness effect*, which is characterized by more negative scalp potentials between 300 and 500 ms after target onset when processing concrete as compared to abstract concepts (Adorni & Proverbio, 2012; Barber, Otten, Kousta, & Vigliocco, 2013). This effect has been interpreted to be caused by more pronounced integrational processes of multimodal information for concrete concepts than for abstract ones (Barber et al., 2013). A source analysis as part of a high density electroencephalography (EEG) study (Dalla Volta, Fabbri-Destro, Gentilucci, & Avanzini, 2014) further suggested that abstract concepts, in contrast to concrete ones, enhanced activity in areas outside sensorimotor regions, putatively supporting their verbal coding as proposed by the Dual Coding Theory. A modulation of latencies of several ERP components by the level of abstractness has furthermore been observed, usually characterized by later electrophysiological effects in abstract concepts than in concrete ones (Borghi et al., 2017). For instance, the emotion related early posterior negativity effect (EPN), which is thought to indicate attentional shifts towards word meaning, was found to be temporally delayed in abstract verbs of different valence compared to concrete concepts when presented in a lexical decision task (Palazova, Sommer, & Schacht, 2013). The existence of differential ERPs for abstract compared to concrete concepts has been interpreted to support the notion of Dual Coding Approaches that the representational neural basis is different for these two word classes (Dove, 2011). Note, however, that existing result patterns are conflicting, shown by studies, in which the comparison of concrete vs. abstract concepts showed ERPs with earlier (P1 - N1; Wirth et al., 2008) and later (N700; West & Holcomb, 2000) latencies as compared to studies demonstrating the *N400 concreteness effect* (Adorni & Proverbio, 2012). In addition, studies revealed inconsistent findings regarding the location of the *N400 concreteness effect* as studies suggested either the right or the left hemisphere as its source (Hnazaee, Khachatryan, & Van Hulle, 2018; Kounios & Holcomb, 1994).

Moreover, recent work on the semantic content of abstract concepts, to which I will return in the next sections, suggested that abstract concepts indeed rely on verbal information, as suggested by Dual Coding Theory, but, to an even bigger extent, on a variety of modal conceptual feature information (Barca, Mazzuca, & Borghi, 2017; Barsalou & Wiemer-Hastings, 2005; Binder et al., 2016; Lynott & Connell, 2009, 2013; Troche, Crutch, & Reilly, 2014; Troche, Crutch, & Reilly, 2017; van Dantzig, Cowell, Zeelenberg, & Pecher, 2011).

1.4.3. Refined grounded cognition theories

Grounded cognition approaches are faced with the apparent paradox to explain the representation of abstract concepts without a clear and perceivable physical referent via their anchoring in the modal systems, including the sensorimotor system. In order to resolve this paradox, grounded cognition approaches extended their framework with regard to the representation of abstract concepts. One of the first refined grounded cognition approaches specifying the relation of abstract concepts to the sensorimotor system was the Conceptual Metaphor Theory (CMT) from Lakoff and Johnson (1980). The CMT proposes that the meaning of abstract concepts is constituted by sensory and motor information through metaphoric relations to concrete concepts. It is further proposed that abstract concepts are understood based on the experience gathered within the concrete knowledge domain, providing their grounding in action and perception. *Life is a rollercoaster*, for instance, illustrates how physical experiences with concrete concepts (*rollercoaster*) are used as a metaphor to represent abstract concepts (*life*). This metaphorical process was investigated in a variety of studies and especially research on the relationship between the abstract concept of time and the concrete notion of space yielded supporting results (Bonato, Zorzi, & Umilta, 2012; Boroditsky & Ramscar, 2002; Casasanto & Boroditsky, 2008). However, over the years, several limitations have been expressed with regard to the CMT (for an overview see Borghi & Binkofski, 2014) rendering it unlikely that all kinds of abstract concepts are grounded through metaphoric relations (Mkrtychian et al., 2019).

In contrast to the CMT (Lakoff & Johnson, 1980), Barsalou and Wiemer-Hastings (2005) propose abstract concepts to be directly grounded in the sensory and motor systems due to their reference to concrete situations. The meaning of abstract concepts is constituted through perceptions and interactions made in these concrete situations. This situational grounding is furthermore thought to be the basis of later simulations in modality-specific brain regions. For instance, thinking about the abstract concept *democracy* might reenact experiences made in a situation, in which several people stood in a row (visual scene) in order to take the chance of putting a cross on the ballot paper (action). Note that this simulation process, which is based upon representations in modal brain networks, does not necessarily depend on conscious experiences such as imagery (Kiefer & Barsalou, 2013). Instead, supported by findings indicating modal brain activity even when not consciously perceived masked stimuli were used (Trumpp, Traub, & Kiefer, 2013b; Trumpp, Traub, Pulvermüller, & Kiefer, 2014), grounded cognition approaches propose that modality-specific activations can be instantiated without any vivid motor or sensory experience (Kemmerer, 2015b; Kiefer et al., 2008).

Extending this view, more recent grounded cognition approaches suggested that the grounding of abstract concepts does not only depend on the perception of external events such as situations, but also on introspective processes (Kiefer & Harpaintner, 2020). For

instance, according to the Affective Embodiment Account (AEA; Kousta et al., 2011), the meaning of abstract concepts is predominantly represented on basis of affective information. Other refined grounded cognition approaches further emphasize the important roles of mental states and social information (Barsalou & Wiemer-Hastings, 2005; Borghi & Binkofski, 2014; Kiefer & Barsalou, 2013). In line with studies relating abstract concept processing to greater activity in left hemispheric language regions (e.g., Wang et al., 2010), several theories put emphasis on linguistic information for the representation of abstract concepts. For instance, the Words as Social Tools Approach (WAT; Borghi & Binkofski, 2014) highlights the fact that abstract concept acquisition often takes place with help of verbal communications providing the basis for the grounding of abstract concepts in the language system and in motor areas involved in articulation. Furthermore, it has been reasoned that verbal associations, which rely on the statistical co-occurrence of different words within a language, might constitute a significant part of abstract concept meaning (Borghi & Binkofski, 2014; Connell, 2018; Dove, 2009, 2014; Louwerse, 2011). The Language and Situated Simulation Theory (LASS; Barsalou et al., 2008) proposes that verbal associations might be a time-saving and efficient alternative enabling the retrieval of abstract concept meaning in case that there is no sufficient time left to simulate sensorimotor information as suggested above. Empirical evidence supporting the proposed importance of affective (Vigliocco et al., 2014), social (Wilson-Mendenhall, Simmons, Martin, & Barsalou, 2013) and linguistic (Sakreida et al., 2013) information as well as of mental states (Wilson-Mendenhall et al., 2013) in the representation of abstract concepts mainly derives from neuroimaging studies that found enhanced brain activity in corresponding brain areas. As in the case of initial grounded cognition approaches, refined ones specified on abstract concept processing agree with the notion of conceptual flexibility (see section 1.2.2.). However, corresponding empirical evidence with regard to flexible abstract concept representation, to my knowledge, is very limited (see Ghio, Haegert, Vaghi, & Tettamanti, 2018 for a rare exception demonstrating a modulation of abstract concept representation by sentential negation).

To summarize the considerations of refined grounded cognition theories (see Fig. 2), let us return to the abstract concept *democracy:* Its meaning might be grounded in interactions or in the perception of external events based on metaphoric mappings or relations to concrete situations (e.g., visual impression of the Statue of Liberty; the act of voting), in the introspection of internal events such as mental states and emotions (e.g., feeling safe and free) as well as in mentalizing social constellations (e.g., composition of the parliament). Its conceptual base might further be provided via verbal associations and linguistic information. Dependent on bottom-up and top-down processes, the representation of *democracy* is considered situationally variant and highly flexible. Note that some of the mentioned theories claim that abstract concept representation exclusively depends on specific knowledge aspects such as

linguistic (Borghi & Binkofski, 2014; Dove, 2014; Dove, Barca, Tummolini, & Borghi, 2020) or emotional (Kousta et al., 2011) information (Kiefer & Harpaintner, 2020). However, it appears unlikely that abstract conceptual knowledge exclusively relies on single meaning aspects. Instead, the representation of abstract concepts seems to be a result of a variety of complementing knowledge aspects. This consideration is partly drawn from studies showing that the semantic content of abstract concepts, similar to that of concrete ones, is highly heterogeneous and dependent on a broad range of conceptual knowledge aspects (Barca et al., 2017; Barsalou & Wiemer-Hastings, 2005; Binder et al., 2016; Lynott & Connell, 2009, 2013; Troche et al., 2014; Troche et al., 2017; van Dantzig et al., 2011). As demonstrated in section 1.3.3., studies in the domain of concrete concepts indicated the existence of higher-level multimodal or even amodal hub regions (Kuhnke et al., 2020; Popp et al., 2019b) rendering it plausible that these integrational regions are also involved in abstract concept representation.

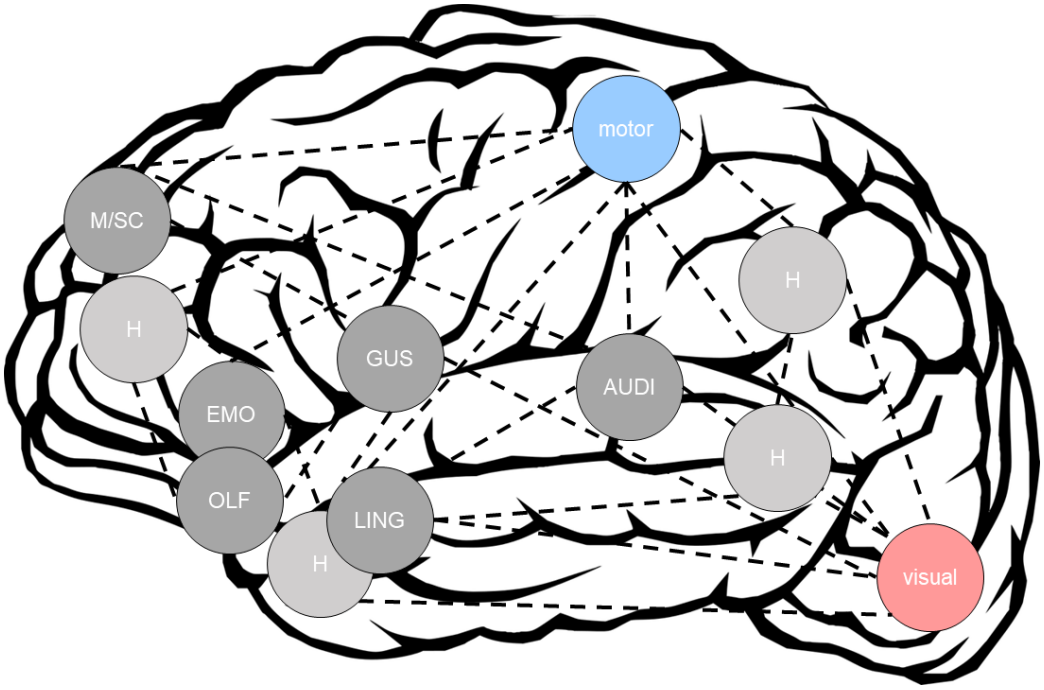

Figure 2. A model of the neural architecture underlying the representation of abstract concepts. The model constitutes a synthesis of previous theories in the domain of concrete concepts and refined grounded cognition and hybrid approaches. Dotted lines indicate that the semantic content of abstract concepts results from multiple interconnected meaning aspects and from an interplay between modality-specific and amodal conceptual hub regions. Approximate localizations of single modal/hub regions are based on the current literature (see above) and projected to the cortical surface. Colored circles: Modal systems of interest comprised in the present dissertation. Dark-gray circles: Other potential modal systems not focused in the present dissertation. Light-grey circles: Potential amodal hub-regions not focused in the present dissertation. Note that this model is simplified as additional modal areas or amodal hub regions might be involved in abstract concept representation. AUDI = auditory; EMO = emotional; GUS = gustatory; H = hub region, LING = linguistic; M/SC = mentalizing/social cognition; OLF = olfactory. Brain picture from https://pixabay.com/de/.

1.4.4. Varieties of abstract concepts and their grounding in sensorimotor systems

Considering the inconsistent empirical evidence regarding the processing of abstract concepts, the approach of contrasting abstract concepts as an undifferentiated and homogeneous conceptual category to concrete concepts (e.g., Wang et al., 2010) appears at least questionable. Instead, some findings of previous studies indicated that different conceptual knowledge aspects and feature types are not equally essential for all types of (abstract) concepts. For instance, a relatively early study by Barsalou and Wiemer-Hastings (2005) demonstrated the significance of meaning aspects related to internal states for the representation of abstract concepts. They asked their participants to generate properties and associations for a small set of concepts, which differed with regard to their concreteness/abstractness level. Abstract concepts were found to evoke properties related to mental states, introspections and social aspects of situations. Properties related to physical settings were also generated in response to abstract concepts, albeit to a smaller degree in comparison to concrete concepts (it is worth mentioning that the latter findings are based on a relatively small set of stimuli including nine concepts in total). More recent rating studies also emphasized the importance of internal and mental states, emotions and social meaning aspects in abstract concept representation when compared to concrete concept representation (Binder et al., 2016; Troche et al., 2014; Troche et al., 2017). The role of sensorimotor experiences in abstract concept processing was implied by studies providing modality ratings by showing that all concepts were related to them, regardless of their concreteness/abstractness level (Lynott & Connell, 2009, 2013; van Dantzig et al., 2011). Given the probable heterogeneity of abstract concepts (Barca et al., 2017; Barsalou & Wiemer-Hastings, 2005; Binder et al., 2016; Ghio, Vaghi, & Tettamanti, 2013; Lynott & Connell, 2009, 2013; Troche et al., 2014; Troche et al., 2017; van Dantzig et al., 2011; Wiemer-Hastings et al., 2001), the notion that their representation is based upon one single feature type such as verbal associations or affective information therefore appears somewhat implausible.

Besides research on the semantic content of abstract concepts with help of rating and property generation studies reviewed above, studies implicating an involvement of the sensorimotor systems for the representation of abstract concepts are rare. One line of evidence indicating a functional significance of the motor system for the representation of abstract concepts comes from studies, which adopted an approach originally used in the research on concrete concepts (Glenberg & Kaschak, 2002). Investigating the so-called *Action-Sentence-Compatibility-Effect* in abstract concepts, Glenberg and colleagues (2008) asked their participants to verify abstract transfer sentences (e.g., *Anna delegates the responsibilities to you*) with help of either congruent (e.g., towards the body) or incongruent (e.g., away from the body) movements as responses. They showed that participant's responses were faster when performing movements congruent to the described transfer, even though the sentences did not contain any specific movement (but abstract concepts such as

responsibility). The authors concluded that the motor system is essentially involved while abstract concepts are processed. Although, in principle, supporting important notions of grounded cognition approaches, studies investigating behavioral compatibility effects cannot exclude the possibility that the effects might be the result of a response stage not directly involved in the conceptual system. Studies making use of neuroscientific methods are therefore indispensable in order to demonstrate the involvement of the sensorimotor systems in abstract concept representation (Kiefer & Harpaintner, 2020).

While the involvement of sensory and motor brain systems in the representation of concrete concepts is well documented, corresponding evidence regarding abstract concepts is scarcer. As already indicated above, an fMRI study observed an increased BOLD-signal in sensorimotor brain areas for both concrete and abstract concepts (Pexman et al., 2007). The involvement of the motor cortex in abstract concept processing was further suggested by a limited number of neuroscientific studies. Processing of abstract concepts associated with mental states (e.g., *thought*, Dreyer & Pulvermüller, 2018) as well as of numerical concepts (e.g., *nine*, Tschentscher, Hauk, Fischer, & Pulvermüller, 2012) was related to an increased BOLD-signal in the motor cortex. Similarly, the processing of abstract emotion words (e.g., *fear*) was associated with an enhanced activity in motor brain areas (Dreyer & Pulvermüller, 2018; Moseley, Carota, Hauk, Mohr, & Pulvermüller, 2012). This result was further complemented by findings of a lesion study suggesting a causal involvement of the motor cortex in the representation of abstract emotion concepts (Dreyer et al., 2015). An increased activation of the motor cortex was even observed in highly abstract physical concepts such as concepts related to periodicity (e.g., *frequency*, Mason & Just, 2016). Processing these periodicity concepts elicited increased activity in motor brain areas, which were also found to be activated by corresponding real-world rhythmic movements. Besides the involvement of the motor cortex, Wilson-Mendenhall and colleagues (2012) also demonstrated an involvement of visual and auditory brain areas when processing the abstract concept *observe*. Moreover, comprehension of the abstract concept *arithmetic* (Wilson-Mendenhall et al., 2013) was associated with an enhanced activity in bilateral intraparietal sulcus (IPS), an area consistently related to numerical cognition. Increased activation in bilateral IPS, as well as in other regions suggested to form a math-responsive network, was additionally observed when processing sentences with abstract mathematical content (Amalric & Dehaene, 2019) supporting the notion of a grounding of abstract mathematical concepts (see also Fischer & Shaki, 2018). Interestingly, applying TMS to the right IPS (but not to the anterior temporal lobe) modulated priming effects in quantity-related abstract concepts (e.g., *immensity*, Catricala, Conca, Fertonani, Miniussi, & Cappa, 2020). The notion of differential modal neural substrates for specific subgroups of abstract concepts was further supported by a review of Desai, Reilly and van Dam (2018). They demonstrated that numerical and emotional abstract concepts as well

as higher-order abstract processes related to morality and mentalizing are grounded through emotional, motor-related and spatial brain circuits and through event- and simulation-based information.

Despite the significance of the latter research findings for the grounded cognition framework, their interpretation is limited for the following reasons: Firstly, not all of the mentioned studies determined the feature composition of the stimuli used in their paradigms a priori. Instead, they inferred the sensorimotor feature composition post-hoc based on the observed pattern of brain activity (Dreyer et al., 2015; Mason & Just, 2016; Moseley et al., 2012). Secondly, in some experiments (Wilson-Mendenhall et al., 2012) stimuli consisted solely of single abstract concepts limiting the generalizability of the results. Thirdly, findings from neuroimaging studies are often exposed to the argument that the effects found in modal brain areas only reflect post-conceptual processes, such as imagery, semantic elaboration or spreading of activation (Mahon & Caramazza, 2008). These late effects, in principle, do not rule out amodal representations of concepts, which are considered to be accessed earlier. ERPs measured with EEG, which have the advantage of a high temporal resolution, are the ideal tool to test opposing assumptions made by amodal vs. grounded cognition approaches. Whereas the investigation of the time course of brain activation during abstract concept processing is limited to the comparison of abstract vs. concrete concepts as a whole (see 1.4.2.), studies contrasting several subgroups of concrete concepts found differential modality-specific ERP effects during conceptual tasks about 150 ms after target onset (Hauk & Pulvermüller, 2004; Hoenig et al., 2008; Kiefer et al., 2011; Proverbio et al., 2007; Pulvermüller, Härle, & Hummel, 2000). This early sensorimotor activity (see also Klepp et al., 2014; Niccolai et al., 2020; Niccolai et al., 2014) indexes access to conceptual representations instead of post-conceptual processes as claimed by representatives of amodal approaches thus providing unequivocal evidence in support of grounded cognition approaches (Kiefer & Pulvermüller, 2012). So far, there is a lack of corresponding evidence with regard to abstract concepts.

1.5. Aims and outline of the present work

The present work aims to provide evidence regarding the grounding of abstract concepts in the sensory and motor systems as predicted by refined grounded cognition theories and similarly as it already has been observed in concrete concepts. More precisely, this dissertation aims to fill the following important research gaps: (i) As the treatment of the abstract concept class as a homogeneous conceptual category is highly questionable, the present work focuses on the probable semantic heterogeneity of abstract concepts, thus considerably going beyond previous research. (ii) Subsequently, based on an a priori determination of the semantic content of abstract concepts by subjectively generated properties, the present work further

aims to investigate the grounding of abstract concepts in sensorimotor brain systems, an area to which little attention has been paid so far. (iii) Furthermore, this dissertation addresses the fact that very little is known about the time course of brain activity during the processing of abstract concepts, even though insights in this regard are inevitable in order to exclude that differential modal effects are exclusively based on post-conceptual processes as claimed by amodal approaches. (iv) Finally, the present work aims to shed light on the validity of the notion of conceptual flexibility, an important assumption made by grounded cognition approaches.

This dissertation consists of four studies, whereby each study addressed one of the research gaps described above: (i) In order to assess the semantic content of abstract concepts and to further provide an estimate of the relative contribution of differential feature types, participants of study I (Harpaintner, Trumpp, & Kiefer, 2018) were asked to generate properties such as features, situations and associations in response to 296 abstract concepts, which were subsequently categorized by a coding scheme enabling a classification into modal and verbal contents. In comparison to earlier studies making use of a similarly approach (Barsalou & Wiemer-Hastings, 2005), the present property generation study examined a much more extensive amount of abstract concepts. (ii) Based on this property generation study, 32 abstract words strongly related to motor properties and 32 abstract words strongly related to visual properties were contrasted in a subsequent fMRI study (study II; Harpaintner, Sim, Trumpp, Ulrich, & Kiefer, 2020a), thus adopting a theory-driven approach often used in the investigation of concrete concepts. A within subject design and localizer tasks (motor vs. visual localizer) were chosen in order to assess the neural substrate of processing specific subgroups of abstract concepts. This design further allowed to test whether conceptual processing of motor and visual abstract concepts elicits enhanced activity in corresponding motor and sensory brain areas similarly as real world movements and object observation. Note that, in contrast to previous neuroimaging experiments (Dreyer et al., 2015; Mason & Just, 2016; Moseley et al., 2012; Wilson-Mendenhall et al., 2012), the processing of a larger set of abstract stimuli was assessed, in which the sensorimotor feature composition was determined a priori. (iii + iv) Finally, two ERP studies (studies IIIa and IIIb; Harpaintner, Trumpp, & Kiefer, 2020b) and the associated high temporal resolution allowed to investigate the time course of brain activity during the processing of motor and visual abstract concepts, thus allowing the determination whether sensorimotor brain activity reflects early and rapid access to conceptual information (between 150 and 300 ms) or later post-conceptual processes. Furthermore, the notion of conceptual flexibility, as indicated by differential task-dependent ERP effects, was tested using tasks with a varying degree of depth of processing.

2. Original research articles

2.1. Study I - The semantic content of abstract concepts: A property listing study of 296 abstract words

Harpaintner, M., Trumpp, N. M., & Kiefer, M. (2018). The Semantic Content of Abstract Concepts: A Property Listing Study of 296 Abstract Words. *Frontiers in Psychology, 9*(1748). doi: 10.3389/fpsyg.2018.01748

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The Semantic Content of Abstract Concepts: A Property Listing Study of 296 Abstract Words

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The relation of abstract concepts to the modality-specific systems is discussed controversially. According to classical approaches, the semantic content of abstract concepts can only be coded by amodal or verbal-symbolic representations distinct from the sensory and motor systems, because abstract concepts lack a clear physical referent. Grounded cognition theories, in contrast, propose that abstract concepts do not depend only on the verbal system, but also on a variety of modal systems involving perception, action, emotion and internal states. In order to contribute to this debate, we investigated the semantic content of abstract concepts using a property generation task. Participants were asked to generate properties for 296 abstract concepts, which are relevant for constituting their meaning. These properties were categorized by a coding-scheme making a classification into modality-specific and verbal contents possible. Words were additionally rated with regard to concreteness/abstractness and familiarity. To identify possible subgroups of abstract concepts with distinct profiles of generated features, hierarchical cluster analyses were conducted. Participants generated a substantial proportion of introspective, affective, social, sensory and motor-related properties, in addition to verbal associations. Cluster analyses revealed different subcategories of abstract concepts, which can be characterized by the dominance of certain conceptual features. The present results are therefore compatible with grounded cognition theories, which emphasize the importance of linguistic, social, introspective and affective experiential information for the representation of abstract concepts. Our findings also indicate that abstract concepts are highly heterogeneous requiring the investigation of well-specified subcategories of abstract concepts, for instance as revealed by the present cluster analyses. The present study could thus guide future behavioral or imaging work further elucidating the representation of abstract concepts.

Keywords: abstract concepts, grounded cognition, hierarchical cluster analysis, embodiment, semantic memory, conceptual representation, embodied cognition, language comprehension

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INTRODUCTION

Research on conceptual knowledge is an important topic in cognitive psychology and in cognitive science in general. Central human abilities, such as problem solving, action planning, object recognition, communication and language crucially depend on conceptual knowledge stored in semantic long-term memory (Tulving, 1972; Humphreys et al., 1988;

Kiefer and Pulvermüller, 2012). There is an agreement that concepts are the basic units of cognition. Concepts are defined as mental entities, which provide factual knowledge by integrating our sensory and motor experiences with the environment in a categorical fashion (Humphreys et al., 1988; Kiefer and Pulvermüller, 2012). They refer to concrete objects, but also to referents, which are not directly observable, like mental or emotional states, abstract ideas, social constellations and scientific theories. A main question in this regard concerns the role of modality-specific systems in the representation of conceptual knowledge.

Traditional models of semantic memory propose that concepts are represented in an amodal, symbolic format distinct from sensory and motor systems (Collins and Loftus, 1975; Anderson, 1978; Pylyshyn, 1980; Fodor, 2001; Mahon and Caramazza, 2009). These models have the advantage to naturally explain the representation of all concepts since an amodal and symbolic code is very potent in terms of computational power (Rogers et al., 2004; Patterson et al., 2007). This becomes especially evident when considering abstract concepts, which lack a clear physical referent by definition. At a first glance, abstract concepts do not rely on sensory and motor or other modality-specific information so that their representation might be quite naturally explained within an amodal theoretical framework. At the neural level, anterior (Patterson et al., 2007; Visser et al., 2010) and posterior (Gold et al., 2006; Hoffman et al., 2012) temporal cortices have been proposed as the central correlates of conceptual representation, serving as amodal semantic hubs. Such amodal theories assume that sensory and motor brain systems are not causally involved in retrieving conceptual information, their engagement is rather seen as an epiphenomenon (McClelland and Rogers, 2003).

More recent embodied or grounded cognition theories (Gallese and Lakoff, 2005; Pulvermüller, 2005; Barsalou, 2008; Borghi and Cimatti, 2009; Kousta et al., 2009; Louwerse, 2011; Meteyard et al., 2012; Kiefer and Barsalou, 2013), in contrast, propose that concepts are essentially represented in distinct modality-specific areas. These theories postulate that conceptual features are represented through cell assemblies distributed over sensory, motor, introspective and emotional brain regions. In accordance with Hebbian theory (Hebb, 1949), these functional neural networks result from simultaneous activations of already existing local and distributed cell assemblies in modality-specific areas (Pulvermuller and Fadiga, 2010). Hence, conceptual knowledge is highly dependent on individual experience (Kiefer et al., 2007; Beilock et al., 2008; Lyons et al., 2010; Willems et al., 2010; Hoenig et al., 2011). It is assumed that these modality-specific areas functionally contribute to conceptual comprehension (Pulvermüller, 2005). According to recently emerging hybrid models, conceptual knowledge is the result of processing in modality-specific brain circuits, which interact with multimodal connection hubs (Kiefer and Pulvermüller, 2012; Garagnani and Pulvermuller, 2016). The latter are thought to serve general semantic binding and integration.

Studies supporting grounded cognition theories mainly investigated the representation of concrete concepts, like "hammer" or "to ring" (for reviews see: Kiefer and Pulvermüller, 2012; Meteyard et al., 2012; Kiefer and Barsalou, 2013; for an extension of grounded cognition theories to abstract concepts, see below). Several studies using functional neuroimaging techniques showed that processing of action- (e.g., Hoenig et al., 2008), visual- (Simmons et al., 2007), gustatory- (e.g., Barros-Loscertales et al., 2012), olfactory- (Gonzalez et al., 2006), and sound-related (Kiefer et al., 2008) concepts elicits activations in corresponding modality-specific brain regions. Similar results providing evidence in favor of grounded cognition theories derived from electrophysiological (e.g., Trumpp et al., 2014), behavioral (e.g., Garcia and Ibanez, 2016), neuropsychological (e.g., Trumpp et al., 2013) and transcranial magnetic stimulation (TMS) studies (e.g., Pulvermüller et al., 2005).

While the grounding of concrete object concepts in the sensory and motor systems is well documented, the mere existence of abstract concepts such as "beauty", "freedom" and "justice" is a serious challenge for the grounded cognition framework. Abstract concepts are characterized by a lack of unique physical features, such as form, color and texture and hence lack a clearly perceivable referent (Crystal, 2004). As a clear physical referent, which can be experienced by our senses, is missing (Paivio, 1986), grounded cognition approaches must be extended in order to account for the representations of abstract concepts. To this end, refined grounded cognition approaches to abstract concepts such as the affective embodiment account (AEA; Kousta et al., 2009), the language and situated simulation theory (LASS; Barsalou et al., 2008) and the words as social tools approach (WAT; Borghi and Binkofski, 2014) have been developed (for similiar approaches, also see Louwerse, 2011; Connell and Lynott, 2012, 2014). They emphasize the importance of linguistic (Barsalou et al., 2008; Kousta et al., 2009; Borghi and Binkofski, 2014), social (Borghi and Binkofski, 2014), introspective (Kiefer and Barsalou, 2013), and affective (Kousta et al., 2009) experiential information for the representation of abstract concepts, in addition to sensorimotor information (see Connell, 2018) – which is utilized through metaphoric relations to concrete concepts as stated in the conceptual metaphor theory (Lakoff and Johnson, 1980). The significance of social, affective and introspective information can be illustrated when considering the concepts "freedom" and "justice". Thinking about freedom might simulate experiential information one gathered within the hippie movement in the 1960s, feeling free and maybe a bit rebellious (affective and introspective aspects) while protesting with like-minded people for a social upheaval (social aspect). Thinking about justice on the other hand might evoke information about a court hearing with two opposing parties (e.g., hippies vs. policemen; social aspect), where the winning party gets into the flush of victory while the losing party feels shocked and ruined (affective and introspective aspects).

Based on these considerations, a clear-cut distinction between concrete and abstract concepts, as suggested for instance by Paivio (1986) in his Dual Code Theory, is at least questionable (see also Wiemer-Hastings et al., 2001; Connell and Lynott, 2012): Paivio proposed that abstract concepts are stored in a verbal-symbolic code only, whereas concrete concepts rely on both a visual imaginary and a verbal-symbolic code. In line with Paivio's reasoning, it has been claimed more

recently that abstract concepts require amodal, verbal-symbolic representations (Mahon and Caramazza, 2009).

However, this notion of a strict dichotomy between concrete and abstract concepts with abstract concepts relying only on verbal-symbolic representations has been challenged (Wiemer-Hastings and Xu, 2005). Abstract concepts frequently activated left hemispheric language regions in neuroimaging studies (Desai et al., 2011; Sakreida et al., 2013) suggesting a relatively higher importance of verbal associations for this conceptual category. However, activity within the sensorimotor system was also obtained for both abstract and concrete words (Pexman et al., 2007), indicating that abstract concepts also depend on sensory and motor information.

Other research also suggested that concrete and abstract concepts rather differ with regard to their situational content than their representation format (Wiemer-Hastings and Xu, 2005). Although a bimodal distribution of concreteness ratings indicated a categorization of abstract and concrete concepts into two large clusters, there was also a large variance within these clusters (Wiemer-Hastings et al., 2001). Furthermore, introspection-based aspects determined abstractness ratings. The role of internal states for the meaning of abstract concepts was confirmed in a further property listing study by Barsalou and Wiemer-Hastings (2005). Participants of their study were asked to generate associations with regard to abstract (e.g., "freedom"), concrete (e.g., "car") and intermediate (e.g., "farm") concepts. Concrete concepts evoked properties related to objects, locations and behaviors in situations, whereas abstract concepts were mainly associated with introspections, mental states and social aspects of situations with intermediate concepts lying in between. More recent studies using ratings and subsequent hierarchical cluster analyses for a large set of concrete and abstract words also found abstract concepts to be more strongly associated with emotions, social cognition, internal and mental states than concrete concepts (Troche et al., 2014, 2017; Binder et al., 2016). The involvement of introspection and internal states in the processing of abstract concepts is also indicated by neuroimaging work. For instance, Wilson-Mendenhall et al. (2013) showed their participants the abstract concept "convince" during a concept-scene matching task, where brain areas underlying mental states and social interaction became active.

In addition to introspections, social aspects and verbal associations, the semantic content of abstract concepts also seems to depend on the sensory and motor systems, similar to concrete object concepts, albeit perhaps to a somewhat smaller extent (Barsalou and Wiemer-Hastings, 2005; Troche et al., 2014, 2017; Binder et al., 2016). Studies providing modality ratings for concrete and abstract concepts showed an association of sensory experience with all concepts, regardless of whether they are classed as abstract or concrete (Lynott and Connell, 2009, 2013; van Dantzig et al., 2011). Behavioral studies examining the "Action-Sentence-Compatibility Effect" (Glenberg and Kaschak, 2002; Glenberg et al., 2008) indicated a contribution of the motor system to the comprehension of abstract concepts, when participants processed them within sentences. Neuroimaging studies also demonstrated the involvement of sensory and motor brain systems during the processing of abstract emotion words similar to face- and arm-related action words (Moseley et al., 2012; see also Dreyer et al., 2015; Vukovic et al., 2017) or during the processing of physical concepts (e.g., "frequency") similar to performing rhythmic movements (Mason and Just, 2016).

Taken together, behavioral and neuroimaging studies indicated that abstract concepts not only depend on the verbal system (Wang et al., 2010), but also on a variety of modal systems involving perception, action, emotion and internal states. Although many studies considered abstract concepts as an undifferentiated conceptual category, defined solely by a lack of a perceivable physical referent and contrasted them as a uniform class to concrete concepts (see Wang et al., 2010), the semantic content of abstract concepts might be much richer and highly heterogeneous (Wiemer-Hastings et al., 2001). For instance, differential patterns of conceptual relations for abstract emotional and non-emotional concepts were found (Barca et al., 2017). This might explain, why neuroimaging studies reviewed above revealed inconsistent brain areas implicated in the processing of abstract concepts.

Given the probable heterogeneity of abstract concepts, in the present study, we characterized the semantic content of a large set of 296 abstract concepts using property listings. We determined the relative contribution of modal sensory, motor, introspective or social properties to the semantic content of abstract concepts, in addition to verbal associations. The present work had two goals: (i) Although our property listing study does not formally allow to test competing theories of the representation of abstract concepts, the results of our study are nevertheless informative: The presence of modal properties in participants' listings would be an important prerequisite for the validity of grounded cognition theories. (ii) The obtained property listings for a large set of abstract concepts should provide an estimate of their semantic feature composition. The property listings provide information with regard to the heterogeneity of feature types across concepts and allows to determine possible subcategories. Results are provided as **Supplementary Material** (see **Supplementary Dataset S1**), which might thus guide future behavioral and neuroimaging work investigating the representation of abstract concepts.

To assess the semantic content of abstract concepts, we used a property generation task similar to Barsalou and Wiemer-Hastings (2005). Participants were asked to write down properties such as features, situations and associations coming into mind for 296 abstract concepts. These properties were categorized by a coding-scheme making a classification into modality-specific and verbal contents – namely into sensorimotor features, features describing social constellations, internal states and emotions as well as verbal associations – possible. These 296 concepts were furthermore rated with regard to their familiarity and concreteness/abstractness in two ratings. Lemma frequency and word length were also part of the analysis. Hierarchical cluster analyses were used to shed light into the heterogeneity of abstract concepts. In line with the aforementioned theories of the grounded cognition framework, we hypothesized that abstract concepts are grounded in various modal systems, as it already has been shown with regard to social, affective and introspective experiential information. We furthermore expected that abstract

concepts are grounded in the sensorimotor system as well, indicated by a considerable percentage of generated sensorimotor properties in the property generation task. Finally, we assumed that abstract concepts can be divided in several subcategories depending on conceptual feature relevance similar to concrete ones.

MATERIALS AND METHODS

Participants

Sixty healthy volunteers (M_{age} = 22.4 years, range = 18 – 46 years, 44 females) from Ulm University participated in the property generation task. All participants were native German speakers (two participants grew up bilingually) with no history of psychiatric or neurological disorders. Another 30 healthy, native German speakers – who did not participate in the property generation task – took part in two ratings: 15 of these subjects (M_{age} = 24.6 years, range = 19 – 49 years, 10 females) participated in the first rating, another 15 subjects (M_{age} = 27.0 years, range = 23 – 32 years, 10 females) took part in the second rating. Subjects gave written informed consent and were paid eight Euro for participation in the property generation task and study credits for taking part in the rating studies, respectively. The procedure of the study was approved by the Ethical Committee of Ulm University.

Stimuli

Three-hundred word stimuli were selected from a German dictionary (Scholze-Stubenrecht, 2009) on the basis of the operational definition of abstract concepts (Paivio, 1986; Crystal, 2004): Abstract concepts do not relate to entities that can be directly experienced by our senses and hence lack a clearly perceivable referent. To avoid any effects attributable to the word category, we decided to select abstract nouns only. Words, which were too concrete and hardly used in common parlance as well as foreign words, religious concepts and scientific concepts, were not included. To avoid excessive work load in the property generation task, the 300 abstract words were randomly assigned to one of six questionnaires, comprising 50 words each. To further avoid sequence effects, pages within the six questionnaires were randomized five times. Hence, properties for each abstract word were generated by 10 subjects. Four of the 300 words were excluded subsequently, because three of them ("Pech" – "bad luck"/"pitch", "Vorstellung" – "imagination"/"show", "Einstellung" – "attitude"/"setting") turned out to be ambiguous and one of them ("Lachen" – "laugh") proved to be too concrete. Therefore, a total of 296 abstract words were included in the analyses.

Procedure

Property Generation Task

Participants were informed that the study investigates word generation. The instruction was kept as open as possible in order not to direct answers in any direction. Subjects were asked to generate and write down associations, properties or situations that come into their mind when thinking about the presented words as spontaneously as possible, but without any temporal limitations. Participants were further instructed to write down about four properties and to avoid synonyms for the respective terms. If no property/situation came into mind, participants were told to skip this particular word. Within the instruction, subjects were given two words (e.g., "hallucination") and potential properties (e.g., "colorful", "loud", "hearing voices") as examples, which were not part of the actual word stimuli.

Ratings

Participants were asked to rate 300 abstract and 77 concrete words with regard to familiarity and concreteness/abstractness (valence and arousal ratings were also obtained. However, they were considered for use in future studies and hence were not analyzed here). Familiarity was rated on a 6-point Likert scale on basis of the two poles "low familiarity" and "high familiarity", with higher scores indicating higher familiarity. The instructions asked the subjects to make their decision based on whether they often use, see or hear the named concepts, or whether the term is rather rarely encountered. A similar scale with the poles "abstract" and "concrete" was used regarding concreteness/abstractness, with higher scores indicating higher concreteness. Subjects were guided by the classical definition of abstractness whereby named concepts with a lack of perceivable physical features should receive ratings of high abstractness (i.e., low scores of concreteness), while terms referring to perceivable objects, persons or materials should be rated with high concreteness scores. The written instructions provided subjects with three examples and potential ratings each (e.g., "joy", high familiarity, high abstractness; not used in the critical ratings). Subjects were instructed to rate the words as spontaneously as possible.

Ratings were obtained in two separate samples in order to decrease the number of ratings in each subject. In the first sample, participants rated 190 abstract and 49 concrete words on a paper-pencil questionnaire. In the second sample, the remaining 110 abstract as well as 28 concrete words were rated. For better practicability an online questionnaire was used[1]. Concrete words (e.g., "table", "donkey") were included in the questionnaires in order to avoid response bias (ratio of abstract to concrete words in both rating studies was approximately equal [∼ 1:4]).

Data Analysis

Data Coding Scheme

A coding scheme adopted from Barsalou and Wiemer-Hastings (2005) was developed in order to qualitatively analyze the generated properties and to assign these properties to one of five main categories. The categories and their definitions are as follows:

(I) *Sensorimotor feature*: A feature that can be experienced by our senses. It describes the meaning of the abstract concept, or the abstract concept can be applied to this feature. In order to investigate the modality-specific nature of abstract concepts more closely, the category "sensorimotor

[1]http://www.unipark.com/

feature" was further divided into seven subcategories: visual (e.g., "colorful painting" for "creativity"), acoustic (e.g., "loud" for "argument"), motor-related (e.g., "hug" for "sympathy"), tactile (e.g., "fluffy" for "comfort"), olfactory (e.g., "sulfurous" for "disgust"), gustatory (e.g., "bitter" for "disgust") and interoceptive (e.g., "stomach ache" for "hunger") feature.

(II) *Social constellation*: a feature or a situation that describes the coexistence of different persons or which implies an interaction between at least two different persons, e.g., "friends" for "sympathy".

(III) *Internal state and emotion*: a feature or a situation that reflects internal, cognitive processes (e.g., motivation, emotion, volition). Also a feature or a situation that describes the character of an individual and which implies an evaluation of the respective abstract concept, e.g., "joy" for "sympathy".

(IV) *Association*: a feature or a situation that does not describe the abstract concept, but which is thematically or symbolically related to it. This feature does not directly contribute to the understanding of the abstract concept, e.g., "sun" for "sympathy".

(V) *Other abstract concept*: an abstract feature that describes the abstract concept or to which the abstract concept can be applied. This category also includes all terms that are identical to one of the other words used in the questionnaire, e.g., "karma" for "sympathy".

Hence, the subjects' responses were classified into eleven categories. Double coding was possible (e.g., "to paint" as visual and motor-related feature of "talent").

Two independent coders used the aforementioned coding scheme to classify the generated properties. Coders were trained to achieve high reliability and to keep inter-individual variance as low as possible (see Barsalou and Wiemer-Hastings, 2005; Barca et al., 2017; Trumpp and Kiefer, 2018 for similiar coding procedures). The two coders were different from the authors and naïve to the purpose of the study. They saw the abstract word while coding each property in order to decide whether the generated feature reflects a verbal association or a semantic property of the respective concept. Inter-rater reliability (see Barsalou and Wiemer-Hastings, 2005 for a similar method of reliability analysis) in terms of joint probability of agreement was 76.79 %.

Statistical Analysis

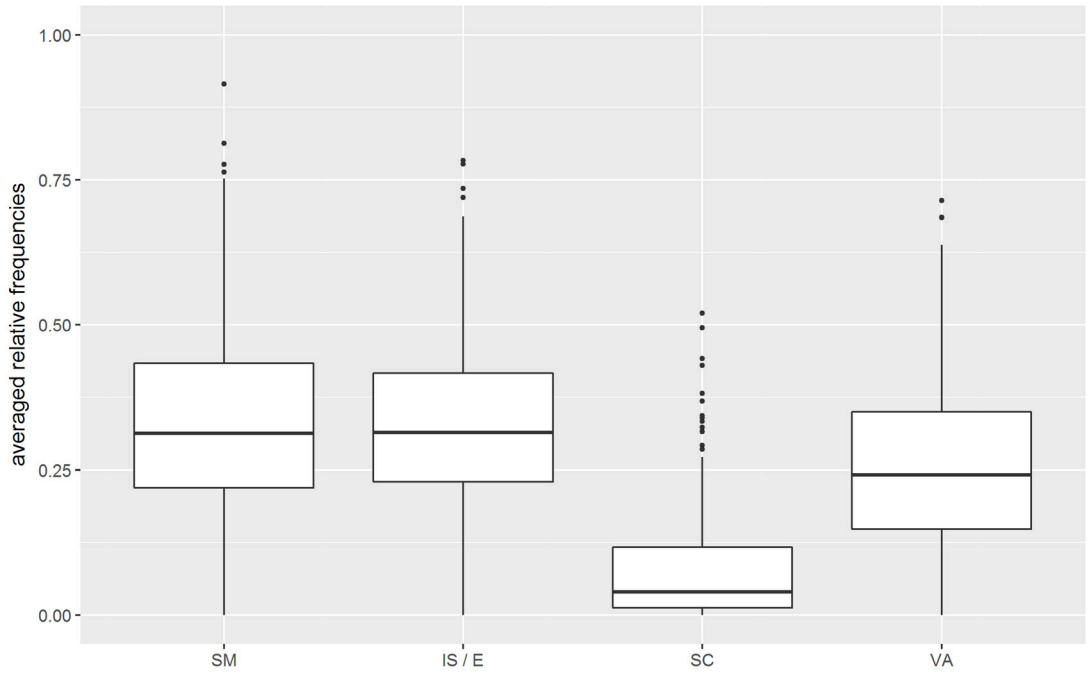
Data was analyzed using RStudio (version 1.0.153; RStudio-Team, 2015) and R's (R-Core-Team, 2017) packages "ez" (Lawrence, 2016), "car" (Fox and Weisberg, 2011), "cluster" (Maechler et al., 2017) and "NbClust" (Charrad et al., 2014). After coding was completed, relative frequencies were calculated for each feature type per concept within each subject (e.g., a participant reported four properties for a specific concept: two motor-related features, one visual feature and one association. Thus, the relative frequency for motor-related features was 2/4 = 0.5, for visual related features and associations 1/4 = 0.25, each). In a second step, relative frequencies for each feature type and concept were averaged across all subjects.

In order to identify significant differences of relative frequencies of generated features between categories, univariate repeated measures analyses of variance were carried out. Level of significance was defined as $p < 0.05$. When significant variation between categories was indicated, *post hoc* testing (Bonferroni *post hoc* tests) was performed. Since we assumed (on the basis of the aforementioned theories) that both categories "association" and "other abstract concept" reflect verbal associations, these categories were combined into the superordinate category "verbal association". The first analysis considered the category "sensorimotor feature" as a whole and thus consisted of the four factor levels "sensorimotor feature", "social constellation", "internal state/emotion" and "verbal association". To further investigate the distribution of the sensorimotor features in detail, a second analysis was carried out in which the seven specific sensorimotor features were compared.

Welch's *t*-test was used to compare concreteness/abstractness and familiarity ratings of concrete and abstract concepts. This analysis also had the purpose of validating the selection of our stimuli by showing that our selected abstract concepts were indeed rated abstract. Welch's *t*-test was chosen because of the different number of stimuli per word category. Levene's test also indicated that the assumption of homogeneity of variances was not fulfilled.

Additional correlation (Pearson's *r*) analyses were performed to examine possible relationships between concreteness/abstractness ratings and the generated characteristics, the ratings of familiarity and eventually lemma frequency (derived from the German lexical database dlexDB; Heister et al., 2011) and word length (number of letters). Subsequent regression analyses with concreteness/abstractness ratings as the dependent variable aimed at answering the questions of what constitutes abstractness and of how the observed heterogeneity within the concreteness/abstractness ratings can be explained.

To further identify possible homogeneous subgroups of abstract concepts with distinct profiles of generated features, hierarchical cluster analyses were conducted (see **Supplementary Data S2, S3** for the R script of our cluster analyses and the matching data set). Hierarchical cluster analyses were used in order to generate internally homogeneous clusters while variability between clusters is maximized. Cluster Analysis 1 was based on the four clustering variables "sensorimotor feature", "social constellation", "internal state/emotion" and "verbal association". Cluster Analysis 2 was based on the seven specific sensorimotor features (e.g., visual, motor-related, . . .) in order to investigate the structure of the data in a more detailed fashion. Cluster analyses were carried out on the basis of Euclidean distances as a measure of distances between clusters. To identify and subsequently remove outliers, the single-linkage clustering method was used. The single-linkage method, which is based on minimal distances between clusters and tends to produce chaining effects, is highly sensitive to the presence of outliers, since objects with extreme differences to all other objects are the last ones to converge. Visual inspection of the resulting dendrogram can consequently be



	SM	IS / E	SC	VA
M	.337	.325	.078	.260
SD	.156	.152	.096	.148
$x_{0.1}$ - $x_{0.9}$	.158 - .540	.131 - .524	.000 - .222	.086 - .476
Ex_{High}	„disgust“	„emotion“	„advice“	„revolution“
Ex_{Low}	„assumption“	„tradition“	„fitness“	„shyness“

FIGURE 1 | Descriptive statistics of Analysis 1 and corresponding boxplots. *M* = mean; *SD* = standard deviation; $x_{0.1/0.9}$ = first and ninth decile. SM = sensorimotor feature; IS/E = internal state/emotion; SC = social constellation; VA = verbal association. Ex_{High}/Ex_{Low} depicts exemplary abstract concepts with a high/low portion of generated features in the respective categories.

used as a tool to remove outliers (Steinbach et al., 2004). After eliminating the outliers, Ward's (1963) method, which minimizes within-group dispersion based on a sum-of-squares criterion (Murtagh and Legendre, 2014), was applied to the data. Because there is no universally accepted method for determining the optimal number of clusters, we took into account theory-driven, visual (inspection of the dendrograms, and the "elbow test") and statistical (based on the "NbClust" package in R 3.4.1.: a package providing 26 indices, such as Calinski and Harabasz index and Silhouette index; Charrad et al., 2014) criteria.

We did not conduct an additional factor analysis because we were interested in finding different subcategories of abstract concepts characterized by a multidimensional feature space and not in reducing the number of underlying feature dimensions.

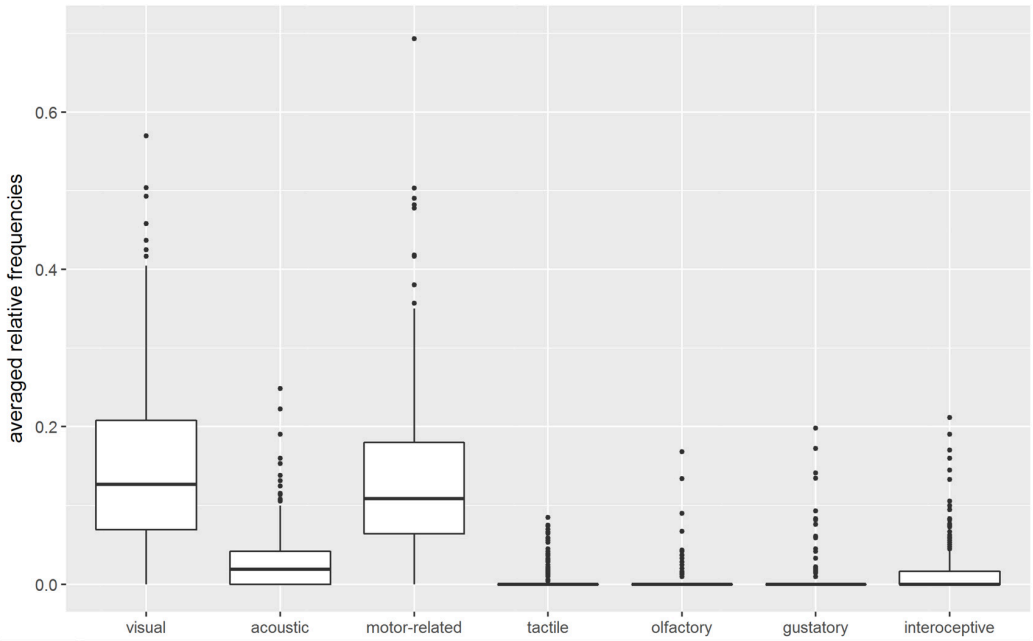
RESULTS

On average, 3.37 properties per word were generated showing that participants followed the instructions.

Analysis 1 – Overview

The first analysis comprised four categories: "sensorimotor feature" (SM), "social constellation" (SC), "internal state/emotion" (IS/E) and "verbal association" (VA). **Figure 1** shows relevant descriptive statistics and the corresponding boxplots. At the descriptive level, participants generated the highest portion of features within the "sensorimotor feature" category (M = 0.337) followed by the "internal state/emotion" (M = 0.325), the "verbal association" (M = 0.260) and the "social constellation" (M = 0.078) categories. A univariate repeated measures ANOVA revealed that relative frequency of generated features differed significantly between categories [$F(3,885) = 161.19$, $p < 0.001$; Greenhouse–Geisser-corrected p-value]. *Post hoc* comparison using Bonferroni tests revealed significant differences between all conditions (all $ps < 0.001$).

As can be seen in the boxplots (**Figure 1**), the ranges within categories were quite large, reflecting a rather heterogeneous generation of properties. This becomes particularly evident when considering the "sensorimotor feature" category, where subjects generated between 0.0 and 91.6% sensorimotor features per



	visual	acoustic	motor-related	tactile	olfactory	gustatory	interoceptive
M	.148	.029	.131	.007	.003	.006	.013
SD	.103	.038	.099	.016	.015	.022	.030
$x_{0.1}$ - $x_{0.9}$	.034 - .283	.000 - .077	.025 - .253	.000 - .025	.000 - .000	.000 – .017	.000 - .046
Ex_{High}	„disgust“	„wit“	„activity“	„protection“	„disgust“	„appetite“	„pain“
Ex_{Low}	„gratitude“	„assumption“	„expectation“	„appearance“	„assumption“	„expectation“	„appearance“

FIGURE 2 | Descriptive statistics of Analysis 2 and corresponding boxplots. *M* = mean; *SD* = standard deviation; $x_{0.1/0.9}$ = first and ninth decile. Ex_{High}/Ex_{Low} depicts exemplary abstract concepts with a high/low portion of generated features in the respective categories.

word. A similar result pattern was also observed with regard to the other categories ($range_{internal\ state/emotion}$ = 0.00 – 0.783, $range_{social\ constellation}$ = 0.00 – 0.521, $range_{verbal\ association}$ = 0.00 – 0.715). **Figure 1** (lower part) gives an overview of examples reflecting a rather high or a rather low portion of generated features in the respective categories.

Analysis 2 – Distribution of Sensorimotor Features in Detail

The second analysis comprised the seven modality-specific subcategories “visual”, “acoustic”, “motor-related”, “tactile”, “olfactory”, “gustatory” and “interoceptive”. Descriptive statistics and corresponding boxplots are shown in **Figure 2**. At the descriptive level the highest relative frequencies were generated within the categories “visual” (M = 0.148) and “motor-related” (M = 0.131), followed by the acoustic category (M = 0.029). All other categories ($M_{tactile}$ = 0.007, $M_{olfactory}$ = 0.003, $M_{gustatory}$ = 0.006, $M_{interoceptive}$ = 0.013) only played a marginal role in the generation of properties. Relative frequencies differed significantly between the subcategories as shown by a second univariate repeated measures ANOVA [$F(6,1770)$ = 346.34, $p < 0.001$; Greenhouse–Geisser-corrected p-value]. *Post hoc* Bonferroni tests revealed that relative frequency did not differ between the “visual” and “motor-related” categories (p = 1.00) and between the “tactile”, “gustatory” and “olfactory” categories (all ps > 0.10). All other comparisons were statistically significant (all ps < 0.05).

Inspection of the boxplots in **Figure 2** also indicates that ranges within single categories were relatively large. Especially the categories “visual”, “motor-related” and “acoustic” showed a broad range ($range_{visual}$ = 0.00 – 0.569, $range_{motor-related}$ = 0.00 – 0.693, $range_{acoustic}$ = 0.00 – 0.248). Examples reflecting a rather high or a rather low portion of generated features in these categories are shown in the lower part of **Figure 2**.

Comparison Between Concrete and Abstract Concepts

In order to validate that our selected abstract concepts were indeed abstract, abstract and concrete concepts were compared with regard to concreteness/abstractness ratings. Data from concrete concepts were obtained from two ratings, in which concrete concepts served as fillers. In these rating studies, in addition to concreteness/abstractness, ratings of familiarity were also available. Welch’s t-test revealed that concreteness/abstractness ratings (for relevant descriptive statistics see **Table 1**) differed significantly between the two

concept classes [$t(83.2) = -51$, $p < 0.001$]. Abstract concepts ($M = 2.55$; $SD = 0.53$; range = 1.33 – 4.27) were rated significantly more abstract than concrete concepts ($M = 5.72$; $SD = 0.38$; range = 3.80 – 6.00). When looking at the quantiles, it is noticeable that concreteness/abstractness ratings were much more heterogeneous within abstract concepts than in concrete concepts. Considering concrete concepts, 90% of the values were lying between 5.40 and 5.95, while 90% of the ratings regarding abstract concepts were lying within a much broader window between 1.93 and 3.27. Taking this into account, it is not surprising that the abstract concept class yielded some isolated outliers ($\tilde{x} \pm 2\sigma$) with regard to their concreteness/abstractness ratings. Concepts like "thirst" ($M = 4.27$), "work" ($M = 4.13$) and "assassination" ($M = 4.07$) were rated relatively concrete, whereas concepts like "fantasy" ($M = 1.33$), "honor" ($M = 1.40$) and "miracle" ($M = 1.40$) were rated rather abstract.

While concreteness/abstractness ratings were quite diverging, familiarity ratings showed no significant differences [$t(60.2) = 0.551$, $p = 0.584$]. Abstract concepts were rated with $M = 4.46$ ($SD = 0.73$; range = 2.47 – 5.80) on average, concrete concepts were rated with a mean rating of $M = 4.39$ ($SD = 0.86$; range = 1.73 – 5.80).

Correlation and Regression Analyses

In order to explain the observed range within the abstract concept class and to investigate possible relationships between concreteness/abstractness ratings and other variables, correlation analyses were carried out. Significant correlations within the superordinate categories were observed between concreteness/abstractness ratings and relative frequency of the "sensorimotor feature" and "internal state/emotion" categories, familiarity ratings and lemma frequency, respectively (**Table 2A**; all ps < 0.01).

Within the seven modality-specific subcategories, significant positive correlations between concreteness/abstractness ratings and relative frequency of the "visual", "motor-related", "olfactory", "gustatory" and "interoceptive" feature categories were found (**Table 2B**; all ps < 0.05).

In order to examine the direction of the relationship more precisely, a first multiple linear regression analysis was conducted – on the basis of the aforementioned correlation analysis – to predict concreteness/abstractness ratings based on relative frequency of the "sensorimotor feature" and "internal state/emotion" superordinate categories, familiarity ratings and lemma frequency (**Table 3A**). A significant regression equation was found [$F(4,291) = 34.3$, $p < 0.001$], with an adjusted R^2 of 0.311. Relative frequency of the categories "sensorimotor feature" [$\beta = 0.280$, $t(291) = 4.97$, $p < 0.001$] and "internal state/emotion" [$\beta = -0.228$, $t(291) = -4.04$, $p < 0.001$] as well as familiarity ratings [$\beta = 0.330$, $t(291) = 6.49$, $p < 0.001$] were identified as significant predictors of concreteness/abstractness ratings. Relative frequency of the "sensorimotor feature" category and familiarity ratings had significant positive regression weights, indicating words with higher scores on these scales were expected to be rated more concrete, after controlling for the other variables in the model. Relative frequency of the "internal state/emotion" category had a significant negative weight, indicating that after accounting for the other variables, those concepts with a higher portion of "internal state/emotion" features were expected to be rated more abstract. Lemma frequency did not account for a significant portion of the variance after controlling for the other variables ($p = 0.115$).

Similarly, a second multiple linear regression analysis, in which the superordinate category "sensorimotor feature" was replaced as predictor by the more fine-grained subcategories "visual", "motor-related", "olfactory", "gustatory" and "interoceptive", was conducted to predict concreteness/abstractness ratings (**Table 3B**). Again, a significant regression equation was found [$F(8,287) = 18.2$, $p < 0.001$], with an adjusted R^2 of 0.318. Relative frequency of the categories "motor-related" [$\beta = 0.164$, $t(287) = 3.20$, $p < 0.01$], "gustatory" [$\beta = 0.141$, $t(287) = 2.17$, $p < 0.05$], "interoceptive" [$\beta = 0.158$, $t(287) = 2.99$, $p < 0.01$] and "internal state/emotion" [$\beta = -0.265$, $t(287) = -4.44$, $p < 0.001$] as well as familiarity ratings [$\beta = 0.322$, $t(287) = 6.26$, $p < 0.001$] were identified as significant predictors of concreteness/abstractness ratings. Visual features as predictor for concreteness/abstractness just failed to reach significance ($p = 0.051$). Relative frequency of the "motor-related", "gustatory" "interoceptive" and "visual" subcategories as well as familiarity ratings had significant positive regression weights, indicating words with higher scores on these scales were expected to be rated more concrete. Again, relative frequency of the "internal state/emotion" category had a significant negative weight, indicating that those concepts with a higher portion of "internal state/emotion" features were expected to be rated more abstract. Lemma frequency, here too, did not account for a significant portion of the variance ($p = 0.093$).

Hierarchical Cluster Analyses

Cluster Analysis 1

Cluster Analysis 1 was based on the four clustering variables "sensorimotor feature", "social constellation", "internal

TABLE 1 | Descriptive statistics of concreteness/abstractness and familiarity ratings for abstract and concrete concepts.

		M	*SD*	*Min*	*Max*	$x_{0.1}$	$x_{0.5}$	$x_{0.9}$
Concreteness	Abstract concepts	2.552	0.532	1.333	4.267	1.933	2.533	3.267
	Concrete concepts	5.722	0.378	3.800	6.000	5.400	5.800	5.947
Familiarity	Abstract concepts	4.463	0.732	2.467	5.800	3.400	4.533	5.467
	Concrete concepts	4.392	0.855	1.733	5.800	3.480	4.400	5.293

M = mean; SD = standard deviation; Min = minimum; Max = maximum; $x_{0.1/0.9}$ *= first and ninth decile;* $x_{0.5}$ *= median.*

TABLE 2A | Results of correlation analyses for abstract concepts with the superordinate categories.

	SM	IS/E	SC	VA	Familiarity	Word length	Lemma frequency
Concreteness	0.397***	−0.354***	0.058	−.092	0.346***	−0.026	0.175**

*SM = sensorimotor feature; IS/E = internal state/emotion; SC = social constellation; VA = verbal association. *p < 0.05; **p < 0.01; ***p < 0.001.*

TABLE 2B | Results of correlation analyses for abstract concepts with the modality-specific subcategories.

	Vis	Acou	Mot	Tac	Olf	Gus	Int
Concreteness	0.218***	0.103	0.208***	0.082	0.126*	0.240***	0.203***

*vis = visual; acou = acoustic; mot = motor-related; tac = tactile; olf = olfactory; gus = gustatory; int = interoceptive. *p < 0.05; **p < 0.01; ***p < 0.001.*

state/emotion" and "verbal association". The single-linkage clustering method led to the exclusion of ten outliers. **Figure 3A** shows the dendrogram based on the subsequent cluster analysis with Ward's method. The structure of the dendrogram as well as the "elbow test" (**Supplementary Figure S1**) indicated that the optimal number of clusters is $k = 3$. In addition, most of the criteria of the "NbClust" function (7 of 26; across $k = 2$ and $k = 5$ clusters) spoke in favor of a three cluster solution.

TABLE 3A | Results of multiple linear regression analysis for abstract concepts with concreteness/abstractness as dependent variable and relative frequency of the "sensorimotor feature" and "internal state/emotion" categories, familiarity ratings and lemma frequency as predictors.

$R^2_{adj.}$ = 0.311 [$F(4,291) = 34.3$, $p < 0.001$]

	Coefficient estimate (β)	*SE*	*t*
Sensorimotor feature	0.280***	0.056	4.97
Internal state/Emotion	−0.228***	0.057	−4.04
Familiarity	0.330***	0.051	6.49
Lemma frequency	0.081	0.051	1.58

*All variables in the model have been tested for collinearity by using variance inflation factors (VIFs). All VIFs were < 5.0 indicating that the independent variables are not collinear (Urban and Mayerl, 2006); $R^2_{adj.}$ = adjusted R^2; β = standardized coefficient; SE = standard error, t = t-value. *p < 0.05; **p < 0.01; ***p < 0.001.*

TABLE 3B | Results of multiple linear regression analysis for abstract concepts with concreteness/abstractness as dependent variable and relative frequency of the "visual", "motor-related", "olfactory", "gustatory", "interoceptive" and "internal state/emotion" categories, familiarity ratings and lemma frequency as predictors.

$R^2_{adj.}$ = 0.318 [$F(8,287) = 18.2$, $p < 0.001$]

	Coefficient estimate (β)	*SE*	*T*
Visual	0.114	0.058	1.96
Motor-related	0.164**	0.051	3.20
Olfactory	−0.072	0.061	−1.17
Gustatory	0.141*	0.065	2.17
Interoceptive	0.158**	0.053	2.99
Internal state/Emotion	−0.265***	0.060	−4.44
Familiarity	0.322***	0.051	6.26
Lemma frequency	0.087	0.052	1.68

*All variables in the model have been tested for collinearity by using variance inflation factors (VIFs). All VIFs were < 5.0 indicating that the independent variables are not collinear (Urban and Mayerl, 2006); $R^2_{adj.}$ = adjusted R^2; β = standardized coefficient; SE = standard error, t = t-value. *p < 0.05; **p < 0.01; ***p < 0.001.*

Figure 3B shows boxplots of generated features per cluster. Cluster 1, the largest cluster ($n = 131$), was characterized by a relatively high portion of sensorimotor features ($M = 0.459$, $CI_{0.95} = [0.438;0.480]$). Features in the "social constellation" category played only a subordinate role in this cluster ($M = 0.041$, $CI_{0.95} = [0.034;0.049]$), while properties of both the "internal state/emotion" ($M = 0.257$; $CI_{0.95} = [0.239;0.275]$) and the "verbal association" ($M = 0.243$; $CI_{0.95} = [0.223;0.263]$) categories were generated to an intermediate extent. Abstract concepts in this cluster are for example "observation", "insight" and "fitness".

Specific for Cluster 2, which contains $n = 113$ abstract concepts, was a large portion of generated features of the "internal state/emotion" category ($M = 0.437$; $CI_{0.95} = [0.411;0.463]$). Besides that, compared to the other two clusters, this cluster had more than twice as many properties generated in the "social constellation" category ($M = 0.115$; $CI_{0.95} = [0.095;0.134]$). While sensorimotor features ($M = 0.255$; $CI_{0.95} = [0.240;0.271]$) were generated at a medium level, verbal associations ($M = 0.193$; $CI_{0.95} = [0.176;0.210]$) played a marginal role. Typical examples in this cluster are "nightmare", "argument" and "criticism".

The situation is quite different with Cluster 3, the smallest cluster ($n = 42$) in which verbal associations were clearly in the foreground ($M = 0.508$; $CI_{0.95} = [0.479;0.537]$). Like in Cluster 1, features in the "social constellation" category were subordinate ($M = 0.049$; $CI_{0.95} = [0.033;0.065]$). Although the categories "sensorimotor feature" ($M = 0.188$; $CI_{0.95} = [0.167;0.209]$) and "internal state/emotion" ($M = 0.255$; $CI_{0.95} = [0.220;0.290]$) were generated at an intermediate level, they play the least important role here compared to the other clusters. "Present", "theory" and "dignity" are examples in this cluster.

Cluster Analysis 2

Cluster Analysis 2 comprised the seven modality-specific subcategories "visual", "acoustic", "motor-related", "tactile", "olfactory", "gustatory" and "interoceptive". Ten outliers were identified by the single linkage clustering method. The remaining 286 abstract concepts were subsequently analyzed using Ward's method (see **Figure 4A** for the resulting dendrogram). The structure of the dendrogram, the "elbow test" (**Supplementary Figure S2**) as well as most of the criteria of the "NbClust" function (15 of 26; across $k = 2$ and $k = 5$ clusters) spoke in favor of a $k = 3$ cluster solution.

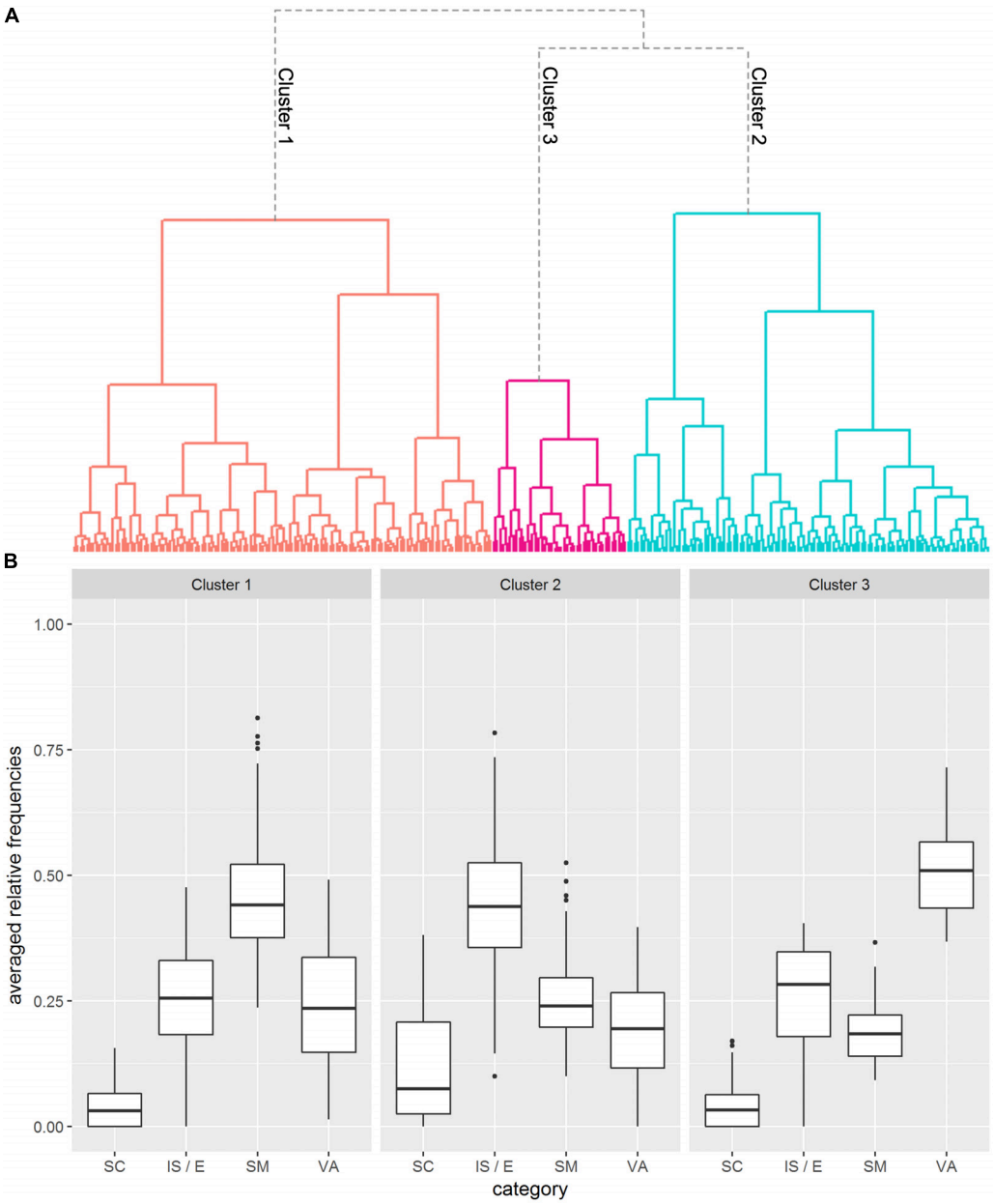


FIGURE 3 | Results of Cluster Analysis 1. **(A)** Dendrogram visualizing the $k = 3$ cluster solution. The different clusters are marked by different colors. **(B)** Boxplots depicting generated features per cluster (SM = sensorimotor feature; IS/E = internal state/emotion; SC = social constellation; VA = verbal association).

Inspection of **Figure 4B** reveals that the three clusters hardly differ with regard to acoustic, tactile, olfactory, gustatory and interoceptive features. These categories played a rather subordinate role in the clusters. Considering that these features were generated less frequently in general (see point "Analysis 2"), this is not very surprising. Categories distinguishing the clusters were the "visual" and "motor-related" categories.

Cluster A, which was the smallest cluster with $n = 49$ abstract concepts, was characterized by a large proportion of motor-related features ($M = 0.279$; $CI_{0.95} = [0.254;0.305]$), the largest proportion across the three clusters. Visual features were less frequently generated ($M = 0.146$; $CI_{0.95} = [0.128;0.163]$). Typical examples in this cluster are "fitness", "fight" and "performance".

For Cluster B, by far the biggest cluster ($n = 175$), visual ($M = 0.092$; $CI_{0.95} = [0.084;0.100]$) and motor-related ($M = 0.102$; $CI_{0.95} = [0.093;0.111]$) features were approximately equally generated, albeit at an intermediate level. Abstract concepts in this cluster are for example "experience", "challenge" and "humor".

Feature structure of Cluster C ($n = 62$) almost looked like a mirror-inverted version of Cluster A. It was characterized by the highest portion of generated features in the "visual"

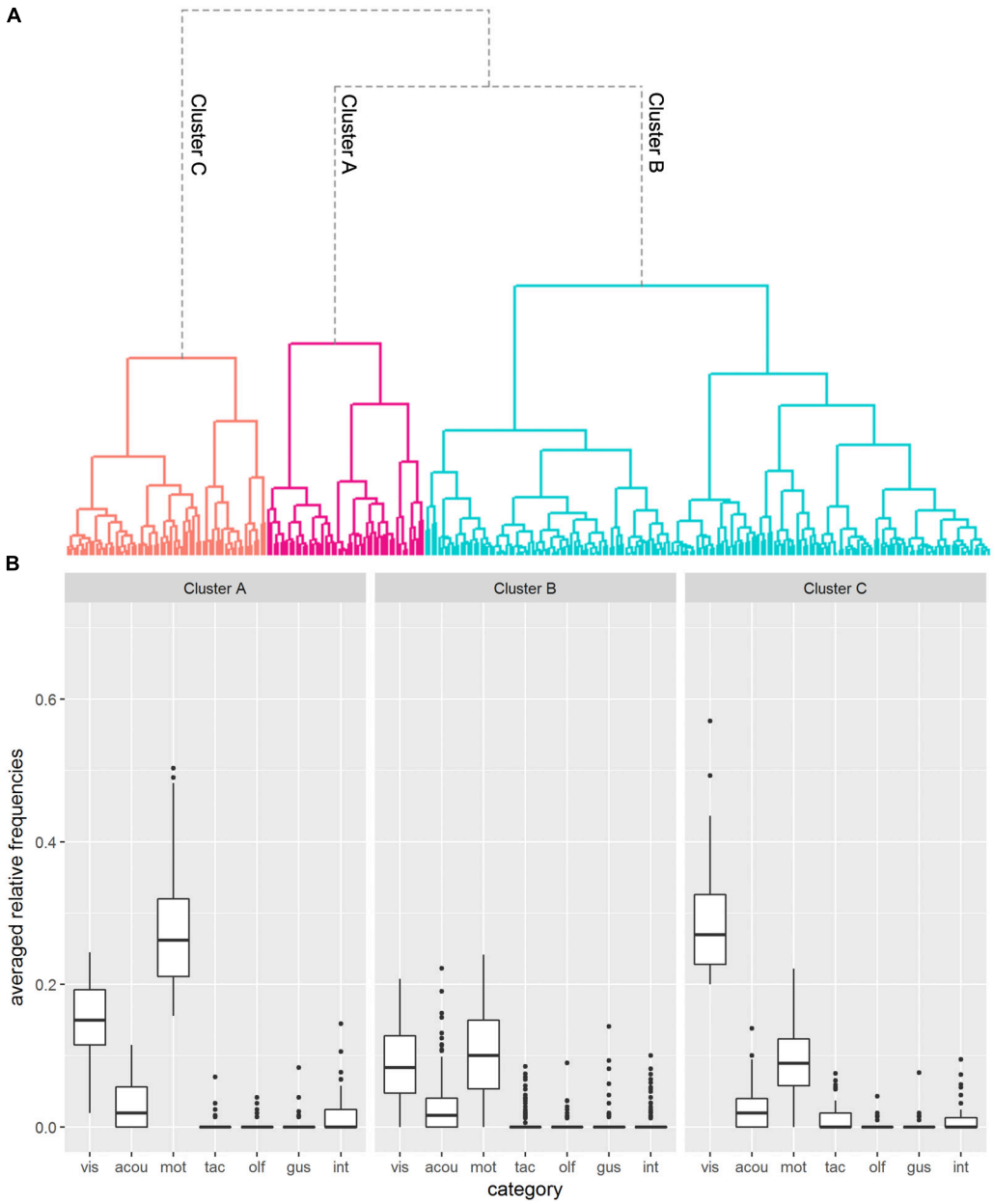


FIGURE 4 | Results of Cluster Analysis 2. **(A)** Dendrogram visualizing the $k = 3$ cluster solution. The different clusters are marked by different colors. **(B)** Boxplots depicting generated features per cluster (vis = visual; acou = acoustic; mot = motor-related; tac = tactile; olf = olfactory; gus = gustatory; int = interoceptive).

category compared to the other clusters ($M = 0.289$; $CI_{0.95} = [0.270;0.308]$). Features of the "motor-related" category ($M = 0.092$; $CI_{0.95} = [0.078;0.107]$), on the other hand, were generated at an intermediate level. "Observation", "vanity" and "beauty" are examples in this cluster.

DISCUSSION

The present study investigated the semantic content of 296 abstract concepts using a property generation task similar to Barsalou and Wiemer-Hastings (2005). The quintessence of our results is that abstract concepts are heterogeneous, as shown by our descriptive and cluster analyses. Our study therefore extends previous work on the semantic content of abstract concepts (Lynott and Connell, 2009, 2013; van Dantzig et al., 2011; Troche et al., 2014, 2017; Binder et al., 2016) by showing that different clusters of abstract concepts can be distinguished according to their specific semantic featural composition.

Participants generated a considerable amount of properties in all feature categories. The distribution of the observed properties fits well into the picture of previous work investigating the

representation of abstract concepts. Our results suggest that social (Carpenter et al., 1998; Bergelson and Swingley, 2013; Borghi et al., 2017) and emotional/introspective features (Wiemer-Hastings et al., 2001; Kousta et al., 2011; Vigliocco et al., 2014) as well as verbal associations (Simmons et al., 2008; Wang et al., 2010; Recchia and Jones, 2012) play a crucial role in the processing of abstract concepts as demonstrated in previous behavioral, developmental, brain imaging and patient studies (Kiefer and Pulvermüller, 2012; Meteyard et al., 2012; Borghi et al., 2017). Similarly, recent rating studies targeting the semantic content of concrete and abstract concepts also indicated the specific relevance of social, emotional and introspective features for constituting the semantic content of abstract concepts (Troche et al., 2014, 2017; Binder et al., 2016). In terms of quantity, sensorimotor features played the most important role in our study. This is quite remarkable, given that sensorimotor features are thought to be only associated with concrete concepts, but not with abstract concepts (Wang et al., 2010). More recent studies, however, indicate the significance of the sensory and motor system even in the representation of abstract concepts (Lynott and Connell, 2009, 2013; Moseley et al., 2012; Troche et al., 2014, 2017; Dreyer et al., 2015; Binder et al., 2016; Mason and Just, 2016; Vukovic et al., 2017). The importance of sensorimotor features becomes evident when thinking, for example, about the abstract concept "beauty", where, at least in the western society, visual properties seem to play a pivotal role in conceptual representation.

The cluster analyses furthermore demonstrated that the class of abstract concepts is characterized by a multidimensional feature space with differential dominant properties (Troche et al., 2014, 2017) as outlined in recent theories on conceptual cognition (Binder et al., 2016). Similar to concrete concepts, abstract concepts can be divided into different subcategories according to the dominance of certain conceptual features, although the number of subcategories appears to be more limited, probably because some features are less dominant in abstract concepts (e.g., olfactory or gustatory features). The subcategories found with help of Cluster Analysis 1 correspond to refined grounded cognition theories, which emphasize the role of social, emotional and introspective features as well as verbal associations: Cluster 2, which was characterized by high proportions of generated features in the "internal state/emotion" and "social constellation" categories, is compatible with assumptions made by Barsalou and Wiemer-Hastings (2005); Vigliocco et al. (2014), and Borghi and Binkofski (2014), all theories underlining the importance of emotional, introspective and/or social features in the representation of abstract concepts. Cluster 3, in which features of the "verbal association" category were dominant, can also be reconciled with theories such as WAT (Borghi and Binkofski, 2014) and LASS (Barsalou et al., 2008), which highlight the role of linguistic experiential information. Beyond that, Cluster 1 showed that sensory and motor-related features also play a crucial role in the representation of abstract concepts. Cluster Analysis 2 showed that, within the sensorimotor feature category, visual and motor-related features are closely related (Jeannerod, 1999), as it already has been reported in the case of concrete concepts (Tyler and Moss, 2001). Since we have not conducted a similar hierarchical cluster analysis with concrete concepts, the comparison of abstract and concrete concepts and possible resulting clusters must remain speculative. Based on previous results (Barsalou and Wiemer-Hastings, 2005; Wang et al., 2010; Troche et al., 2014, 2017; Trumpp and Kiefer, 2018), it is likely that the cluster characteristics of abstract and concrete concepts would have differed. Clusters within the concrete concept class might be characterized by an even higher portion of sensorimotor features, whereas social, emotional and introspective features as well as verbal associations might play a less important role (Trumpp and Kiefer, 2018). A final answer to this question might be given by future studies directly comparing cluster analyses of abstract and concrete concepts.

Results from the ratings validated the abstractness of the selected abstract words. The selected abstract concepts were indeed rated more abstractly than the concrete concepts, while they were, at the same time, not generally more unfamiliar. Similar to Wiemer-Hastings et al. (2001), we found a bimodal distribution of concreteness ratings forming two almost distinct patterns localized over the concrete and abstract center of the scale, respectively. However, we also observed a wide variance within these patterns, weakening the strict dichotomous view of classical approaches (e.g., Paivio, 1986). Especially the concreteness/abstractness ratings of abstract concepts showed a relatively large variance. This large variance within abstract concepts can partly be explained by their semantic content and their familiarity (see also Troche et al., 2014, 2017; Binder et al., 2016). Within abstract concepts, familiarity ratings were lower the less concrete these concepts were. This might be due to the fact that the most abstract concepts, like "boycott", play only a subordinate role in everyday life. As a consequence, less frequent use of these concepts could reduce the possibility for situational sensory and motor experiences resulting in ratings of higher abstractness. In accordance with earlier findings of Wiemer-Hastings et al. (2001), but based on a much larger sample of abstract concepts, we found that emotional/introspective features were related to higher abstractness ratings, while higher concreteness ratings were more likely to go hand in hand with a high portion of sensorimotor features and high familiarity ratings (see also Troche et al., 2014, 2017). This differential relation of sensorimotor and emotional/introspective features to concreteness/abstractness becomes particularly evident when considering the two abstract concepts "expectation" (emotional/introspective) and "fitness" (sensorimotor). While thinking about the word meaning of "expectation" is accompanied by a myriad of possible contexts and situational components, the less abstract entity "fitness" is much more stronger linked to specific context information rendering it relatively more concrete (see also Schwanenflugel and Shoben, 1983; Schwanenflugel et al., 1992; Schwanenflugel and Akin, 1994). When considering the different sensorimotor features separately, motor-related, gustatory and interoceptive features were significantly related to concreteness. The association between visual features and concreteness just failed to reach the conventional significance level ($p = 0.051$). Note, however, that several concerns have been raised regarding traditional approaches of gathering concreteness/abstractness

ratings. Connell and Lynott (2012), for example, point out that concreteness/abstractness ratings can be biased by unfavorable instructions, resulting in different decision criteria at the two poles "concrete" and "abstract" of the scale (e.g., excessive focus on vision while neglecting other modalities).

Although the present property listing study does not formally allow to test competing theories of the representation format of abstract concepts, our findings are difficult to reconcile with theories claiming that abstract concepts purely rely on a verbal-symbolic code, like Paivio's (1986) Dual Code Theory does. If the assumptions of the Dual Code Theory were true, we would have expected a much higher proportion of verbal associations in our study. Although Cluster 3 from Cluster Analysis 1 is compatible with Paivio's assumption, the remaining two clusters – which are characterized by dominant modal features – clearly oppose it. Additionally, the large variance of generated properties also speaks against Paivio's (1986) theory, although the frequency of verbal associations might be somewhat underestimated in our property generation task, whose instruction emphasized semantic properties of the concepts as well as associations. The broad diversity in participants' listings is rather consistent with refined grounded cognition theories by showing that the semantic content of abstract concepts – just like that of concrete concepts – includes introspective, affective, social, sensory and motor-related features. Our results are thus consistent with theories such as LASS (Barsalou et al., 2008), AEA (Kousta et al., 2009), WAT (Borghi and Cimatti, 2009), and Louwerse's (2011) Symbol Interdependency Hypothesis, which emphasize the importance of linguistic, social, introspective and affective experiential information for the representation of abstract concepts. Our results, of course, do not necessarily imply that the modal feature types found here are also represented in the corresponding modal brain areas as claimed by grounded cognition theories. However, our results constitute an important prerequisite for further tests of the validity of the grounded cognition framework.

Based on the present results we propose for future studies to abandon the traditional approach (Paivio, 1986) of considering abstract concepts as undifferentiated conceptual category and to contrast them with concrete concepts. Instead, we show that abstract concepts have a rich and heterogeneous semantic content with emphasis on different feature categories. We therefore suggest that a comparison of well-specified subcategories of abstract concepts – as revealed by the present cluster analyses – is more appropriate to investigate the processing of abstract concepts at a behavioral or neural level (Wilson-Mendenhall et al., 2012, 2013; Barca et al., 2017). For instance, a comparison of visual- and motor-related abstract concepts might clarify to what extent the motor and visual system is involved in the representation of those abstract concepts. Further imaging studies could shed light on the neural correlates of conceptual processing using the present results for their stimulus selection (see **Supplementary Dataset S1**), while studies with brain lesioned patients and with TMS would allow conclusions, which dominant features are functionally relevant for specific subcategories of abstract concepts.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the Ethical Committee of Ulm University with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Ethical Committee of Ulm University.

AUTHOR CONTRIBUTIONS

MH, NT, and MK planned the study design. NT and MK supervised the study. MH performed the data acquisition, analyzed the data, and wrote the first draft of the paper. MH, MK, and NT revised the manuscript. All the authors approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2018.01748/full#supplementary-material

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2.2. Study II - The grounding of abstract concepts in the motor and visual system: An fMRI study

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Research Report

The grounding of abstract concepts in the motor and visual system: An fMRI study

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ABSTRACT

The grounding of concepts in the sensorimotor brain systems is controversially discussed. Grounded cognition models propose that concepts are represented in modality-specific sensorimotor, but also emotional and introspective brain areas depending on specific experiences during concept acquisition. Accumulating evidence suggests that concrete concepts are closely linked to modality-specific systems, whereas the mere existence of abstract concepts seems to contradict grounded cognition approaches. Here, using functional magnetic resonance imaging, we adopted a theory-driven approach frequently used for investigating concrete concepts to the domain of abstract concepts: We compared brain activation to abstract concepts with a known motor versus visual feature content as determined by a previous property listing study. Carefully matched motor (e.g., fitness) and visual (e.g., beauty) abstract words were presented to 24 participants along with pseudowords while performing a lexical decision task. Furthermore, participants performed two localizer tasks by actually moving their hands (motor localizer) and by looking at real pictures (visual localizer). Processing of motor abstract words specifically activated frontal and parietal motor areas, whereas processing of visual abstract words specifically elicited higher activity in temporo-occipital visual areas, albeit at a more lenient statistical threshold. According to inclusive masking analyses, this differential activity pattern to motor and visual abstract concepts overlapped with brain activations observed during hand movements (pre- and postcentral gyrus) and object perception (fusiform and lingual gyrus). Thus, consistent with the grounded cognition framework, our results suggest that, similar to concrete concepts, abstract concepts related to action and vision are grounded in modality-specific brain systems typically engaged in actual perception and action depending on their conceptual feature content.

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1. Introduction

"Beauty is in the eye of the beholder" is a common English proverb expressing the opinion that beauty is subjective. The noun "beauty" does not refer to a physical referent and can therefore considered as being abstract. Nevertheless, the proverb implies that the abstract concept "beauty" might be related to visual sensory experiences, that is, to the perception of properties of a visual scene. The content of this saying thus illustrates the basic assumptions of the grounded cognition approach to conceptual cognition. Consistent with the literal sense of this proverb, grounded (or embodied) cognition approaches (for reviews see Barsalou, 2008, 2010; Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Pulvermüller, 2005, 2013) claim that the concept "beauty" (i) crucially depends on visual brain circuits (Gallese & Lakoff, 2005; Kiefer & Pulvermüller, 2012) and (ii) is highly dependent on individual sensory and possible motor experiences (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008; Hoenig et al., 2011; Kiefer, Sim, Liebich, Hauk, & Tanaka, 2007; Lyons et al., 2010; Trumpp & Kiefer, 2018; Willems, Hagoort, & Casasanto, 2010).

For a long time, traditional amodal approaches (Anderson, 1978; Collins & Loftus, 1975; Fodor, 2001; Mahon & Caramazza, 2009; Pylyshyn, 1980) dominated the scientific debate in cognitive science of how concepts are organized at a functional and neural level. There is an agreement that concepts form the basic units of cognition and constitute the meaning of words (Humphreys, Riddoch, & Quinlan, 1988; Kiefer & Pulvermüller, 2012; Tulving, 1972). Amodal approaches propose that all forms of conceptual knowledge are represented in amodal semantic hubs (Rogers et al., 2004). In these hubs, concepts are represented detached from the original perceptual impressions or motor interactions by transforming the initial modality-specific experiential information into a common amodal code (Caramazza & Mahon, 2003). In the view of these amodal theories, concrete and abstract concepts like "hammer", "beauty" or "fight" are represented in the same abstract code separately from the sensory and motor systems. An engagement of the sensorimotor systems in conceptual processing is not denied per se by all amodal approaches. However, instead of assuming a causal role of modal brain circuits in conceptual processing, these approaches explain the involvement of sensorimotor brain areas in terms of spreading activation from the amodal conceptual level to the modality-specific input/output levels. Sensory and motor brain areas are therefore not considered to be causally involved in retrieving conceptual information (Mahon, 2015a; 2015b), their engagement is rather seen as an epiphenomenon. Considering "beauty" from the beginning of this article, amodal theories would assume that experiences related to vision made during concept acquisition are lost or at least extenuated due to the transformation into an abstract code (Anderson, 1978; Caramazza & Mahon, 2003; McClelland & Rogers, 2003). There is some disagreement with regard to number, function and anatomical location of amodal conceptual hubs (Meteyard, et al., 2012). Posterior middle temporal (Gold et al., 2006; Hoffman, Pobric, Drakesmith, & Ralph, 2012; Price, 2000), inferior-parietal (Binder & Desai, 2011), anterior inferior-temporal (Patterson, Nestor, & Rogers, 2007; Visser, Jefferies, & Ralph, 2010) and prefrontal cortex (Devlin, Matthews, & Rushworth, 2003) have been suggested to serve as amodal hub regions.

Grounded cognition approaches assume that concepts are represented through cell assemblies distributed over several distinct brain areas (Barsalou, 2008; Borghi et al., 2017; Ghio, Vaghi, Perani, & Tettamanti, 2016; Kiefer & Barsalou, 2013; Pulvermüller & Fadiga, 2010), including regions responsible for sensory, motor, introspective and emotional processes. In accordance with Hebbian theory (1949), these functional neural networks are seen as a result from simultaneous activations of cell assemblies in these brain areas during concept acquisition (Pulvermüller & Fadiga, 2010). In line with the proverb "beauty is **in the eye** of the beholder", grounded cognition approaches would presume a relative dominance of visual perception and corresponding neural brain networks during processing of the concept "beauty". Furthermore, grounded cognition approaches would support the idea that beauty is subjective ("beauty is **in the eye of the beholder"**) in the sense that conceptual knowledge is highly dependent on individual experience.

Recently, hybrid frameworks were developed which combine assumptions of amodal and grounded cognition theories. These hybrid models propose that conceptual knowledge is the result of an interaction between modality-specific, multimodal and amodal conceptual hub areas, the latter serving general semantic binding and integration (Kiefer & Pulvermüller, 2012; Patterson, et al., 2007). For instance, hub-and-spokes models assume that unifying non-physical semantic information is stored in a hub region, but still connected with concrete-experiential regions (Patterson & Ralph, 2016; Ralph, Jefferies, Patterson, & Rogers, 2017). Furthermore, based on neural network modeling and neuroimaging findings, it has been suggested that conceptual processing involves a hierarchy of interconnected neural circuits involving modality-specific and adjacent multimodal areas as well as amodal heteromodal hub regions (Fernandino et al., 2016; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016; Garagnani & Pulvermuller, 2016; Popp, Trumpp, & Kiefer, 2019; Simmons & Barsalou, 2003).

Evidence favoring the grounded cognition approach including hybrid theories mainly comes from studies investigating the representational format of concrete concepts, like "hammer" or "to throw" (Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Meteyard, et al., 2012). In addition to evidence from behavioral (e.g., Garcia & Ibanez, 2016), electrophysiological (e.g., Trumpp, Traub, Pulvermüller, & Kiefer, 2014), neuropsychological (e.g., Trumpp, Kliese, Hoenig, Haarmeier, & Kiefer, 2013; see also the discussion section) and transcranial magnetic stimulation (TMS) studies (e.g., Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005), results supporting the grounded cognition approach are especially derived from neuroimaging studies. Several functional magnetic resonance imaging (fMRI) studies investigating the processing of motor- (Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008), visual- (Simmons et al., 2007), sound- (Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008), gustatory- (Barros-Loscertales et al., 2012) and olfactory-related (Gonzalez et al., 2006) concepts found an increased MR-signal in

corresponding modality-specific brain regions. EEG studies, which track the time course of conceptual processing with a high temporal resolution showed differential ERPs in response to subgroups of concepts starting at about 150 msec after target onset (Hauk & Pulvermüller, 2004; Hoenig, et al., 2008; Kiefer, Sim, Helbig, & Graf, 2011; Pulvermüller, Härle, & Hummel, 2000). The early onset of differential effects contradicts the assumption of a spreading of activation or semantic elaboration after amodal concepts had been accessed (where we would expect a later occurrence of differential effects). These early ERP effects speak in favor of early lexico-semantic processes in conceptual processing (see also Pulvermüller, 2005). Furthermore, another ERP study indicated an earlier onset of sensory-motor activity compared with activity in the anterior lobe (Kiefer, et al., 2011), a putative hub region. Of course, neuroimaging and electrophysiological studies only provide correlational information, but do not demonstrate that sensory-motor processing functionally contributes to performance in a conceptual task.

While the grounding of concrete concepts in the sensory and motor system has been well investigated, the mere presence of abstract concepts seems to favor an amodal approach to conceptual cognition (Mahon & Caramazza, 2008). As indicated already above, abstractness goes hand in hand with a lack of unique physical features of the referent, such as form, color or texture (Crystal, 2004). Therefore, abstract concepts, like "beauty", lack a clearly identifiable referent, which can be experienced by our senses by definition (Paivio, 1986). This seems to contradict the assumption of grounded cognition approaches that the content of concepts is rooted in modal brain systems. In fact, Dual Coding Theory (Paivio, 1986) assumes that the content of abstract concepts exclusively involves the verbal semantic system, whereas concrete concepts can additionally be represented within a visual imaginary system.

While Dual Coding Theory (Paivio, 1986) does not consider an involvement of modal systems in the representation of abstract concepts, in particular refined grounded or embodied cognition approaches aimed at specifying the relation of abstract concepts to the modal brain systems. The Conceptual Metaphor Theory (Lakoff & Johnson, 1980), for example, assumes that sensorimotor information constitutes the meaning of abstract concepts through metaphoric relations to concrete concepts. Barsalou and Wiemer-Hastings (2005) further emphasize the importance of direct sensorimotor experience for constituting the meaning of abstract concepts. They assume that the conceptual system encodes memories of situational perceptions, which are simulated when accessing conceptual knowledge. Abstract concepts are thus thought to be grounded in situations and can be simulated in modality-specific brain systems. Thinking about "beauty", for example, might simulate visual experiential information one gathered in the Louvre, admiring the Mona Lisa, her enigmatic facial expression and the subtle modeling of forms. Since the semantic content of abstract concepts is highly heterogeneous (Barca, Mazzuca, & Borghi, 2017; Harpaintner, Trumpp, & Kiefer, 2018; Wiemer-Hastings, Krug, & Xu, 2001; Wiemer-Hastings & Xu, 2005), the importance of other types of conceptual knowledge besides sensorimotor information is also highlighted by grounded cognition approaches. According to these approaches, experiential representations may also draw on linguistic/verbal [Language And Situated Simulation Theory (LASS), Barsalou, Santos, Simmons, & Wilson-Mendenhall, 2008; Words As Social Tools Approach (WAT), Borghi & Binkofski, 2014; Louwerse's Symbol Interdependency Hypothesis, Louwerse, 2011], affective [Affective Embodiment Account (AEA), Kousta, Vigliocco, Vinson, & Andrews, 2009], introspective (Kiefer & Barsalou, 2013) and social information (Barsalou & Wiemer-Hastings, 2005; WAT; Borghi & Binkofski, 2014).

Previous evidence regarding the relation of abstract concepts to the verbal or the modal systems is mixed and supports both amodal and grounded cognition theories. In support of amodal theories including Dual Coding Theory, abstract concepts elicited enhanced brain activity in left anterior and middle temporal language regions compared with concrete concepts (Desai, Binder, Conant, Mano, & Seidenberg, 2011; Sakreida et al., 2013). A meta-analysis (Wang, Conder, Blitzer, & Shinkareva, 2010), which combined brain data of several fMRI and positron emission tomography (PET) studies on the processing of concrete versus abstract concepts, yielded a greater engagement of the perceptual system for concrete concepts, more specifically in left precuneus, posterior cingulate, fusiform and parahippocampal gyrus, whereas abstract concepts were found to recruit left temporal language regions, particularly the middle and superior temporal gyri, and the left inferior frontal gyrus more strongly than concrete concepts. This line of evidence indicates that abstract concepts depend primarily on the amodal symbolic verbal system.

Recent work on the subjective semantic content of abstract concepts, however, has suggested that the meaning of abstract concepts is grounded in perception and action information, in addition to verbal and introspective or emotional content. Rating (Binder et al., 2016; Lynott & Connell, 2009, 2013; Troche, Crutch, & Reilly, 2014; Troche, Crutch, & Reilly, 2017; van Dantzig, Cowell, Zeelenberg, & Pecher, 2011) and property generation studies (Barsalou & Wiemer-Hastings, 2005; Harpaintner, et al., 2018) showed that information related to sensorimotor experiences is associated with all types of concepts, regardless of whether they are abstract or concrete. Barsalou and Wiemer-Hastings (2005), for instance, asked their participants to generate properties and associations for several concepts differing with regard to their level of concreteness/abstractness. Besides social, mental and introspective content, content about physical settings has also been found to play a role in abstract concepts, albeit to a somewhat smaller extent compared to concrete concepts. Participants of a recent property listing study examining a large set of abstract concepts (Harpaintner, et al., 2018) furthermore generated a substantial proportion of introspective, emotional and social properties, in addition to verbal associations. In terms of quantity, however, sensory and motor properties played the most crucial role in this study. Hierarchical cluster analyses in this study further demonstrated that several subgroups of abstract concepts exist, with one of those clusters being characterized by a high proportion of generated sensory and motor properties. This indicates that contrasting abstract concepts as an undifferentiated conceptual category, defined solely by the lack of a clearly identifiable referent, with concrete concepts remains questionable when

considering the heterogeneity of the abstract concept class. Instead, subgroups of abstract concepts with a strong relevance of sensorimotor information can be found. Within the sensorimotor feature category, motor and visual properties played the most important role. Although property listing (Barsalou & Wiemer-Hastings, 2005; Harpaintner, et al., 2018) and rating studies (Binder, et al., 2016; Lynott & Connell, 2009, 2013; Troche, et al., 2014; Troche, et al., 2017; van Dantzig, et al., 2011) highlight the importance of sensory and motor information for the semantic content of abstract words, this type of studies of course does not address the question, whether sensory and motor information associated with abstract concepts is represented in corresponding modal cortex, a crucial assumption of grounded cognition theories.

The involvement of modal cortex in the processing of abstract concepts has not been systematically investigated so far, but has been suggested by a few neuroimaging studies: Pexman, Hargreaves, Edwards, Henry, and Goodyear (2007) observed activation within the sensorimotor system for both abstract (e.g., "reason") and concrete (e.g., "earth") concepts. Processing the abstract concept "observe" enhanced activity in visual and auditory cortex (Wilson-Mendenhall, Barrett, Simmons, & Barsalou, 2012), while abstract emotion words (e.g., "fear") activated the primary motor cortex (Dreyer & Pulvermuller, 2018; Moseley, Carota, Hauk, Mohr, & Pulvermüller, 2012), a region which is crucial for the communication of internal emotional states by gesture and facial expressions. Based on findings of another study in brain-lesioned patients, Dreyer (2015) suggested a causal role of the motor cortex in the processing of abstract emotion words. Even abstract physical concepts elicited activations in wide-spread modal brain regions (Mason & Just, 2016). For instance, physical concepts related to periodicity (e.g., "frequency") activated postcentral and parietal brain regions. The same regions were found to be active when performing corresponding real-world rhythmic movements (Chen, Zatorre, & Penhune, 2006). Enhanced activity in the motor cortex was furthermore observed in the case of numerical concepts (e.g., "nine", Tschentscher, Hauk, Fischer, & Pulvermüller, 2012) as well as abstract concepts related to mental processes (e.g., "thought", Dreyer & Pulvermuller, 2018). Finally, in line with the proposed distinguished role of emotions (Vigliocco et al., 2014), mental states (Wilson-Mendenhall, Simmons, Martin, & Barsalou, 2013) and social interactions (Wilson-Mendenhall, et al., 2013) for the meaning of abstract concepts, activity in the corresponding neural circuits has been observed.

While the contribution of linguistic information, emotions, mental states and social interactions to the meaning of abstract concepts has been well recognized (see Borghi, et al., 2017), the importance of sensorimotor features for such concepts without a concrete physical referent lacks systematical investigation and has been implied only by a few studies as indicated above. Despite the importance of this research question, interpretation of findings from previous studies is limited for two reasons: Sometimes only single abstract concepts served as stimuli (Wilson-Mendenhall, et al., 2012). Furthermore, sensorimotor feature composition was not determined a priori, but only inferred post-hoc from the activation pattern (Dreyer, et al., 2015; Mason & Just, 2016; Moseley, et al., 2012).

In the present fMRI study, we systematically examined the relation of abstract concepts to the sensory and motor brain systems in a larger set of abstract nouns ($N = 64$). We adopted a theory-driven approach frequently used for investigating concrete concepts (e.g., Kiefer, et al., 2008; Kiefer et al., 2012; Popp, Trumpp, & Kiefer, 2016) to the domain of abstract concepts and compared brain activation to well-defined subtypes of abstract concepts with a known feature content. Words have been a priori selected on the basis of sensory and motor features obtained in a previous property listing study (Harpaintner, et al., 2018). The present study focused on motor and visual features because these feature types were generated most frequently. Using this word list, we selected 32 abstract words strongly linked to motor properties (e.g., "fight") and other 32 abstract words strongly linked to visual conceptual properties (e.g., "beauty"). These two stimuli lists are henceforth called motor abstract concepts and visual abstract concepts, respectively.

Using fMRI, we investigated the neural substrate of processing abstract words with differential motor and visual feature relevance with a high spatial resolution. We presented motor and visual abstract words among pseudowords within a lexical decision task enabling an implicit access to conceptual word meaning (Dilkina, McClelland, & Plaut, 2010; Kiefer, 2002). The lexical decision task does not require explicit retrieval of specific conceptual information such as motor or visual features (Simmons, Hamann, Harenski, Hu, & Barsalou, 2008). Participants were thus discouraged from using semantic elaboration and imagery to solve the task (Kiefer, et al., 2012). Participants performed a go/no-go task, which did not require a motor response to the critical word stimuli. This avoids interference of the overt motor response with conceptual processing, in particular within the motor system (Schomers & Pulvermüller, 2016). To test whether conceptual processing of motor and visual abstract concepts activates corresponding sensorimotor brain regions similar to action and perception, we implemented a motor and a visual localizer task. In these tasks, participants performed real hand movements (motor localizer) or observed object pictures passively (visual localizer). We related activations to motor and visual abstract concepts during the lexical decision task to activation patterns during the localizer tasks using inclusive masking analyses. We hypothesized that (i) processing motor abstract concepts enhances activity in motor and premotor brain areas similar to action execution, while (ii) processing visual abstract concepts activates occipital brain regions similar to the observation of object pictures. In line with grounded cognition theories, such a result pattern would indicate that a grounding in the sensory and motor systems is also relevant for the meaning of abstract concepts and not only for concrete object concepts with a clear physical referent.

2. Materials and methods

2.1. *Participants*

Twenty-five healthy, right-handed and native German-speaking undergraduate students from Ulm University

participated in the study (sample size was determined according to similar earlier studies; e.g., Moseley, et al., 2012; Vigliocco, et al., 2014). One participant was excluded from the analysis due to excessive motion during the fMRI scanning session (motion parameters: translation: > ± 3 mm, rotation: > ± 3 mm). Final analysis included imaging data of 24 (M_{age} = 23.7 years, range = 18–34 years, 12 females) participants. Participants had normal or corrected-to-normal vision and were free from a history of neurological or psychiatric disorders. No contraindications regarding the fMRI procedure were reported. Inclusion/exclusion criteria were established prior to data analysis. Participants gave written informed consent and were paid 20 Euros or course credits for participation. Procedures were approved by the Ethical Committee of Ulm University.

2.2. General procedures

Visual stimuli of the lexical decision task and the localizer tasks were delivered via MR-compatible video goggles (VisuaStim Digital, Resonance Technology Inc., Northridge, CA, USA). Text (stimuli, instructions) was presented as white letters on black background in the middle of the screen (font size: 14 points character height). Stimulus presentation and behavioral data acquisition was controlled by the Experimental Runtime System software package (Berisoft, Frankfurt, Germany). All participants first performed a lexical decision task followed by visual and motor localizer tasks (fixed order). After completing all tasks, structural T1-weighted images were recorded. Participants were carefully instructed outside the scanner as well as directly before each task inside the scanner. Participants furthermore had the opportunity to practice the lexical decision task outside the scanner. Preceding the motor localizer task, participants were provided with an elastic hand training ball for each hand.

No part of the study procedures or analyses was preregistered prior to the research being undertaken.

2.3. Lexical decision task: stimuli and procedures

Sixty-four abstract words (critical words) and 32 pseudowords served as stimuli in the lexical decision task with a go/no-go response mode (see Supplementary Material for the full set of the verbal stimuli). Pseudowords (go trials) served as distractors and were not further analyzed. Critical abstract words were thus presented without interference from a motor response (no-go trials). Half of the critical abstract word stimuli (32 words) had a strong link to motor properties, whereas the other half had a strong link to visual conceptual properties. This critical stimulus set was selected on the basis of a previous study (Harpaintner, et al., 2018), in which participants generated properties for 296 abstract concepts. None of these participants contributed data to the present study. The generated properties were subsequently categorized according to modality-specific and verbal contents (for further details see Harpaintner, et al., 2018). In order to be assigned to the respective subcategory for the present study, at least 15% of properties coded as motor or visual had to be generated with regard to the respective abstract concept. This threshold was chosen because a proportion of 15% modality-specific properties exceeded the mean proportions of motor and visual properties generated for all 296 abstract concepts in our previous study (M_{motor} = 13.1%, M_{visual} = 14.8%). To achieve a substantial difference in the conceptual feature dominance of the two subcategories, the difference of generated motor and visual properties of each word had to be at least 10%.

Finally, the chosen motor (M_{motor} = 31.60%, M_{visual} = 8.97%; e.g., "fight") and visual (M_{visual} = 30.18%, M_{motor} = 6.49%; e.g., "beauty") abstract concepts were carefully matched for confounding conceptual features (proportion of generated acoustic features, valence, arousal, concreteness/abstractness, familiarity) and psycholinguistic variables (word length, lemma frequency, bigram and trigram frequency; Table 1). Fifteen participants not participating in the main study were asked to rate the abstract concepts with regard to concreteness/abstractness [six-point Likert scale with the poles "abstract" (1) and "concrete" (6) with higher scores indicating higher concreteness] and familiarity [six-point Likert scale with the poles "low familiarity" (1) and "high familiarity" (6) with higher scores indicating higher familiarity; for details see Harpaintner, et al., 2018]. Similarly, the same sample rated the emotional valence of the respective abstract concept on a six-point Likert scale (ranging from −3 till +3 with the two poles "negative" and "positive") and the associated level of arousal using self-assessment manikins (SAM; Bradley & Lang, 1994). Psycholinguistic variables were obtained using the dlex database (Heister et al., 2011). Motor and visual abstract concepts differed with regard to the proportion of generated motor [$t(62) = 5.38$; $p < .0001$] and visual [$t(62) = -4.77$; $p < .0001$] properties, but were comparable with respect to confounding conceptual and psycholinguistic variables (all $ps > .05$). Abstractness ratings confirmed that the selected critical words referred to abstract concepts ($M_{abstract}$ = 2.57 *vs* $M_{concrete}$ = 5.72).

Thirty-two pseudowords were obtained by replacing one consonant and one vowel of abstract concepts not used in the experimental conditions by another consonant and vowel resulting in meaningless but pronounceable letter strings (e.g., "Antordirung"). Pseudowords and words of the experimental conditions were matched with regard to word length [M_{motor} = 8.19, M_{visual} = 7.88, M_{pseudo} = 7.94, $F(2,93) = .168$, $p = .85$].

Each trial started with a fixation cross of 500 msec duration followed by the target lasting for 400 msec. Target words and pseudowords were presented in a pseudorandomized sequence within an event-related design. Participants had to respond within a time window of 1900 msec. After an inter-trial interval (ITI) with a mean duration of 3200 msec (range = 9–16824 msec) the next trial started. In order to achieve an optimal sampling of the hemodynamic response function (Dale, 1999), a pseudorandomized sequence of stimulus categories (motor and visual abstract concepts, pseudowords) with the associated ITI was created using optseq2 (https://surfer.nmr.mgh.harvard.edu/optseq/). Within the fixed sequence of experimental conditions, the assignment of words/pseudowords to the slots in the sequence was randomized for each participant.

Participants had to decide whether the presented stimulus is a real German word or a pseudoword. If the stimulus was a pseudoword, participants should press a button on the

Table 1 – Mean values and standard deviation (in parentheses) of conceptual and psycholinguistic variables for motor and visual abstract concepts.

	Motor abstract concepts	Visual abstract concepts	Motor *vs* visual (*p*-values)
Proportion motor properties	.32 (.12)	.06 (.04)	$p < .001$
Proportion visual properties	.09 (.06)	.30 (.09)	$p < .001$
Proportion acoustic properties	.03 (.04)	.04 (.05)	$p = .536$
Concreteness/abstractness	2.65 (.61)	2.49 (.53)	$p = .276$
Familiarity	4.18 (.67)	4.07 (.57)	$p = .454$
Valence	.51 (1.83)	.26 (1.87)	$p = .582$
Arousal	2.74 (.78)	2.62 (.95)	$p = .561$
Word length	8.19 (2.58)	7.88 (2.06)	$p = .595$
Lemma frequency p. Mio.	63.14 (91.72)	38.21 (45.17)	$p = .173$
Character bigram frequency p. Mio.	652936.87 (379468.24)	631388.19 (278144.87)	$p = .796$
Character trigram frequency p. Mio	229175.80 (124964.62)	218018.45 (103100.90)	$p = .698$

Depicted *p*-values were obtained using two-tailed *t*-tests.

response keyboard with the index finger of their right hand (go trial). In case of a real German word, participants were instructed to passively read the word, but not to react (no-go trial). The assignment of abstract words to the no-go condition was chosen deliberately in order to avoid overt motor activity to the critical word stimuli. Participants were instructed to decide as fast and accurately as possible.

In order to rule out that differential brain activations to motor versus visual abstract concepts were due to differences in task difficulty, we carried out an additional behavioral study using a classical lexical decision task with 12 participants not participating in the original fMRI study. Stimuli and their timing were the same as in the fMRI study, but participants were instructed to press a key, both in the case of a real German word and in the case of a pseudoword with their right index or middle finger, respectively. The assignment of the conditions to reactions with the right index or middle finger was counterbalanced. Thus, reaction time and error rate data were available for pseudowords as well as for motor and visual abstract concepts. Univariate repeated measures analyses of variance (ANOVA) were carried out in order to investigate whether task difficulty, as measured by mean reaction times and error rates, differed significantly between conditions (single factor). The ANOVA yielded significant differences in mean RTs between motor and visual abstract concepts and pseudowords [$F(2,22) = 38.94$, $p < .001$]. According to a *post hoc* test (Bonferroni test) this difference was due to slower reaction times in response to pseudowords ($M = 649.53$ msec) as compared to motor ($M = 578.60$ msec, $p < .001$) and visual ($M = 566.91$ msec, $p < .001$) abstract concepts. Importantly, reaction times to motor versus visual abstract concepts did not differ significantly ($p = .78$). A further ANOVA revealed a similar pattern with regard to mean error rates. Significant differences between the conditions were found [$F(2,22) = 7.98$, $p < .005$], but again, a *post hoc* test (Bonferroni test) revealed that differences were due to higher error rates in response to pseudowords ($M = 2.00\%$) as compared to motor ($M = .50\%$, $p < .01$) and visual ($M = .42\%$, $p < .01$) abstract concepts. Mean error rates in response to motor versus visual abstract concepts did not differ significantly ($p = 1.00$). Based on these results, it can be concluded that task difficulty was comparable for motor and visual abstract concepts.

2.4. *Visual localizer task*

The visual localizer task consisted of 13 blocks in total, each lasting 24 sec. Seven fixation blocks and six experimental blocks alternated. The localizer task started and ended with a fixation block, in which the participants were presented with a white fixation cross on a black background. The fixation cross was continuously shown for 24 sec. In the six experimental blocks, a total of 120 pictures of every-day objects (220 × 220 pixels), derived from a previous study (Trumpp & Kiefer, 2018), were presented. One half of the picture set depicted living objects (e.g., a bird). The other half showed non-living objects (e.g., a screwdriver). Each picture was presented once. Each trial of one experimental block started with a picture, which was presented for 500 msec on a black background. The subsequent white fixation cross was also shown on a black background and lasted 500–900 msec ($M = 700$ msec). Per block, 20 images and 20 fixation crosses alternated. The sequence of images was identical for each participant. The assignment of ten images each showing living and non-living objects was pseudo-randomized per block. Participants were instructed to watch the fixation cross or to carefully look at the presented images, respectively.

2.5. *Motor localizer task*

The motor localizer task (see Popp et al., 2019) consisted of 17 blocks, each lasting 24 sec. Nine fixation blocks and eight experimental blocks alternated. Both the beginning and the end of the motor localizer task consisted of a fixation block, in which the participants were presented with ten white fixation crosses on a black background for 300 msec, separated by a clear screen lasting between 1255 and 2752 msec ($M = 2100$ msec). Participants were instructed to look at the fixation crosses. The experimental blocks were identical to the fixation blocks, except that double arrows were presented instead of the fixation crosses. Four blocks, in which the arrows pointed to the left (<<) and 4 blocks, in which the arrows pointed to the right (>>), alternated. During the experimental block, participants were asked to press a hand training ball in each hand ten times with their right or left hand firmly and evenly in the rhythm of the flashing arrows. Arrows pointing

to the right indicated the right hand to move, and vice versa. To avoid motion artifacts, participants were asked to limit the movement to their hands.

2.6. Data acquisition and analysis

Because of the go/no-go design of the lexical decision task, in which participants reacted only to the theoretically irrelevant pseudowords, analysis of reaction times were not informative. However, mean error rates (ERs) were calculated for each participant and each feature category (motor and visual). Subsequent univariate repeated measures analyses of variance (ANOVA) were carried out in order to investigate, whether error rates differed significantly between the conditions.

MR images were recorded with a 3-T scanner (Siemens MAGNETOM Prisma, Siemens Healthcare GmbH, Erlangen, Germany) in combination with a head neck 64 A3Tim coil. Structural T1-weighted images were obtained using a magnetization prepared rapid acquisition gradient echo sequence (TR = 2000 msec, TE = 2.32 msec, inversion time = 1000 msec, flip angle = 8°, matrix = 256 × 256, FOV = 240 × 240 mm, voxel size = .9 × .9 × .9 mm^3). Functional T2*-weighted images were recorded by a single shot gradient-echo EPI sequence (TR = 2000 msec, TE = 34 msec, flip angle = 90°, matrix = 76 × 76, FOV = 192 × 192 mm, voxel size = 2.5 × 2.5 × 3.5 mm^3). Thirty-three transversal brain slices were recorded in ascending order. Slice orientation was parallel to a line connecting the base of the frontal lobe and the cerebellum (see Ulrich, Hoenig, Gron, & Kiefer, 2013). A total of 280 EPI volumes were acquired within approximately 10 min during the lexical decision task. For the visual/motor localizer task, which lasted approximately six/seven minutes, 170/215 EPI volumes were recorded.

Acquired neuroimaging data was pre-processed and analyzed using SPM12 (r7219; Wellcome Trust Centre for Neuroimaging, London, United Kingdom) running on Matlab R2017b (version 9.3.0.713579, The Mathworks Inc., Natick, USA). During preprocessing, functional images were motion-corrected by rigid-body transformation of all images per series and by realigning to the first image on the basis of three translation and three rotation parameters. Temporal realignment was achieved by slice time correction based on the 16th slice. Co-registration was performed using individual T1-weighted images. After normalization of anatomical structures to the Montreal Neurological Institute (MNI) template (resampled voxel size: 2 × 2 × 2 mm^3), normalized images were smoothed with an isotropic 8 mm FWHM Gaussian kernel.

Statistical analyses of all experiments (lexical decision task, localizer tasks) were performed hierarchically using the General Linear Model (GLM) approach. Preprocessed data of the lexical decision task were subject-wise modeled by separate regressors representing the onsets of motor abstract concepts, visual abstract concepts, pseudowords, and errors from all conditions, respectively. Resulting delta functions were convolved with the canonical hemodynamic response function. Additionally, head movement parameters based on the realignment output were included as regressors of no interest, resulting in a design matrix with altogether ten regressors (four experimental regressors, six motion parameters). Low-frequency scanner drifts were removed by high-pass filtering (cut-off: 128 sec). A first-order autoregressive model was used to account for intrinsic temporal autocorrelation of the image series. After model estimation, one-sided *t*-contrast images were computed to represent the magnitude of estimated neural activation for visual abstract concepts, and for motor abstract concepts, against implicit baseline. These images, obtained from each participant, were subjected to a random-effects analysis implemented as flexible factorial design with subjects as random factor. The contrasts of interest were motor > visual and visual > motor. A voxel-height threshold of $p < .001$ and a family-wise error (FWE)-corrected cluster threshold of $p < .05$ were applied (Eklund, Nichols, & Knutsson, 2016). Because the contrast visual > motor did not yield significant activation patterns at a voxel threshold of $p < .001$, we applied a more liberal voxel threshold of $p < .005$ (uncorrected for multiple comparisons, minimum cluster size = 10 voxel) in an exploratory analysis. To identify regions underlying general abstract concept processing, we conducted a conjunction analysis. Results of two different contrasts (motor abstract concepts > implicit baseline, and visual abstract concepts > implicit baseline; see Lanius et al., 2002), which are hypothesized to reflect the same process, were combined, while excluding areas for which activations differ significantly between both conditions (Price & Friston, 1997). For this analysis, a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons was used (minimum cluster size = 10 voxels).

Analyses of the two localizer tasks were performed as follows: First-level analyses included blocks of picture/action/fixation periods as regressors convolved with the canonical hemodynamic response function. The six motion parameters based on the realignment output were included as regressors of no interest. At the second level, parameter estimates for each localizer task and each participant and the two critical conditions (fixation *vs* observation/movement) were entered into a flexible factorial design with subjects as random factor. The contrasts of interest were picture observation > fixation and movement > fixation. A voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons was used (minimum cluster size = 10 voxels).

Based on the a priori hypothesis that processing of motor and visual abstract concepts activates similar brain regions as execution of real movements and observation of real pictures, activations obtained during the two localizer tasks were related to activations obtained from the differential contrasts motor versus visual abstract concepts and vice versa using inclusive masking. Accordingly, activation patterns of the motor and visual localizer tasks served as inclusive masks. In the masking analyses, the image of the thresholded (motor or visual) localizer contrast is used as inclusive mask (function as provided by SPM12) for computing the motor versus visual abstract concepts contrast of the lexical decision task and vice versa. Hence, only voxels, which were included in the masking image, were considered in the whole brain analysis evaluating the contrast in the lexical decision task. This inclusive masking procedure yields thresholded overlapping activation patterns between localizer and lexical decision task displayed in Fig. 2B. As the mask generated from the localizer task is the basis, this form of analysis computes the overlap even in

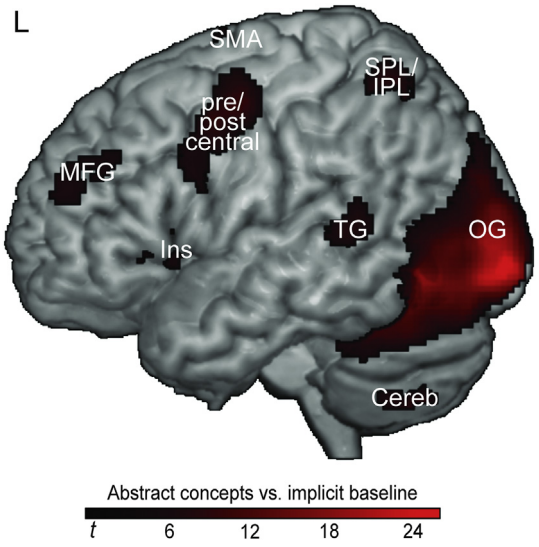

Fig. 1 – Greater activation to abstract concepts (motor and visual) versus implicit baseline, voxel thresholded at $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Due to the lateralization of general word processing, only the left hemisphere is shown. The color range bar indicates T-scores. Cereb = cerebellum; Ins = insula; IPL = inferior parietal lobule; MFG = middle frontal gyrus; OG = occipital gyri; pre/postcentral = pre- and postcentral gyrus; SMA = supplementary motor area; SPL = superior parietal lobule; TG = temporal gyri; L = left hemisphere.

different anatomical locations as long as they belong to the statistically significant clusters obtained in the localizer tasks. Please note that Fig. 2A only displays the anatomical overlap at a descriptive level without applying a statistical threshold to the overlapping voxels.

Although the present study was designed to investigate effects of motor and visual abstract concepts on brain activation in a categorical fashion, we additionally explored whether the relative proportions of motor and visual features inherent to a given concept would modulate the amplitude of the BOLD signal parametrically. To that end, further first-level GLMs were set up that were similar to those described above, but with two differences. First, onsets of motor and visual abstract concepts were combined to form one single regressor. Second, a parametric modulation regressor was included in the model, which was derived as follows: For each concept, a single value was computed according to the formula "(proportion of motor features - proportion of visual features)/(proportion of motor features + proportion of visual features)". The rationale was to obtain a condensed measure of the relative predominance of motor versus visual features of a given concept. By losing its strict categorical definition, each concept now fell on a continuum between high visual predominance (most negative value) and high motor predominance (most positive value). These values were mean-centered before entering the GLM as a linear parametric regressor. After model estimation, a *t*-contrast was created representing the degree of parametric modulation, which was collected from all participants and subjected to a second-level one-sample *t*-test. A contrast weight of +1 was specified to test for a significant, modulatory effect of the predominance of motor features on BOLD amplitude, and a contrast weight of −1 tested for a respective association with the predominance of visual features. Statistical testing was confined to regions of interest (ROI). The +1 contrast was only applied to voxels of a mask containing significant clusters from the analysis of the motor localizer task, and the −1 contrast was restricted to clusters from the visual localizer task. Significance was assessed at a voxel-height threshold of $p < .001$, with the additional requirement that resulting clusters had to survive FWE-correction for multiple comparisons ($p < .05$) after accounting for the adjusted search volume making up the respective ROI.

SPM's Anatomy toolbox and the implemented probabilistic cytoarchitectonic mapping procedure (Eickhoff et al., 2007) were used in order to determine anatomical locations of peak activations of significant clusters.

3. Results

3.1. Behavioral data

Analysis of behavioral data yielded a mean error rate (ER) of 2.0% (*SD* = 1.50%). Participants failed to respond to pseudowords in 1.43% of the trials (*SD* = 2.91%). ER in word trials (failure to withhold response) was 2.34% for motor abstract concepts (*SD* = 2.30%) and 2.21% for visual abstract concepts (*SD* = 2.34%). A univariate repeated measures ANOVA revealed no significant differences in mean ER between motor and visual abstract concepts and pseudowords, respectively [$F(2,46) = .93$, $p = .40$].

3.2. Neuroimaging data

3.2.1. Lexical decision task

Conjunction analysis identified brain regions activated for both motor and visual abstract concepts, compared to the implicit baseline. This analysis revealed enhanced activity in wide-spread brain regions including occipital (inferior and middle occipital gyrus), temporal (middle and superior temporal gyrus), frontal (supplementary motor area, precentral gyrus, opercular inferior frontal gyrus, middle frontal gyrus) and parietal (inferior parietal lobule) brain areas, as well as the insula, the middle cingulate cortex and the thalamus (see Table 2 and Fig. 1 for details).

Comparing the processing of motor versus visual abstract concepts at the whole brain level yielded broad activations in a network of fronto-parietal brain areas, partly extending to the limbic lobe as well as in subcortical structures with peak activations in bilateral precentral and postcentral gyrus, left precuneus, left posterior cingulate cortex and left thalamus (Table 3, Fig. 2).

Contrasting visual versus motor abstract concepts did not reveal any suprathreshold voxels for a threshold of $p < .001$ (uncorrected). Applying a more liberal statistical threshold ($p < .005$ uncorrected, cluster size > 10 voxels), however, revealed greater activations for visual abstract concepts in occipital, temporal, frontal and limbic lobe regions with peak

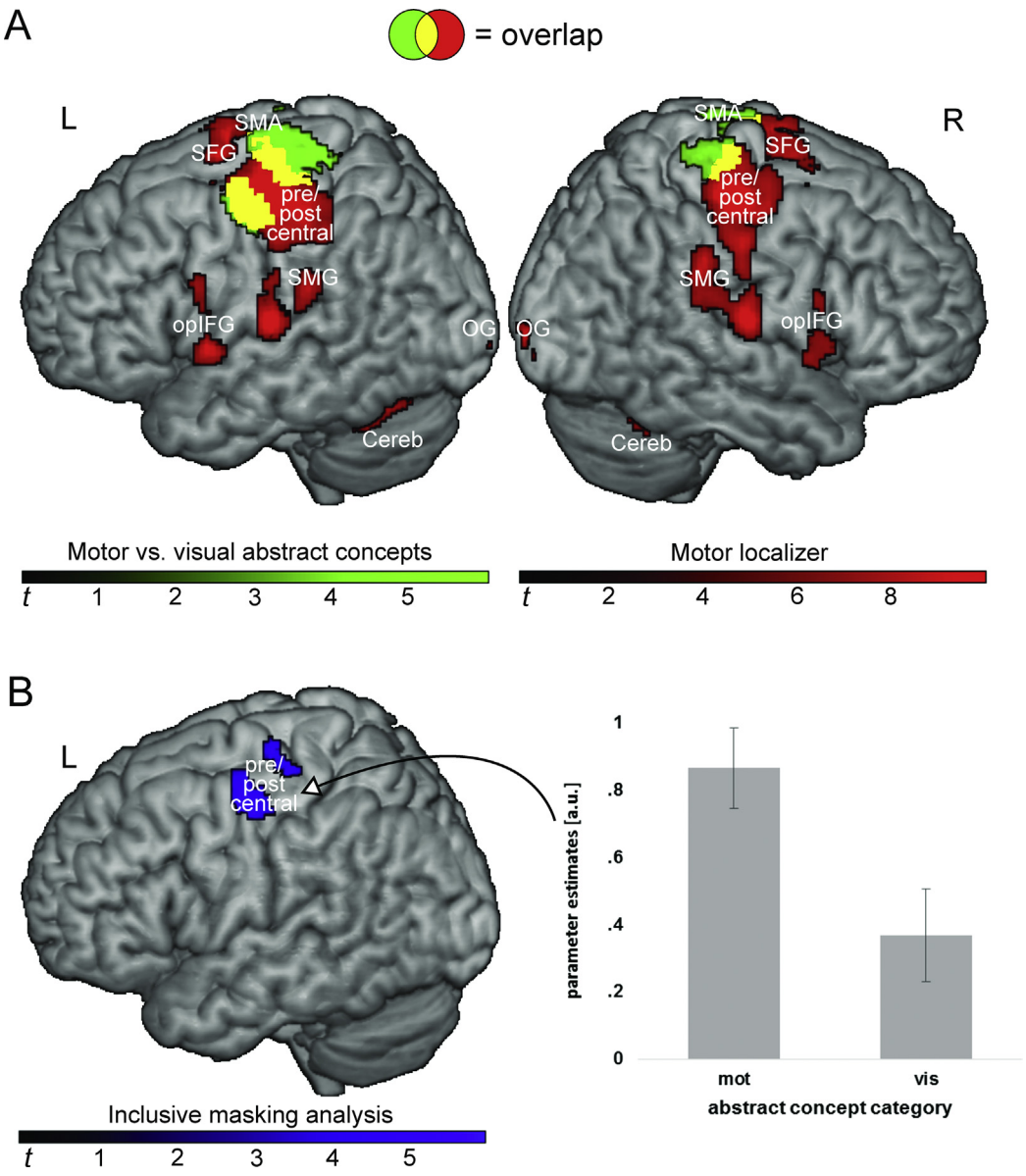

Fig. 2 – (A) Greater activation to motor versus visual abstract concepts (depicted in green) during the lexical decision task, overlaid with activations during the motor localizer task (depicted in red). Overlapping activations are depicted in yellow. The contrast motor versus visual abstract concepts was voxel thresholded at $p < .001$, cluster-corrected at $p_{FWE} < .05$. Results of the motor localizer task are reported at a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Note that the cluster of overlapping voxels was only determined by quantitatively overlaying the activation patterns of the localizer and lexical decision tasks for visualization purposes, without formal statistical analyses (B) Results of formal inclusive masking analysis to reveal common activation for motor abstract concepts and the motor localizer task. Significant overlap was found in left pre- and postcentral gyri. Inclusive masking analysis (depicted in blue) were voxel thresholded at $p < .001$, cluster-corrected at $p_{FWE} < .05$. The right bar graph depicts the magnitude of neural activation of the whole cluster as a function of motor versus visual abstract concepts, as represented by averaged parameter estimates. Color range bars indicate *T*-scores. Error bars represent *SEM*. Cereb = cerebellum; OG = occipital gyri; opIFG = opercular inferior frontal gyrus; pre/postcentral = pre- and postcentral gyrus; SFG = superior frontal gyrus; SMA = supplementary motor area; SMG = supramarginal gyrus; mot = motor abstract concept; vis = visual abstract concept; L/R = left/right hemisphere; a.u. = arbitrary unit.

activations in left lingual gyrus, bilateral fusiform gyrus, left temporal pole, right opercular inferior frontal gyrus, right superior temporal and parahippocampal gyrus, as well as in the insula (Table 3, Fig. 3).

3.2.2. *Motor localizer task*

Comparing the execution of bilateral hand movements with the fixation condition revealed enhanced bilateral activity in frontal (supplementary motor area, precentral gyrus,

Table 2 – Peak activations of the conjunction analysis identifying brain regions activated for both motor and visual abstract concepts, compared to the implicit baseline.

Region	MNI			Cluster size	T-value
	x	y	z		
Inferior Occipital Gyrus L	−24	−96	−4	23176	26.34
Middle Occipital Gyrus R	28	−92	0		23.44
Middle Occipital Gyrus L	−28	−92	2		20.83
Precentral Gyrus R	44	6	32	1146	11.19
Middle Frontal Gyrus R	34	−2	54		9.88
Precentral Gyrus R	52	4	48		6.97
Supplementary Motor Area L	−2	6	60	1646	10.84
Middle Cingulate Cortex R	6	14	44		10.07
Supplementary Motor Area R	8	12	52		9.98
Insula R	32	26	4	551	10.45
Precentral Gyrus L	−46	−4	50	1069	10.07
Precentral Gyrus L	−52	2	46		9.59
Precentral Gyrus L	−44	4	34		7.97
Insula L	−28	26	2	672	9.51
Insula L	−30	20	10		8.78
Opercular Inferior Frontal Gyrus L	−36	14	16		6.78
Middle Frontal Gyrus R	36	44	36	235	7.94
Middle Frontal Gyrus R	34	54	26		7.17
Middle Frontal Gyrus R	48	44	20		6.73
Middle Temporal Gyrus L	−58	−42	8	286	7.69
Superior Temporal Gyrus L	−48	−42	12		6.89
Middle Temporal Gyrus L	−56	−30	0		6.18
Thalamus R	24	−26	−2	44	7.26
Thalamus L	−24	−28	−2	40	7.07
Superior Temporal Gyrus R	44	−34	6	108	6.79
Superior Temporal Gyrus R	56	−38	10		6.28
Middle Frontal Gyrus L	−36	54	20	71	6.74
Middle Frontal Gyrus L	−32	52	30		5.98
Middle Frontal Gyrus L	−40	42	32		5.97
Inferior Parietal Lobule L	−40	−36	40	32	6.44

Reported are significant results at a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Listed are peak voxels with highest t-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

opercular inferior frontal gyrus), parietal (postcentral gyrus, supramarginal gyrus), occipital (calcarine sulcus) and subcortical (cerebellum, thalamus, putamen) brain areas as well as in the insula (Table 4, Fig. 2A).

3.2.3. *Visual localizer task*

Observation of images compared to the fixation condition increased the BOLD signal in widespread parts of the brain involving peak activations in occipital (bilateral inferior occipital gyrus), temporal (bilateral fusiform gyrus, bilateral temporal pole), frontal (left supplementary motor area, bilateral inferior frontal gyrus, bilateral precentral gyrus, right superior medial frontal gyrus), parietal (left postcentral gyrus) and subcortical (bilateral amygdala, cerebellum) brain regions (Table 5, Fig. 3).

3.2.4. *Functional overlap across tasks*

Inclusive masking revealed that both, processing of motor abstract concepts (*vs* visual abstract concepts) in the lexical decision task and execution of real hand movements activated precentral and postcentral gyrus (Table 6, Fig. 2B). Furthermore, processing of visual abstract concepts (*vs* motor abstract concepts) and observation of real pictures showed functional overlaps within fusiform and lingual gyrus (Table 6, Fig. 3).

3.2.5. *Parametric modulation of neural activation by predominance of motor/visual features*

Relative predominance of conceptual motor features significantly predicted the amplitude of estimated neural activation in two clusters that were primarily located in the left pre- and postcentral gyrus (Table 7, Fig. 4). There were, however, no significant clusters when testing for a relationship between the degree of predominance of visual features and BOLD amplitude.

4. Discussion

The present fMRI study investigated brain activation to motor and visual abstract concepts during a lexical decision task, which implicitly probes semantic processing. Motor abstract concepts generated enhanced BOLD signals in bilateral fronto-parietal brain areas, partially overlapping with activations during the execution of real movements. In addition to these activations in motor areas, motor abstract concepts activated cingulate and subcortical brain structures. The processing of visual abstract concepts, in contrast, was associated with enhanced brain activity in occipital and temporal brain regions, the insula and the limbic lobe, partially overlapping with activations during the observation of real pictures, particularly in the ventral visual stream. Specific activation to visual abstract concepts was less robust and only observed at a more lenient statistical threshold. Our findings were obtained with specific subcategories of abstract concepts which were characterized by empirically determined differentially strong modal feature associations (for other subgroups of abstract concepts see below). Our results are nevertheless in line with the grounded cognition approach which assumes that conceptual knowledge is represented in sensorimotor brain regions (Barsalou, 2008; Borghi, et al., 2017; Ghio, et al., 2016; Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Meteyard, et al., 2012; Pulvermüller & Fadiga, 2010).

Conjunction analysis identifying brain regions activated for both motor and visual abstract concepts compared to the implicit baseline, revealed enhanced activity in classic perisylvian language regions, the visual cortex, sensorimotor areas, the limbic lobe, the insula and the thalamus. This activation pattern is in line with previously published studies examining semantic processing (e.g., Carota, Moseley, & Pulvermuller, 2012; Dreyer & Pulvermuller, 2018; Ulrich, et al., 2013; Ulrich, Kiefer, Bongartz, Gron, & Hoenig, 2015), indicating that participants processed word stimuli at several levels of lexical representations. Evidence regarding the common involvement of typical hub regions in the processing of both categories of abstract concepts is limited in our data. In particular, there was no common activity in anterior temporal (Patterson, et al., 2007) or inferior parietal regions (Binder & Desai, 2011). Most likely the increased BOLD signal in the

Table 3 – Peak activations of motor versus visual abstract concepts (and vice versa) in the lexical decision task at the whole brain level.

Region	MNI			Cluster size	T-value
	x	y	z		
Whole brain analysis: motor > visual (voxel-height threshold of $p < .001$ and FWE-corrected cluster threshold of $p < .05$)					
Precentral Gyrus L	−26	−24	66	1625	6.02
Precuneus L	−16	−36	68		6.00
Postcentral Gyrus L	−42	−12	50		5.98
Posterior Cingulate Cortex L	−12	−40	14	143	5.32
Thalamus L	−18	−28	10		4.15
Precentral Gyrus R	16	−26	66	311	4.59
Precentral Gyrus R	26	−24	72		4.35
Postcentral Gyrus R	22	−36	70		4.25
Whole brain analysis: visual > motor (uncorrected voxel-height threshold of $p < .005$ and $k \geq 10$ voxels per cluster)					
Temporal Pole L	−36	12	−18	106	4.48
Opercular Inferior Frontal Gyrus R	30	4	30	98	4.03
Insula R	30	14	−14	83	3.66
Fusiform Gyrus R	30	−62	−6	28	3.48
Lingual Gyrus L	−20	−44	−8	15	3.30
Fusiform Gyrus L	−26	−42	−14		3.03
Parahippocampal Gyrus R	26	−26	−18	10	3.27
Superior Temporal Gyrus R	46	−42	16	13	3.24

Reported are significant results at a voxel threshold of $p < .001$, cluster-corrected at $p_{FWE} < .05$ for the contrast motor > visual. In the case of the contrast visual > motor significant results are reported at a voxel threshold of $p < .005$ (uncorrected for multiple comparisons) with a minimum cluster size of 10 voxels. Listed are peak voxels with highest *t*-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

posterior temporal gyri found in the conjunction analysis can be seen as an indication for the involvement of an amodal hub in posterior temporal cortex (Gold, et al., 2006; Hoffman, et al., 2012; Price, 2000) in the processing of both motor and visual abstract concepts, even though the activation pattern does not encompass prominent candidates for hub regions in inferior parietal cortex or the anterior temporal lobe. Nevertheless, the present results are in line with hybrid theories of conceptual representation assuming an interaction between modality-specific, multimodal and amodal hub areas (Fernandino, Binder, et al., 2016; Fernandino, Humphries, et al., 2016; Garagnani & Pulvermuller, 2016; Popp et al., 2019; Simmons & Barsalou, 2003).

Since we were primarily interested in brain activations during processing of motor and visual abstract concepts, which functionally overlap with the motor and the visual localizer, respectively, we focus on the results of the masking analyses in the following discussion. Results of the whole brain analysis are therefore only briefly outlined.

Peak activations obtained for motor versus visual abstract concepts during the lexical decision task at the whole brain level were mainly located in the motor cortex, the primary somatosensory cortex, the posterior cingulate cortex and the thalamus. Activation to motor abstract concepts partially overlapped with activity during the motor localizer, in which peak activations were mainly located in the primary motor cortex, the primary somatosensory cortex and visuo-motor coordination areas within the cerebellum, occipital areas and in motor areas of the parietal cortex. Overlapping brain activity was found within the left precentral and postcentral gyrus, which are associated with imagery (Kosslyn, Ganis, & Thompson, 2001; Parsons et al., 1995), planning, initiation, guidance, sequencing and execution (Halsband & Lange, 2006; Yokoi, Arbuckle, & Diedrichsen, 2018) of simple and skilled movements (Shibasaki et al., 1993; Yokoi, et al., 2018) as well as with sensory feedback loops (Johansson & Flanagan, 2009) and motor learning (Halsband & Lange, 2006). Brain activity in response to action-related words predominantly in left (but not homolog right) hemisphere motor regions has already been observed previously (e.g., Martin, Wiggs, Ungerleider, & Haxby, 1996) and is thought to reflect the dominance of the left hemisphere in language processing, especially in right handed individuals (Szaflarski et al., 2002).

The contrast visual versus motor abstract concepts yielded peak activations within occipital and temporal brain areas usually referred to the ventral visual stream and within the opercular inferior frontal gyrus, the insula and the parahippocampal gyrus at the whole brain level, albeit only at a more liberal statistical threshold. These activations in response to visual abstract concepts partially overlapped with activations obtained during the visual localizer task. Observation of object pictures elicited activations in the expected modality-specific brain areas, more precisely in primary and secondary visual cortex as well as in visual association cortex (cf. Grill-Spector & Malach, 2004; Kosslyn, Thompson, Kim, & Alpert, 1995; Zeki, 1993) and in fronto-parietal and subcortical brain areas associated with evaluative processes (Kensinger & Schacter, 2006; Zald, 2003). Masking the contrast visual versus motor abstract concepts inclusively with the results of the visual localizer task revealed overlapping brain activity within bilateral fusiform and left lingual gyrus. These areas are associated with various visual functions: Fusiform gyrus in temporo-occipital cortex is associated with complex visual processing (Weiner & Zilles, 2016), like facial (Kanwisher, McDermott, & Chun, 1997; Sergent, Ohta, & Macdonald, 1992), body (Peelen & Downing, 2005;

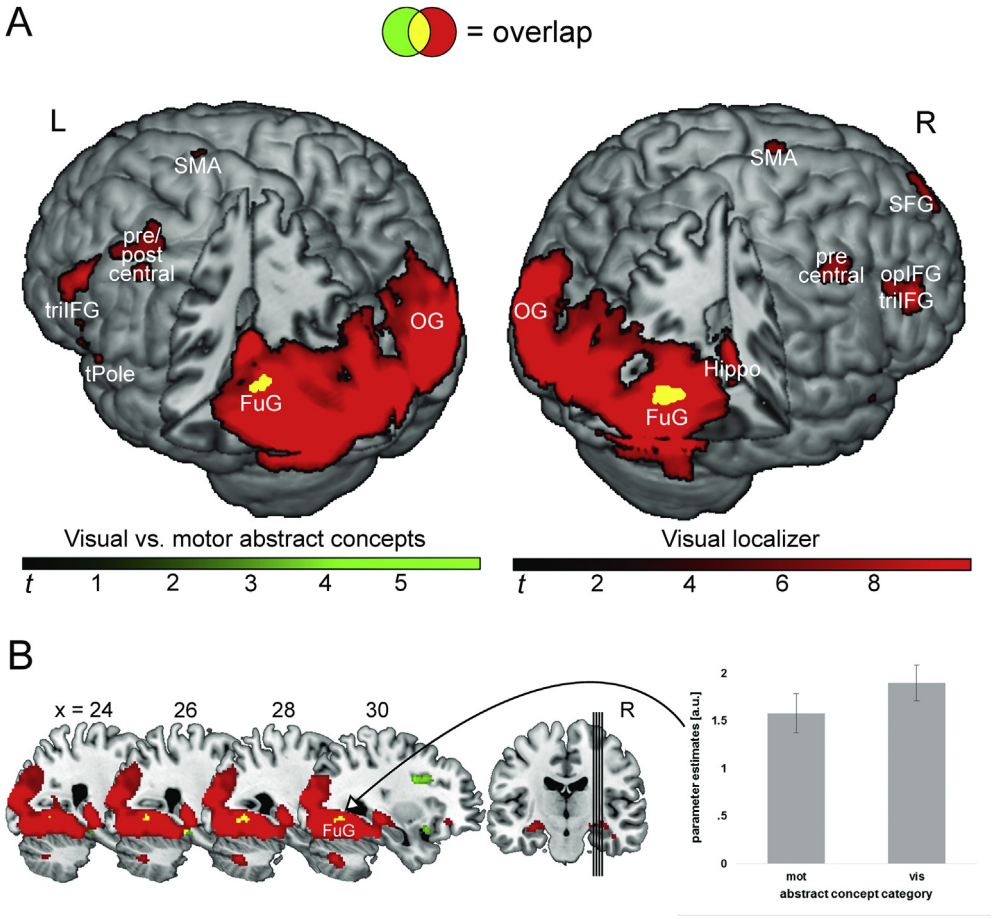

Fig. 3 – (A) Greater activation to visual versus motor abstract concepts (depicted in green) during the lexical decision task visually overlaid with activations during the visual localizer task (depicted in red). Overlapping activations are depicted in yellow. Activations below the brain surface are visualized by a cutout. (B) Multislice image of overlapping activations to visual versus motor abstract concepts and activations obtained during the visual localizer task in the right fusiform gyrus. The right bar graph depicts the magnitude of neural activation of the whole cluster as a function of visual versus motor abstract concepts, as represented by averaged parameter estimates. The contrast visual versus motor abstract concepts was voxel thresholded at $p < .005$ (uncorrected for multiple comparisons) with a minimum cluster size of 10 voxels. Results of the visual localizer task are reported at a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Color range bars indicate *T*-scores. Error bars represent *SEM*. FuG = fusiform gyrus; Hippo = hippocampus; OG = occipital gyri; opIFG = opercular inferior frontal gyrus; pre/postcentral = pre- and postcentral gyrus; SMA = supplementary motor area; SFG = superior frontal gyrus; tPole = temporal pole; triIFG = triangular inferior frontal gyrus; mot = motor abstract concept; vis = visual abstract concept; L/R = left/right hemisphere; a.u. = arbitrary unit.

Schwarzlose, Baker, & Kanwisher, 2005), color (Chao & Martin, 1999; Pulvermüller & Hauk, 2006; Simmons, et al., 2007), shape and object recognition (Bona, Herbert, Toneatto, Silvanto, & Cattaneo, 2014; Grill-Spector, Kourtzi, & Kanwisher, 2001; Malach et al., 1995; Pulvermüller & Hauk, 2006). The lingual gyrus, as well, is associated with facial (Kitada, Johnsrude, Kochiyama, & Lederman, 2010; Kozlovskiy et al., 2014) and color (Bartels & Zeki, 2000; Chao & Martin, 1999; Murphey, Yoshor, & Beauchamp, 2008) processing, in addition to general processing, encoding and retrieval of complex images (Machielsen, Rombouts, Barkhof, Scheltens, & Witter, 2000).

It is noticeable that the overlap of activations is smaller and statistically less robust for visual abstract concepts and the visual localizer task compared to motor abstract concepts and the motor localizer task. The underlying causes must remain speculative, but a closer look at the generated properties (Table 1) of motor abstract concepts reveals that those concepts also had a considerable visual feature relevance, in addition to the high motor feature relevance [the magnitude of visual features of motor abstract concepts differed significantly from zero ($t(31) = 8.37$, $p < .05$)]. The visuo-motor linkage may explain why significant differences between visual and motor abstract concepts were only detectable at a more liberal threshold. The processing of motor abstract concepts recruited related visual occipital brain areas, similarly to visual abstract concepts (but to a smaller extent), as also shown by Fig. 3B. Furthermore, both, motor and visual abstract concepts, were presented visually (written words) regardless of the respective feature class. It might be possible that the presentation of the stimuli in written word form already

Table 4 – Peak activations of the motor localizer task (bilateral hand movements > fixation condition).

Region	MNI			Cluster size	T-value
	x	y	z		
Supplementary Motor Area L	−2	−8	58	2498	16.21
Supplementary Motor Area R	4	0	48		12.97
Supplementary Motor Area L	−8	2	50		11.47
Precentral Gyrus L	−40	−20	58	1726	14.30
Precentral Gyrus L	−34	−12	56		13.57
Precentral Gyrus L	−32	−16	68		9.78
Cerebellum (IV – V) L	−16	−52	−18	3059	13.67
Cerebellum (VI) L	−30	−52	−28		13.19
Cerebellum (IV – V) R	18	−50	−22		12.74
Cerebellum (VIII) R	22	−62	−50	248	13.48
Thalamus L	−14	−18	10	1284	12.45
Opercular Inferior Frontal Gyrus L	−48	0	4		11.61
Putamen L	−32	−6	−2		10.91
Thalamus R	18	−14	10	1344	12.42
Putamen R	34	−4	−2		10.55
Insula R	46	4	6		10.36
Precentral Gyrus R	40	−22	60	1224	12.11
Postcentral Gyrus R	54	−18	44		9.02
Precentral Gyrus R	38	−10	52		8.97
Calcarine Sulcus R	14	−92	−4	284	11.06
Opercular Inferior Frontal Gyrus L	−50	−22	18	472	10.71
Postcentral Gyrus L	−58	−20	16		10.49
Supramarginal Gyrus L	−58	−34	28		8.63
Opercular Inferior Frontal Gyrus R	58	−16	16	749	10.53
Supramarginal Gyrus R	50	−32	34		9.62
Opercular Inferior Frontal Gyrus R	44	−24	20		8.36
Cerebellum (VIII) L	−26	−56	−48	244	9.60
Calcarine Sulcus L	−12	−92	−8	83	8.34
Calcarine Sulcus L	−10	−102	−4		7.01
Opercular Inferior Frontal Gyrus R	58	10	24	14	7.21
Insula L	−32	14	10	10	6.81

Reported are significant results at a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Listed are peak voxels with highest t-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

recruited the visual system to such an extent that the additional evoked activation by the visual abstract concepts turned out to be comparatively small (for a comparable example see van Ackeren, Schneider, Müsch, & Rueschemeyer, 2014). Therefore, it is possible, that the result pattern would have been more unequivocal if the stimuli had been, for example, acoustically presented. A simultaneous recruitment of the visual system by the visual stimulus presentation on the one hand and the visually grounded abstract concepts on the other hand, would have thus been avoided. Future studies should take into account the possible influence of the presentation modality of stimuli.

Parametric modulation analysis testing whether relative proportions of motor features would modulate the amplitude of the BOLD signal parametrically yielded peak activations in two clusters located in the left pre- and postcentral gyrus, thus paralleling the results of the masking analysis based on categorical conceptual differences. For the relative proportions of visual features, we failed to find a significant relation to brain activity. Again, this might be due to the recruitment of the visual system by both, visual stimulus presentation and processing of visual conceptual features (see above). Furthermore, the present study was designed in order to investigate effects of motor and visual abstract concepts on brain activation in a categorical fashion. For that reason, proportion of visual and motor features was not continuously distributed. Future studies could address this fact by using linearly increasing proportions of features in their stimuli set.

The present fMRI results are in line with recent rating (Binder, et al., 2016; Lynott & Connell, 2009, 2013; Troche, et al., 2014; Troche, et al., 2017; van Dantzig, et al., 2011) and property generation studies (Barsalou & Wiemer-Hastings, 2005; Harpaintner, et al., 2018) on the subjective semantic content of abstract concepts. These studies showed that information related to sensorimotor experiences is associated with both, concrete and abstract concepts. Besides social, introspective, affective and linguistic content, content related to sensorimotor experiences seems to play an important role in the representation of abstract concepts. The present study goes one step further by showing that the subjectively reported motor and visual feature content of abstract concepts is indeed associated with activity in corresponding modal brain areas. At the same time, the present study differs from recent neuroimaging studies by investigating a priori selected stimuli whose feature compositions were determined beforehand according to property listings (Harpaintner, et al., 2018). Previous studies have already shown that the sensorimotor system is involved in the processing of abstract concepts, but to

Table 5 – Peak activations of the visual localizer task (picture observation > fixation condition).

Region	MNI			Cluster size	T-value
	x	y	z		
Fusiform Gyrus R	32	−52	−12	22782	26.92
Fusiform Gyrus R	38	−58	−12		26.85
Inferior Occipital Gyrus L	−40	−74	−8		26.49
Amygdala R	22	−4	−14	96	11.73
Triangular Inferior Frontal Gyrus R	54	32	26	75	10.52
Opercular Inferior Frontal Gyrus R	54	24	34		7.59
Temporal Pole L	−46	18	−18	736	10.50
Temporal Pole L	−40	24	−20		9.28
Orbital Inferior Frontal Gyrus L	−46	22	−4		8.44
Temporal Pole R	52	16	−16	65	10.30
Temporal Pole R	42	22	−20		7.79
Temporal Pole R	36	18	−26		7.46
Triangular Inferior Frontal Gyrus L	−52	22	26	168	9.65
Triangular Inferior Frontal Gyrus L	−56	26	20		8.48
Cerebellum (X) L	−18	−40	−40	16	8.24
Precentral Gyrus L	−36	4	30	27	7.94
Supplementary Motor Area L	−6	12	56	99	7.82
Supplementary Motor Area L	−4	2	64		7.11
Orbital Inferior Frontal Gyrus R	34	34	−8	44	7.72
Precentral Gyrus R	50	0	50	35	7.35
Superior Medial Frontal Gyrus R	10	62	32	20	7.35
Precentral Gyrus L	−42	0	46	86	7.29
Precentral Gyrus L	−44	−8	52		6.96
Precentral Gyrus L	−50	6	48		6.86
Postcentral Gyrus L	−54	−8	46	13	7.28
Precentral Gyrus R	42	6	32	28	7.22
Cerebellar Vermis (IX)	0	−56	−40	17	7.13

Reported are significant results at a voxel threshold of $p_{FWE} < .05$ corrected for multiple comparisons with a minimum cluster size of 10 voxels. Listed are peak voxels with highest *t*-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

our knowledge, this has been done with a broad range of abstract concepts, from affective (Dreyer & Pulvermuller, 2018; Moseley, et al., 2012; Vigliocco, et al., 2014) to physical (Mason & Just, 2016) abstract concepts, without a priori sensory and motor feature determination. We furthermore made use of a larger set of stimuli than previous studies (Wilson-Mendenhall, et al., 2012), which increases the generalizability of the results. Our study thus extends the existing empirical findings and provides further evidence that the grounded cognition approach is also applicable to abstract concepts related to action and vision.

In addition, the present results fit well into the picture that emerged from numerous studies on concrete concepts. Studies investigating the neural correlates of conceptual representation of motor-related concrete concepts constantly found peak activations in primary and premotor regions, similar to the present results (de Zubicaray, Arciuli, & McMahon, 2013). More precisely, previous studies have already reported an association between processing of motor-related concrete concepts and enhanced activity in precentral (Hauk, Johnsrude, & Pulvermüller, 2004; Hauk & Pulvermuller, 2011; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Pulvermüller, Cook, & Hauk, 2012; Pulvermüller, Kherif, Hauk, Mohr, & Nimmo-Smith, 2009; Raposo, Moss, Stamatakis, & Tyler, 2009; Rüschemeyer, Brass, & Friederici, 2007; Tomasino, Weiss, & Fink, 2010; Willems, et al., 2010) and postcentral (Hauk, et al., 2004; Pulvermüller, et al., 2009) gyri. The peak activations found in these studies are in direct proximity to the results of the masking analysis with the motor localizer reported here. Similar converging evidence is available for abstract concepts with predominance of visual features, although fewer studies on this modality are available (Devlin et al., 2002; Perani et al., 1995; Simmons, et al., 2007). Empirical evidence concerning the grounding of visual-related concrete concepts mainly comes from early studies examining neural correlates of category-specific knowledge (Devlin, et al., 2002). Perani et al. (1995), for example, found that the recognition of visual stimuli representing animals, in which visual properties are the essential means by which different members of a category can be distinguished, was selectively associated with enhanced activity within the left fusiform and lingual gyrus when compared to the recognition of artefacts. Similar peak activations in the occipital lobe in response to living versus nonliving categories were found by other neuroimaging studies (Devlin, et al., 2002). Further evidence consistent with the present findings is provided by Simmons et al. (2007), who investigated the involvement of color-sensitive areas in occipital cortex in color knowledge retrieval. They found the left fusiform gyrus to be activated during retrieving color versus motor knowledge, just as we found the fusiform gyrus to be associated with visual versus motor abstract concepts. Since we assume abstract concepts to be grounded in situations through various visual features, like form, texture and color, the findings of our study are in line with those of Simmons et al. (2007).

Table 6 – Peak activations of the inclusive masking analyses.

Region	MNI			Cluster size	T-value
	x	y	z		
Masking analysis: motor > visual inclusively masked with activity to the motor localizer task					
Precentral Gyrus L	−42	−8	54	420	5.98
Precentral Gyrus L	−28	−30	58		5.86
Postcentral Gyrus L	−32	−28	48		5.26
Masking analysis: visual > motor inclusively masked with activity to the visual localizer task					
Fusiform Gyrus R	30	−62	−6	28	3.48
Lingual Gyrus L	−20	−44	−8	15	3.30
Fusiform Gyrus L	−26	−42	−14		3.03

Reported are significant results at a voxel threshold of $p < .001$, cluster-corrected at $p_{FWE} < .05$ for the contrast motor > visual abstract concepts inclusively masked with activity to movements versus fixation in the motor localizer task. In the case of the contrast visual > motor abstract concepts significant results are reported at a voxel threshold of $p < .005$ (uncorrected for multiple comparisons) with a minimum cluster size of 10 voxels inclusively masked with activity to picture observation versus fixation in the visual localizer task. Listed are peak voxels with highest *t*-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

Findings of the present study thus parallel results of earlier studies on the representation of concrete motor and visual concepts. Furthermore, the present results extend existing evidence with regard to abstract concepts by investigating a priori selected stimuli and by showing that category-specific effects for motor and visual conceptual feature types can also be obtained for abstract concepts. However, as already discussed in more detail above, unlike activity to motor abstract concepts, feature-specific activation to visual abstract concepts was only obtained at a more liberal statistical threshold. Nevertheless, the present study is in line with grounded cognition approaches (Barsalou, 2008, 2010; Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Meteyard, et al., 2012; Pulvermüller, 2005, 2013) by confirming the assumption that the content of concepts is rooted in modal brain areas, even if they are abstract and hence lack a clear physical referent. Our comparison of motor and visual abstract concepts suggests that the representation of abstract concepts does not differ essentially and necessary from that of concrete concepts (see also Löhr, 2019). Most likely, encoded memories of situational perceptions are simulated when accessing conceptual knowledge for abstract concepts (Barsalou & Wiemer-Hastings, 2005; Kiefer & Pulvermüller, 2012). Furthermore, metaphoric relations between abstract and concrete concepts (Lakoff & Johnson, 1980) might lead to a grounding of abstract concepts in modal brain systems. At this point it should be emphasized once again that – in addition to sensory and motor information – emotional information, social constellations and verbal associations provide an essential contribution to the representation of abstract concepts (see Harpaintner, et al., 2018). However, as we only investigated motor and visual abstract concepts, it remains open whether abstract concepts, which are characterized by other modal features are similarly represented in modality-specific brain regions.

As the feature composition of abstract concepts has been shown to be highly heterogeneous (Barsalou & Wiemer-Hastings, 2005; Binder, et al., 2016; Harpaintner, et al., 2018; Lynott & Connell, 2009, 2013; Troche, et al., 2014; Troche, et al.,

Table 7 – Peak activations of the parametric modulation of neural activation by relative predominance of conceptual motor features.

Region	MNI			Cluster size	T-value
	x	y	z		
Precentral Gyrus L	−28	−26	62	79	4.89
Precentral Gyrus L	−26	−20	54		4.00
Precentral Gyrus L	−26	−22	72		3.75
Postcentral Gyrus L	−44	−12	56	83	4.30
Precentral Gyrus L	−36	−10	62		3.57

Reported are significant results at a voxel threshold of $p < .001$, cluster-corrected at $p_{FWE} < .05$ after accounting for the adjusted search volume of the motor localizer task. Listed are peak voxels with highest *t*-values for significant clusters and their local maxima more than 8 mm apart. MNI = Montréal Neurological Institute coordinates, R = right, L = left.

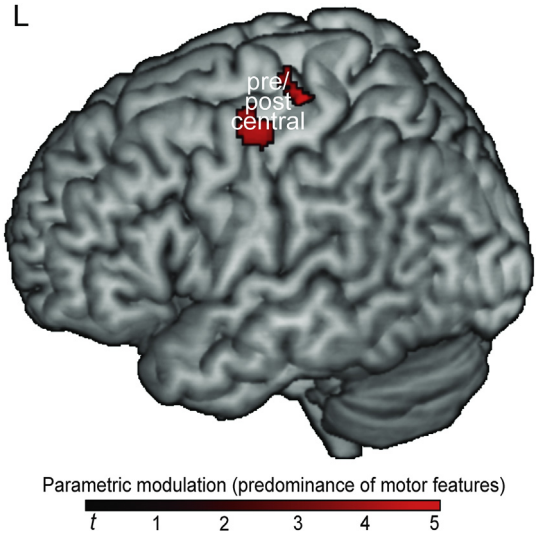

Fig. 4 – Peak activations of the parametric modulation of neural activation by relative predominance of conceptual motor features. The color range bar indicates T-scores. Pre/postcentral = pre- and postcentral gyrus; L = left hemisphere.

2017; van Dantzig, et al., 2011), it is likely that other subgroups of abstract concepts, which have not been investigated in the present study, are represented in other neural subsystems. Abstract concepts with a strong link to emotions (e.g., "fear") might be represented in brain structures associated with affective processing (Vigliocco, et al., 2014). Abstract concepts with a strong link to social constellations and mental states (e.g., "convince") might be represented in brain areas associated with social cognition and mentalizing (Wilson-Mendenhall, et al., 2013). The present results furthermore do not rule out the possibility that concepts at the extreme end of the abstractness scale (e.g., "justice" or scientific concepts like "gravity") with a strong link to verbal associations predominantly depend on language regions or amodal hub regions (Wang, et al., 2010). Future neuroimaging studies investigating other specific abstract subcategories (e.g., sound-related abstract concepts or abstract concepts specifically related to emotions, social constellations and verbal associations) could shed light on their neural correlates and extend the present results. Sensory-motor activation observed in the present and earlier neuroimaging studies could in principle arise from spreading of activation from an amodal conceptual level to modality-specific input/output levels (Mahon, 2015a; 2015b). However, this spreading of activation should be comparable for different conceptual categories (here: motor and visual abstract concepts). It is difficult to explain how spreading of activation should result in differential sensory-motor activation as a function of the conceptual content (here differential relevance of motor and visual content), unless additional assumptions are made.

Of course, as studies using neuroimaging techniques can only provide correlational evidence, methods allowing for causal conclusions, as transcranial magnetic stimulation (Pulvermüller, et al., 2005; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017), investigation of brain-lesioned patients (Dreyer, et al., 2015; Neininger & Pulvermüller, 2003; Trumpp, et al., 2013) or behavioral interference paradigms (Shebani & Pulvermüller, 2013; Vermeulen, Corneille, & Niedenthal, 2008), are mandatory in order to demonstrate a functional role of sensorimotor representations for the processing of abstract concepts.

Note that available neuropsychological data regarding the representational format of concrete concepts is mixed and controversial. Several studies report dissociations regarding patients with impaired skilled tool use, but retained knowledge of manipulable objects (Buxbaum & Saffran, 2002; Garcea, Dombovy, & Mahon, 2013; Negri et al., 2007; Papeo, Negri, Zadini, & Rumiati, 2010; Rosci, Chiesa, Laiacona, & Capitani, 2003), with impaired color perception but retained object-color knowledge (Shuren, Brott, Schefft, & Houston, 1996), and vice versa (Luzzatti & Davidoff, 1994; Miceli et al., 2001; Stasenko, Garcea, Dombovy, & Mahon, 2014). These sort of neuropsychological findings favor the assumption that conceptual knowledge is represented independent of sensorimotor cortices in an amodal fashion (Mahon, 2015a; Mahon & Caramazza, 2005). However, opposing results have also been reported showing that damage to the motor system through lesions and degenerative brain diseases is accompanied by deficits in processing action-related verbs (Bak, O'Donovan, Xuereb, Boniface, & Hodges, 2001; Cotelli et al., 2006; Daniele, Giustolisi, Silveri, Colosimo, & Gainotti, 1994; Neininger & Pulvermüller, 2001, 2003). Similar effects have been observed when using picture stimuli instead of verbal stimuli (Bak et al., 2006; Kemmerer, Rudrauf, Manzel, & Tranel, 2012). Damage to auditory association cortex has been shown to impair the processing of sound-related concepts (Bonner & Grossman, 2012; Trumpp, et al., 2013). The reasons for these inconsistent findings remain open: On the one hand, lesion studies often investigate damage to primary sensorimotor cortices even though higher-level modality-specific cortices seem to be crucial for conceptual processing (e.g., Trumpp, et al., 2013). On the other hand, mixed evidence might be due to heterogeneous task demands. Following the language and situated simulation theory of Barsalou et al. (2008), the nature of the task and the associated depth of processing determine whether modality-specific cortices are necessary for accomplishing the task. Whereas some tasks demand relatively superficial processing of linguistic associations only (no need to access modality-specific information), other tasks require deep conceptual information and rely on simulations in modal brain areas. Finally, as recent rating and property listing studies suggest (e.g., Barsalou & Wiemer-Hastings, 2005; Harpaintner, et al., 2018; Lynott & Connell, 2009, 2013), the semantic content of concepts typically includes various modalities and types of information. This renders it unlikely that damage to one circumscribed brain sensory-motor area leads to "*catastrophic*" (quoted from Binder & Desai, 2011) conceptual deficits because other involved modal brain areas and even conceptual hub regions might compensate and stabilize conceptual processing. Neuropsychological data regarding abstract concepts, to our knowledge, are scarce. However, the significance of the motor cortex for the processing of abstract concepts has been demonstrated in a brain-lesion study by Dreyer et al. (2015). Further work systematically investigating the influence of primary versus higher-level cortices and task demands on conceptual processing as well as further investigations of abstract concepts in brain-lesioned participants seem to be inevitable in order to resolve the present inconsistent evidence. Such functional evidence would preclude an epiphenomenal (in terms of spreading of activation) or accessory role of sensorimotor activation during conceptual processing as suggested by some variants of amodal theories (Mahon, 2015a, 2015b; Mahon & Caramazza, 2003).

5. Conclusions

The present study found differential activation patterns in response to motor and visual abstract concepts in line with proposals of the grounded cognition approach. Motor abstract concepts were associated with peak activations partially overlapping with activations obtained during the execution of real hand movements in left precentral and postcentral gyrus. Results were paralleled by parametric modulation analysis showing that the concepts' degree of predominance of motor features significantly predicted the amplitude of estimated neural activation in the left pre- and postcentral gyrus. Contrary, the processing of visual abstract concepts revealed enhanced activity in lingual and fusiform gyrus partially

overlapping with activations during the observation of object pictures, albeit at a more liberal statistical threshold. This might be due to a considerable visual feature relevance in motor abstract concepts and the recruitment of the visual system by both, visual stimulus presentation and processing of visual conceptual features. Although the present results do not allow any causal conclusions, they show that partially overlapping brain regions are recruited by conceptual processing of abstract concepts and real hand movements or picture observation. The present results thus indicate that the presently investigated subgroups of abstract concepts with an empirically identified differentially strong motor and visual feature dominance are grounded in sensory and motor brain areas similar to concrete concepts, supposedly through experiential information during concept acquisition. Activity in posterior temporal cortex, common for both categories of abstract concepts indicates that amodal hub regions might interact with modality-specific processing in congruency with hybrid models of conceptual representations. Future work should investigate other subgroups of abstract concepts and demonstrate the functional significance of the sensory-motor systems for the processing of abstract concepts in order to more completely elucidate the nature of conceptual representations and their functional-neuroanatomical implementation in the human brain.

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Additional information

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study (see the Methods section). The full set of verbal stimuli is provided as Supplementary Material. Study data, digital study materials and analysis code related to this manuscript have been archived under https://doi.org/10.17632/k5wkh4bhmw.2. The conditions of our ethics approval do not permit public archiving of anonymized raw MRI data. Readers seeking access to the data should contact the corresponding author Markus Kiefer or the local ethics committee at Ulm University. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must meet the following conditions to obtain the data: They must complete a formal data sharing agreement.

Open practices

The study in this article earned an Open Materials badge for transparent practices. Materials and data for the study are available at https://doi.org/10.17632/k5wkh4bhmw.2.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

CRediT authorship contribution statement

Marcel Harpaintner: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Eun-Jin Sim:** Methodology, Software, Formal analysis, Writing - review & editing, Supervision. **Natalie M. Trumpp:** Conceptualization, Methodology, Software, Writing - review & editing, Supervision. **Martin Ulrich:** Software, Formal analysis, Writing - review & editing. **Markus Kiefer:** Conceptualization, Methodology, Software, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Supplementary data

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2.3. Studies IIIa + IIIb - Time course of brain activity during the processing of motor and vision-related abstract concepts: Flexibility and task dependency

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ORIGINAL ARTICLE

Time course of brain activity during the processing of motor- and vision-related abstract concepts: flexibility and task dependency

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Abstract
Grounded cognition theories assume that conceptual processing depends on modality-specific brain systems in a context-dependent fashion. Although the relation of abstract concepts to modality-specific systems is less obvious than for concrete concepts, recent behavioral and neuroimaging studies indicated a foundation of abstract concepts in vision and action. However, due to their poor temporal resolution, neuroimaging studies cannot determine whether sensorimotor activity reflects rapid access to conceptual information or later conceptual processes. The present study therefore assessed the time course of abstract concept processing using event-related potentials (ERPs) and compared ERP responses to abstract concepts with a strong relation to vision or action. We tested whether possible ERP effects to abstract word categories would emerge in early or in later time windows and whether these effects would depend on the depth of the conceptual task. In Experiment 1, a shallow lexical decision task, early feature-specific effects starting at 178 ms were revealed, but later effects beyond 300 ms were also observed. In Experiment 2, a deep conceptual decision task, feature-specific effects with an onset of 22 ms were obtained, but effects again extended beyond 300 ms. In congruency with earlier neuroimaging work, the present feature-specific ERP effects suggest a grounding of abstract concepts in modal brain systems. The presence of early and late feature-specific effects indicates that sensorimotor activity observed in neuroimaging experiments may reflect both rapid conceptual and later post-conceptual processing. Results furthermore suggest that a deep conceptual task accelerates access to conceptual sensorimotor features, thereby demonstrating conceptual flexibility.

Introduction

What is the meaning of the concept "beauty," a concept, which can be considered as being abstract as it does not refer to a physical referent? Philosophers have tried to define the meaning of this concept for several centuries based on more or less complex considerations (e.g., Baumgarten, 1750–1758). Imagining a tour through the Museum of Modern Art in New York probably makes these considerations much simpler. Imagine standing in front of the Starry Night painted by post-impressionist Vincent van Gogh and admiring the wavelike forms and the color gradient of the nocturne painting. Intuitively, most people would speak of beauty here. This example illustrates that, similar to concrete concepts such as "painting," the meaning of abstract concepts might be related to perception (e.g., vision) through their reference to situations as suggested by grounded (or embodied) cognition theories. Thinking about the abstract concept "fitness" illustrates another notion of grounded cognition theories that (abstract) concept meaning might not only be grounded through its relation to (visual) perception but also through actions, such as lifting weights, doing yoga or bicycling (for reviews see Barsalou, 2008, 2010; Kiefer & Barsalou, 2013; Kiefer & Pulvermüller, 2012; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012; Pulvermüller, 2013).

Whereas it is generally accepted that concepts are the basic units of cognition that make up the meaning of words (Humphreys, Riddoch, & Quinlan, 1988; Kiefer & Pulvermüller, 2012; Tulving, 1972), their representational format and their organization at a neural and functional level are still a matter of debate. Traditional amodal approaches (Anderson, 1978; Collins & Loftus, 1975; Fodor, 2001; Mahon & Caramazza, 2009; Pylyshyn, 1980) would answer these questions by amodal semantic hubs, in which all forms of conceptual knowledge are represented (Rogers et al., 2004).

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In amodal models, the representational format of concepts is considered abstract and independent of motor interactions or perceptual impressions during concept acquisition. Original modality-specific experiential information is transformed into a common symbolic code (Caramazza & Mahon, 2003). Concrete and abstract concepts like "painting," "beauty" or "fitness" are seen to be similarly represented separated from the sensorimotor brain systems in the same amodal code. Considering "beauty" from the beginning of this article, traditional amodal theories would assume that experiences gathered by the visitor of the Museum of Modern Art do not contribute to its representation of the concept "beauty," since the original experiential information is transformed into an abstract code and is therefore seen to be lost or at least extenuated (Anderson, 1978; Caramazza & Mahon, 2003; McClelland & Rogers, 2003). Anterior inferior-temporal (Patterson, Nestor, & Rogers, 2007; Visser, Jefferies, & Ralph, 2010), inferior-parietal (Binder & Desai, 2011), posterior middle temporal (Gold et al., 2006; Hoffman, Pobric, Drakesmith, & Ralph, 2012; Price, 2000) and prefrontal cortex (Devlin, Matthews, & Rushworth, 2003) have been proposed as neural basis of these amodal hub regions, even though their exact number, function and location remain questionable (Meteyard et al., 2012). Activation of modal brain areas during conceptual processing is not denied per se; however, their engagement is considered, if at all, as epiphenomenon, which is not causally involved in conceptual representation: Activation of modal brain areas may occur concomitantly through spreading activation (Mahon, 2015a, 2015b) or strategic imagery (Machery, 2007), after a putatively amodal concept had been accessed.

Grounded cognition theories, in contrast, consider modal brain systems and interconnected networks including regions associated with motor, sensory, emotional and introspective processes as essential for conceptual representation (Barca, Borghi, Dove, & Tummolini, this issue; Barsalou, 2008; Borghi et al., 2017; Ghio, Vaghi, Perani, & Tettamanti, 2016; Kiefer & Barsalou, 2013; Pulvermüller & Fadiga, 2010). Concepts are seen as simulations of previous experiences and implemented in distributed brain networks, which arise from simultaneous activation of cell assemblies during concept acquisition (Pulvermüller & Fadiga, 2010), similarly as it already has been proposed by Hebbian theory (1949). Considering the examples of the beginning of this article, grounded cognition approaches would assume that the representational format of "beauty" or "fitness" is essentially related to the original perceptual impressions during concept acquisition like specific visual (e.g., forms and colors in the Starry Night) and motor (e.g., motor sequence of weight lifting and bicycling) information. Note that mental simulations based on modal representations are not necessarily accompanied by conscious experiences such as imagery (Kiefer & Barsalou, 2013). Instead, grounded cognition theories assume that modal activations can occur in the absence of any vivid sensory or motor experience (Kemmerer, 2015; Kiefer, Sim, Herrnberger, Grothe, & Hoenig, 2008). In fact, activity in modal brain regions has also been observed for masked words, which were not consciously perceived (Trumpp, Traub, & Kiefer, 2013b; Trumpp, Traub, Pulvermüller, & Kiefer, 2014).

Another core assumption of recent grounded cognition theories is that conceptual representations are flexible (Kiefer & Pulvermüller, 2012; Kuhnke, Kiefer, & Hartwigsen, 2020) in the sense that the feature composition of concepts depends on the task or situation at hand (Barsalou, 1982). Pulvermüller (2018) recently provided an explanation for task-related flexibility within modal brain areas based on a neurobiologically inspired model. At a mechanistic level, task-related conceptual flexibility is seen to be a result of cortical gain control processes. Depending on the specific task, gain control of cortical activation is realized through feedback loops regulating excitation or inhibition processes within modality-specific brain areas, respectively. It is assumed that task-related modulations of cortical activity result from attention shifts toward or away from sensorimotor meaning aspects.

Recently developed hybrid theories combine assumptions made by amodal and grounded cognition theories by proposing an interaction between modality-specific, multimodal and amodal conceptual hub areas for conceptual processing (Kiefer & Harpaintner, 2020; Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020; Patterson et al., 2007). These so-called hub and spokes models propose hub regions to store unifying non-physical semantic information while still being connected with concrete-experiential regions (Patterson & Ralph, 2016; Ralph, Jefferies, Patterson, & Rogers, 2017).

While the representation of concrete concepts can be accommodated by grounded cognition theories, including hybrid theories, in a quite straightforward manner, the mere existence of abstract concepts is often interpreted as proof of amodal theories (Mahon & Caramazza, 2008) since abstract concepts do not refer to a physical referent. In a similar vein, Paivio's Dual Coding Theory (1986) claimed that concrete concepts are represented through both, a visual imagery and a verbal semantic system. Abstract concepts, in contrast, are assumed to be represented exclusively within the verbal semantic system.

In order to better account for the representation of abstract concepts, refined grounded cognition theories aimed to specify the relation between modality-specific brain systems and abstract concepts (see also Kiefer & Harpaintner, 2020; Pulvermüller & Henningsen, this issue). For instance, the Conceptual Metaphor Theory (Lakoff & Johnson, 1980) claims that the meaning of abstract concepts results from sensorimotor information originating from metaphoric relations to concrete concepts (see Desai, this issue). Barsalou

and Wiemer-Hastings (2005) emphasize the importance of situational perceptions and therefore of direct sensorimotor experience in the constitution of the meaning of abstract concepts. They assume that conceptual knowledge is instantiated by partly simulating sensorimotor experiences made in specific situations during concept acquisition. The grounding of abstract concepts is thus thought to be based on simulations in modal brain systems. Considering "beauty," for example, might simulate the visual scene of the admiration of the Starry Night described in the beginning of this article (see also Vergallito, Guenther, Marelli, & Petilli, this issue).

Based on the empirical findings that the semantic content of abstract concepts is highly heterogeneous (see below; Barca, Mazzuca, & Borghi, 2017; Harpaintner, Trumpp, & Kiefer, 2018; Kiefer & Harpaintner, 2020; Muraki, Sidhu, & Pexman, this issue; Wiemer-Hastings, Krug, & Xu, 2001; Wiemer-Hastings & Xu, 2005), grounded cognition approaches extended their theoretical framework by emphasizing the importance of additional types of conceptual information besides sensorimotor information. Linguistic/verbal (Barca et al., this issue; Language And Situated Simulation Theory, Barsalou, Santos, Simmons, & Wilson-Mendenhall, 2008; Words As Social Tools Approach, Borghi & Binkofski, 2014; Louwerse's Symbol Interdependency Hypothesis, Louwerse, 2011), social (Barsalou & Wiemer-Hastings, 2005; Borghi & Binkofski, 2014), affective (Affective Embodiment Account, Kousta, Vigliocco, Vinson, & Andrews, 2009) and introspective (Barca et al., this issue; Kiefer & Barsalou, 2013) experiential information is thought to be essential in the representation of abstract concepts.

Evidence favoring the grounded cognition framework mainly comes from studies on concrete concepts. Behavioral (e.g., Garcia & Ibanez, 2016), neuroimaging studies (e.g., Kiefer et al., 2008) as well as transcranial magnetic stimulation studies (TMS; e.g., Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005a) or neuropsychological studies (e.g., Trumpp, Kliese, Hoenig, Haarmeier, & Kiefer, 2013a) demonstrated the involvement of modal brain systems in conceptual processing. Several electroencephalography (EEG) studies, which provide the time course of conceptual processing, found differential event-related potential (ERP) effects as a function of the modal information involved (e.g., Hauk & Pulvermüller, 2004; Trumpp et al., 2014; Martin, 2006 #83).

In line with the notion of conceptual flexibility, previous studies furthermore showed a modulation of cortical activity during conceptual processing depending on the requested task (Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Popp, Trumpp, & Kiefer, 2019; van Dam, van Dijk, Bekkering, & Rueschemeyer, 2012). Deep conceptual decision tasks, in which retrieval of feature-specific information is necessary, led to modality-specific effects in several studies (Papeo, Vallesi, Isaja, & Rumiati, 2009; Popp et al., 2019; Sato, Mengarelli, Riggio, Gallese, & Buccino, 2008). In contrast, shallow lexical decision tasks, in which conceptual retrieval is not task-relevant but occurs through associative processes, led to a diminution or even a disappearance of differential effects (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008) illustrating that conceptual processing is highly flexible in the sense that it is dependent on the task at hand.

While the involvement of the sensorimotor system for the processing of concrete concepts is well documented, corresponding evidence with regard to abstract concepts is limited (for a review see Kiefer & Harpaintner, 2020). One line of evidence indicating a foundation of abstract concepts in perception and action comes from rating studies (Binder et al., 2016; Lynott & Connell, 2009, 2013; Troche, Crutch, & Reilly, 2014, 2017; van Dantzig, Cowell, Zeelenberg, & Pecher, 2011) and property generation studies (Barsalou & Wiemer-Hastings, 2005; Harpaintner et al., 2018) examining the subjective semantic content of abstract concepts. Besides verbal, emotional and introspective information, information associated with sensory and motor experiences was found to be related to all kind of concepts, regardless of their concreteness/abstractness level (Barsalou & Wiemer-Hastings, 2005). For instance, a property generation study (Harpaintner et al., 2018 321), which examined a large set of abstract concepts, yielded substantial proportions of generated verbal associations as well as social, emotional and introspective properties. However, sensorimotor properties were generated most frequently in response to abstract concepts in this study. Additional hierarchical cluster analyses indicated the existence of specific subgroups of abstract concepts characterized by the dominance of certain modal features, with one of those clusters showing a dominance of sensorimotor features. In terms of quantity, visual and motor properties played the most crucial role within the sensorimotor feature category. This indicates that abstract concepts are quite heterogeneous (see also Kiefer & Harpaintner, 2020; Muraki et al., this issue) with regard to their semantic content and cannot be contrasted as a uniform category with concrete concepts. Of course, rating and property generation studies do not indicate whether sensorimotor information related to abstract concepts is represented in corresponding modality-specific brain areas, as it is stated by grounded cognition theories (Kiefer & Pulvermüller, 2012). This information can only be provided by neuroimaging studies.

Several neuroimaging studies investigated the involvement of the modal cortex during the processing of abstract concepts (for a review see Kiefer & Harpaintner, 2020). In line with the suggested crucial role of mental states (Wilson-Mendenhall, Simmons, Martin, & Barsalou, 2013), social constellations (Wilson-Mendenhall et al., 2013) and emotions (Vigliocco et al., 2014) for the representation of abstract concepts, increased brain activity in corresponding neural networks has been found. Results of a few experiments furthermore suggest an association between

sensorimotor cortex and abstract concepts: Processing of numerical concepts (e.g., "nine", see also Glenberg, Fischer, Shaki, & Doricchi, this issue; Tschentscher, Hauk, Fischer, & Pulvermüller, 2012), abstract concepts related to mental states (e.g., "thought", Dreyer & Pulvermüller, 2018) as well as abstract emotion words (Dreyer & Pulvermüller, 2018; Moseley, Carota, Hauk, Mohr, & Pulvermüller, 2012) was associated with enhanced activity in the motor cortex. A lesion study (Dreyer et al., 2015) furthermore suggested the motor cortex to be causally involved in the processing of abstract emotion words. Processing the single abstract concept "observe" led to increased activity in auditory and visual cortices (Wilson-Mendenhall, Barrett, Simmons, & Barsalou, 2012) and even highly abstract physical concepts were associated with enhanced activity in widespread modality-specific brain areas (Mason & Just, 2016). Finally, a recent fMRI study (Harpaintner, Sim, Trumpp, Ulrich, & Kiefer, 2020) indicated that abstract concepts with either a strong motor or a strong visual feature dominance were processed in corresponding modal cortices, which were also activated by action and perception. While the processing of motor-related abstract concepts, similarly as the execution of real movements, was associated with an enhanced BOLD signal in frontal and parietal motor regions, the processing of vision-related abstract concepts specifically elicited enhanced activation in temporo-occipital visual brain areas, similarly as the observation of object pictures (see also Vergallito et al., this issue). Although a shallow lexical decision task was used in this earlier study, which did not encourage semantic elaboration or imagery, it cannot be ruled out that sensorimotor activity was driven by these kinds of strategic processes. Furthermore and most importantly, it cannot be ruled out that sensorimotor activity occurred relatively late during task performance through spreading activation, after a putatively amodal concept had been accessed (Mahon, 2015a, 2015b). However, due to the poor temporal resolution of the fMRI, the time course of feature-specific processing of abstract concepts could not be determined in this earlier study.

Due to their excellent time resolution in the range of milliseconds, event-related potentials (ERPs) are the ideal tool to track the time course of brain activity elicited by conceptual processing. As already indicated above, several ERP studies investigated the processing of some subgroups of concrete concepts (Barber, Kousta, Otten, & Vigliocco, 2010; Grisoni, Dreyer, & Pulvermüller, 2016; Hauk & Pulvermüller, 2004; Kiefer, 2001, 2005; Kiefer et al., 2008; Martin, Hauk, & Pulvermüller, 2006; Popp, Trumpp, & Kiefer, 2016; Trumpp et al., 2013a, 2014). Concrete concepts with a dominance of specific feature types elicited differential ERP effects with a distinct topography suggesting that they are generated in different brain areas. For instance, concepts with a dominance of motor features such as "hammer" were associated with more positive ERPs over the central and frontal scalp, whereas more positive occipito-parietal ERPs were found for concepts with a dominance of visual features such as "cat" (Kiefer, 2001, 2005; Proverbio, Del Zotto, & Zani, 2007). Furthermore, differential ERPs as a function of feature type started at about 150 ms after target onset (Hauk & Pulvermüller, 2004; Hoenig et al., 2008; Kiefer, Sim, Helbig, & Graf, 2011; Proverbio et al., 2007; Pulvermüller, Härle, & Hummel, 2000). The rapid onset of these ERP effects indicates that they reflect early lexico-semantic processes and not later semantic elaboration, imagery or spreading activation processes as predicted by amodal approaches (Mahon & Caramazza, 2008).

To the best of our knowledge, electrophysiological investigations of abstract concepts are predominantly limited to the comparison of concrete vs. abstract concepts (for an exception see Bechtold, Bellebaum, Egan, Tettamanti, & Ghio, 2019). In contrast to abstract concepts, concrete concepts elicited more negative scalp potentials between 300 and 500 ms after target onset (Adorni & Proverbio, 2012; Barber, Otten, Kousta, & Vigliocco, 2013). This so-called N400 concreteness effect, which has been interpreted to reflect greater integration of multimodal information for concrete than abstract concepts (Barber et al., 2013), has been observed across a broad variety of tasks and stimuli (Bechtold, Ghio, & Bellebaum, 2018), even though differential ERPs of earlier (P1—N1; Wirth et al., 2008) and later (N700; West & Holcomb, 2000) latencies have also been found (Adorni & Proverbio, 2012). However, as already indicated above, contrasting abstract concepts as an undifferentiated conceptual category with concrete concepts is questionable when taking into account the heterogeneity of abstract concepts. Also, note that the contrast abstract concepts vs. concrete concepts as a whole renders it difficult to compare the N400 concreteness effect with ERPs related to feature-specific effects described above, which are based on the comparison between different subgroups of concrete concepts (e.g., motor- vs. vision-related concrete concepts).

Abstractness does not only modulate the amplitude of particular ERP components, but also seems to affect latency of specific electrophysiological effects with later ERP effects for abstract concepts than for concrete concepts (Borghi et al., 2017): Palazova, Sommer and Schacht (2013) found a delayed emotion related early posterior negativity effect (EPN), an effect believed to reflect attention shifting to word meaning, for abstract than for concrete verbs of different valence in a lexical decision task. Bardolph and Coulson (2014) presented their participants words literally or metaphorically associated with vertical space (literal: ascend, descend; metaphorical: victory, poverty) while moving marbles either up- or downwards. They found early (200–300 ms after word onset) ERP congruency effects for literal words, while metaphorically related

words elicited ERP congruency effects only 500 ms after word onset indicating that participants integrated abstract concepts and spatial schemas but, compared to concrete concepts, not in a rapid manner (Borghi et al., 2017). Some researchers considered the differential ERPs as an indication that abstract and concrete concepts are processed in different neural systems (Dove, 2011).

Furthermore, the later emergence of ERP effects in abstract than in concrete concepts has been interpreted to reflect mental imagery instead of lexico-semantic processes (Adorni & Proverbio, 2012; Barber et al., 2013; Bechtold et al., 2018; Borghi et al., 2017). As outlined above, it has been argued that late effects, presumably indexing post-conceptual imagery processes (Machery, 2007), do not preclude the existence of amodal conceptual representations, which are accessed earlier. For that reason, only demonstration of early sensorimotor activity during a conceptual task, reflecting access to conceptual representations rather than post-conceptual processes, can be taken as unequivocal evidence for grounded cognition theories (Kiefer & Pulvermüller, 2012). Returning to the ERPs just mentioned, however, results are heterogeneous (Adorni & Proverbio, 2012) with some studies indicating early ERP effects in the time window of P1–N1 for abstract concepts, speaking against late mental imagery processes (Wirth et al., 2008). Additionally, previous ERP studies simply contrasted abstract with concrete concepts and did not differentiate between possible conceptual subgroups of abstract concepts. As outlined above, rating (Binder et al., 2016; Lynott & Connell, 2009, 2013; Troche et al., 2014, 2017; van Dantzig et al., 2011) and property generation (Barsalou & Wiemer-Hastings, 2005; Harpaintner et al., 2018) studies suggest subgroups of abstract concepts with a differential conceptual feature composition. In line with this reasoning, our recent fMRI study showed that abstract concepts with an empirically defined dominance of visual vs. motor features activated corresponding modal cortex (Harpaintner et al., 2020).

In the present ERP study, we therefore systematically investigated the time course of abstract noun processing. We adopted the theory-driven approach and the stimuli from our previous fMRI study (Harpaintner et al., 2020) and compared electrophysiological responses to specific subgroups of abstract concepts with a known feature composition. Stimuli were motor- and vision-related abstract concepts as determined by a previous property listing study (Harpaintner et al., 2018), in which motor and visual features were generated the most. Based on this property listing study, 32 abstract words highly related to motor properties (e.g., "fitness") and 32 abstract words highly related to visual properties (e.g., "similarity") were selected. Please note, that for better readability, these two word lists are called motor and visual abstract concepts from now on, respectively.

This study aimed to address three specific research questions: Firstly, we asked whether feature-specific ERP effects for motor and visual abstract concepts would be similarly observed as for concrete concepts. Secondly, as amodal theories attribute sensorimotor activation to later post-conceptual imagery, elaborative or spreading activation processes, we assessed whether possible differential ERP effects would emerge in early (between 150 and 300 ms) or in later time windows. Visual word recognition is completed at about 150 ms after word onset (Pulvermüller, Shtyrov, & Ilmoniemi, 2005b), and full access to a concept is assumed to be mandatory for imagery (Kosslyn, 1994). For that reason, ERP effects observed immediately after 150 ms most likely reflect semantic access and not imagery. Thirdly, we tested whether processing of abstract concepts is prone to conceptual flexibility and assessed whether a deep conceptual task leads to earlier feature-specific ERP effects compared to a shallow conceptual task, similar to observations in concrete concepts. In a deep conceptual task, retrieval of conceptual information is mandatory for task performance, for instance, when the semantic relatedness of two words has to be determined (Simmons, Hamann, Harenski, Hu, & Barsalou, 2008). In contrast, in a shallow conceptual task, retrieval of conceptual knowledge is not necessary for task performance, but occurs through associative links. For instance, visual word recognition in a lexical decision task (word/pseudoword decision) primarily depends on retrieval of lexical information, whereas access to conceptual information is assumed to occur auxiliary (Dilkina, McClelland, & Plaut, 2010).

In the first experiment, motor and visual abstract concepts, besides pseudowords, were presented within a shallow lexical decision task with a go/no-go response mode, in which retrieval of conceptual knowledge is not necessary for task performance, but occurs through associative links (Simmons et al., 2008). Furthermore, since the go/no-go response mode did not require an overt motor response in case of the critical word stimuli, interference with conceptual processing in the motor system was avoided (Schomers & Pulvermüller, 2016). In the second experiment, participants had to perform a deep conceptual decision task, in which the semantic relation between a context word and subsequent motor and visual abstract concepts had to be determined. Note that the tasks as realized in Experiments 1 and 2 do not only differ with regard to the mandatory requirement of semantic retrieval, but also with regard to the response mode (go/no-go response mode vs. two alternative forced choice) and relational processing (single word vs. relational word processing). Nevertheless, all these factors converge on the fact that deeper semantic processing is required in the conceptual decision task of Experiment 2 compared to the lexical decision task of Experiment 1. In both experiments, we expected different scalp potentials in response to motor

and visual abstract concepts. Similar to previous observations on concrete concepts, motor abstract concepts should elicit more positive ERPs over the fronto-central scalp, whereas visual abstract concepts should be associated with more positive ERPs over the occipito-temporal scalp. Furthermore, the onset of feature-specific ERP effects should be modulated by task with earlier feature-specific ERP effects in the deep conceptual decision task as compared to the shallow lexical decision task, because this type of task demands retrieval of conceptual information (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008). In line with the grounded cognition framework, early ERP effects within 150–300 ms after target onset in response to motor and visual abstract concepts would suggest that feature-specific brain activity reflects rapid access to sensorimotor features and not later post-conceptual processes.

Experiment 1

Methods

Participants

Twenty-nine healthy, right-handed (according to Oldfield, 1971) native German-speaking students from Ulm University participated in the study. Six participants were excluded from the analysis due to excessive artifacts in the EEG recording. Final analysis included electrophysiological data of 23 participants (M_{age} = 22.7 years, range = 18–27 years, 12 females). Participants had normal or corrected-to-normal vision, were free from a history of neurological or psychiatric disorders and did not participate in a previous study of our laboratory using the same stimuli/procedure. Participants gave written informed consent and were paid 24 Euros or course credits for participation. Procedures for Experiments 1 and 2 were approved by the Ethical Committee of Ulm University and adhere to the tenets of the Declaration of Helsinki.

Stimuli

Sixty-four abstract words (see Online Resource 1 for the full set of verbal stimuli) served as critical stimuli in the lexical decision task with a go/no-go response mode. Additional 32 pseudowords (go trials) served as distractors and were not further analyzed. The same verbal stimuli have been used and described in detail in a previous study (Harpaintner et al., 2020). Critical abstract words were embedded as no-go trials and were thus presented without interference from a motor response. Half of those abstract words (32 words) had a strong link to motor properties, whereas the other half had a strong link to visual conceptual properties, as determined on the basis of a previous study (Harpaintner et al., 2018). In this study, participants (not participating in the present study) had to generate properties for 296 abstract concepts, which were subsequently categorized according to modality-specific and verbal contents (for further details see Harpaintner et al., 2018). At least 15% of properties that have been coded as motor or visual had to be generated with regard to the respective abstract concept in order to be assigned to the motor or visual abstract subcategory, respectively. Note that a proportion of 15% modality-specific properties exceeded the mean proportions of motor (M = 13.1%) and visual (M = 14.8%) properties generated for all 296 concepts in our previous study. Furthermore, the difference of generated motor and visual properties of each word had to be at least 10% in order to achieve a substantial difference in the conceptual feature dominance of the two subcategories.

The chosen motor (M_{motor} = 31.60%, M_{visual} = 8.97%; e.g., "fitness") and visual (M_{visual} = 30.18%, M_{motor} = 6.49%; e.g., "beauty") abstract concepts were carefully matched with regard to possible confounding conceptual features (proportion of generated acoustic features, valence, arousal, concreteness/abstractness, familiarity) and psycholinguistic variables (word length, lemma frequency, bigram and trigram frequency; Table 1; for further details see Harpaintner et al., 2020; Harpaintner et al., 2018). Additionally, a previous pilot study (Harpaintner et al., 2020), which used a classical lexical decision task and thus made behavioral data available for pseudowords as well as for motor and visual abstract concepts, confirmed comparable task difficulty for motor and visual abstract concepts, as measured by reaction times (M_{motor} = 578.60 ms, M_{visual} = 566.91 ms, p = 0.78) and error rates (M_{motor} = 0.50%, M_{visual} = 0.42%, p = 1.00). Note that we did not match the number of derived words across the two conditions (n_{motor} = 25 vs. n_{visual} = 18). However, when tested with help of a χ^2-test, there was no significant difference in the distribution of derived words between motor and visual abstract words ($\chi^2(1) = 3.47$, p = 0.062). Possible confounding influences related to differential numbers of derived words between the conditions on ERPs were therefore unlikely.

Thirty-two pseudowords were created by replacing one consonant and one vowel of abstract concepts not used in the experimental conditions by another consonant and vowel. Pseudowords thus consisted of meaningless but pronounceable letter strings (e.g., "Antordirung"). Pseudowords and words of the experimental conditions did not differ with regard to their word length (M_{motor} = 8.19, M_{visual} = 7.88, M_{pseudo} = 7.94, $F(2,93) = 0.168$, p = 0.85).

Procedure

Participants were seated in front of a CRT computer screen synchronous with the screen refresh (refresh rate: 16 ms)

Table 1 Mean values and standard deviation (in parenthesis) of conceptual and psycholinguistic variables for motor and visual abstract concepts

	Motor abstract concepts	Visual abstract concepts	Motor vs. visual (p-values)[a]
Proportion motor properties	0.32 (0.12)	0.06 (0.04)	$p < .001$
Proportion visual properties	0.09 (0.06)	0.30 (0.09)	$p < .001$
Proportion acoustic properties	0.03 (0.04)	0.04 (0.05)	$p = .536$
Concreteness/abstractness[b]	2.65 (0.61)	2.49 (0.53)	$p = .276$
Familiarity[b]	4.18 (0.67)	4.07 (0.57)	$p = .454$
Valence[b]	0.51 (1.83)	0.26 (1.87)	$p = .582$
Arousal[b]	2.74 (0.78)	2.62 (0.95)	$p = .561$
Word length	8.19 (2.58)	7.88 (2.06)	$p = .595$
Lemma frequency p. Mio	63.14 (91.72)	38.21 (45.17)	$p = .173$
Character bigram frequency p. Mio	652,936.87 (379,468.24)	631,388.19 (278,144.87)	$p = .796$
Character trigram frequency p. Mio	229,175.80 (124,964.62)	218,018.45 (103,100.90)	$p = .698$

[a]Depicted p-values were obtained using two-tailed t-tests

[b]Scales of the items: concreteness/abstractness: six-point Likert scale with the poles "abstract" (1) and "concrete" (6); familiarity: six-point Likert scale with the poles "low familiarity" (1) and "high familiarity" (6); valence: six-point Likert scale with the poles "negative" (-3) and "positive" (+3); arousal: self-assessment manikins (Bradley & Lang, 1994) with the poles "weak" (1) and "strong" (5)

at a distance of 70 cm resulting in a viewing angle subtending about 3° horizontally and 1° vertically. Words were presented in a randomized order as white letters (font size: 16 point character height) on a black background in the middle of the screen. Each trial started with a fixation cross of 500 ms duration followed by the target lasting for 400 ms. Participants had to decide whether the presented stimulus is a real German word or a pseudoword. A pseudoword indicated a go trial, and participants were instructed to press a button on the response keyboard with the index finger of their right hand. If the stimulus was a real German word, participants should passively read the word, but were instructed not to react (no-go trial). The assignment of abstract words to the no-go condition prevented an overt motor activity to the critical word stimuli. Participants were instructed to decide as fast and accurately as possible. The screen remained blank until a response was given or for 1400 ms in case of a no-go trial or a missed response, respectively. At the end of each trial, three hash marks lasting for 2000 ms indicated a pause between the trials. Stimulus presentation and behavioral data acquisition were controlled by the Experimental Runtime System software package (Berisoft, Frankfurt, Germany). A training with 20 stimuli not used in the main experiment preceded the experimental session.

EEG-recording, signal extraction, data analysis

The study was carried out in a sound attenuated, dimly illuminated and electrically shielded cabin. Participants were comfortably seated in an upright position and were instructed via detailed written and verbal instructions. To ensure complete understanding of the instructions, participants had to practice the task in a training session preceding the main experiment as indicated above. Participants were furthermore encouraged to blink only during the breaks and to stay relaxed during the whole EEG recordings in order to avoid ocular and movement artifacts.

Scalp voltages were continuously recorded at a sampling rate of 500 Hz (low-pass filter: 70 Hz, 24 dB/octave attenuation, 50 Hz notch filter) by BrainAmp amplifiers and BrainVision Recorder software (BrainProducts, Gilching, Germany) using 64 equidistant Ag/AgCl electrodes mounted in an elastic textile cap (EasyCap, Herrsching, Germany) with a cap size determined by the subjects' head circumference (52, 54, 56, 58, or 60 cm). An electrode between FCz and Cz was used as recording reference; the ground electrode was positioned between AFz and Fz. Eye movements were monitored with supra- and infra-orbital electrodes and with electrodes on the external canthi. All EEG electrode impedances were maintained below 5 kΩ.

EEG data were processed offline by BrainVision Analyzer 2.0 (BrainProducts, Gilching, Germany). After digitally filtering (high pass: 0.1 Hz, 12 dB/octave, low pass: 30 Hz, 24 dB/octave, 50 Hz notch filter) the EEG data, Independent Component Analysis (ICA) was used to remove ocular artifacts (Makeig, Jung, Bell, Ghahremani, & Sejnowski, 1997). Hjorth nearest neighbors interpolation replaced data of single noisy electrodes by interpolated data of four surrounding electrodes. Continuous EEG data were segmented starting 150 ms prior to target presentation, which served for baseline correction, and ended 1000 ms after target onset. Segments exhibiting amplitudes of more than 70 µV or less than -70 µV, showing voltage steps greater than 50 µV/ms and exhibiting 120 µV differences of values in intervals,

Table 2 Results of cluster permutation tests of Experiment 1

Polarity	Cluster[a]	Electrodes within cluster	Time window (ms)	*p*-value
Motor > visual	1	FCz, FC1, CP1, Cz, CP4, C4, FC2, CP2	280–348	< .005
	2	C3, FC3, F1, Fz, FCz, FC1, CP1, Cz, F2, FC2	470–504	< .05
	3	F9, FT9, FT7, AF7, FPz, AFz, AF3, F5, FC5, F1, Fz, AF4	506–564	< .05
	4	F9, FT9, FT7, AF7, FC5, FC3, F1, FCz	606–684	< .05
Visual > motor	5	F10, FT10, T8, FT8, AF8, FP2, AF4, F6, FC6	178–270	< .005
	6	TP10, P10, O10, Iz, O2, P8, TP8	464–516	< .05
	7	O1, P7, PO3, PO1, P1, Oz, Pz	516–554	< .05
	8	O1, P7, TP7, PO3, PO1, P1, Pz	622–666	< .05

[a]Reported clusters were sorted by polarity and ordered by time window (early → late)

were automatically excluded as artifacts from analyses. The remaining artifact-free EEG segments of trials with correct responses were averaged synchronous to the onset of the target separately for each experimental condition in each participant in order to extract individual ERPs. Thereafter, these ERPs were re-referenced to the average reference (Bertrand, Perrin, & Pernier, 1985).

To test for significant differences between conditions across all electrode sites and the whole ERP time window, statistical analyses were performed using BESA Statistics 2.0 (BESA GmbH, Graefelfing, Germany). To avoid the problem of multiple comparisons due to a large number of time points and channels, BESA statistics makes use of a combination of permutation testing and data clustering (Ernst, 2004; Maris & Oostenveld, 2007). In order to exclude post-lexical semantic processes, analyses focused on effects prior to 800 ms after target onset. The initial statistics used for the subsequent permutations were based on two-tailed paired samples *t*-tests comparing ERP data in response to motor vs. visual abstract concepts. A cluster value consisting of the sum of all *t*-values derived from a random permutation procedure (1000 permutations) was determined for each cluster such that the significance of the initial clusters could be determined based on the distribution of the calculated cluster values after permutation. Level of significance was defined as $p < 0.05$, corrected for multiple comparisons. The mean number of artifact-free EEG segments of trials with correct responses was 31.51 ($SD = 0.66$) for motor and 31.56 ($SD = 0.92$) for visual abstract concepts. A two-tailed paired samples *t*-test confirmed that the number of segments did not significantly differ between conditions ($t(22) = -0.24$, $p = 0.81$).

Because of the go/no-go design of the lexical decision task, in which participants reacted only to the theoretically irrelevant pseudowords, analysis of behavioral data in form of reaction times (RTs) were not informative. However, mean error rates (ERs) were calculated for each participant and each condition (motor, visual, pseudo). Subsequent univariate repeated measures analyses of variance (ANOVA) were carried out in order to investigate whether error rates differed significantly between the conditions. Level of significance was defined as $p < 0.05$.

Results

Behavioral data

Analysis of behavioral data yielded a mean ER of 1.27% ($SD = 1.44\%$) showing that participants performed the task carefully. Participants failed to respond to pseudowords in 1.22% of the trials ($SD = 2.05\%$). ER in word trials (failure to withhold response) was 1.36% for motor abstract concepts ($SD = 1.84\%$) and 1.22% for visual abstract concepts ($SD = 2.79\%$). A univariate repeated measures ANOVA revealed no significant differences in mean ERs between motor and visual abstract concepts and pseudowords, respectively ($F(2,44) = 0.03$, $p = 0.97$).

Electrophysiological data

Cluster permutation tests revealed significant differences between the processing of motor vs. visual abstract concepts in eight clusters (Table 2, Figs. 1, 2).

Four fronto-centrally located clusters were characterized by more positive scalp potentials in response to motor vs. visual abstract concepts (Fig. 1): Clusters 1 and 2 comprised overlapping fronto-central electrodes in the time windows from 280 to 348 ms and from 470 to 504 ms. Cluster 3 and 4 were more lateralized to the left hemisphere and encompassed mostly frontal electrodes in the time windows 506 to 564 ms and 606 to 684 ms, respectively.

Similarly, four clusters were characterized by more positive scalp potentials in response to visual vs. motor abstract concepts (Fig. 2): The earliest cluster, Cluster 5, showed significant differences in right fronto-temporal electrodes between 178 and 270 ms. The three remaining clusters were located more occipitally, with Cluster 7 (516–554 ms) and

8 (622–666 ms) being distributed over the left hemisphere and Cluster 6 (464–516 ms) being distributed over the right hemisphere, respectively.

Discussion

Experiment 1 showed differential feature-specific ERP effects in response to motor and visual abstract concepts in a shallow lexical decision task. Motor abstract concepts were related to significantly more positive potentials over frontal and central scalp regions, whereas the processing of visual abstract concepts was specifically associated with more positive scalp potentials over parieto-occipital as well as over right fronto-temporal scalp regions. ERP-effects began to emerge at 178 ms after target presentation. However, later effects beyond 300 ms were also observed.

In spite of the shallow nature of the lexical decision task, we found early feature-specific ERP effects in the present study. This contrasts studies which suggest a diminution or a disappearance of differential effects when using shallow tasks (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008). The early emergence of feature-specific scalp potentials indicates that effects reflect rapid access of motor and visual information. At the same time, post-conceptual processes such as imagery, semantic elaboration or spreading activation might also take place after this initial conceptual access, as indicated by the relatively late differential ERPs.

The time course, the polarity as well as the topography of the differential ERP effects parallel results from earlier studies, which examined the processing of concrete concepts (Kiefer, 2001, 2005; Sim & Kiefer, 2005; Trumpp et al., 2014). These findings indicated that the processing of concrete motor concepts is associated with more positive potentials in fronto-central scalp regions (Hauk & Pulvermüller, 2004; Kiefer, 2001, 2005; Popp et al., 2016; Pulvermüller, Lutzenberger, & Preissl, 1999; Pulvermüller, Preissl, Lutzenberger, & Birbaumer, 1996; Trumpp et al., 2014), whereas the processing of concrete visual concepts was related to significantly more positive ERPs in temporal and occipital scalp regions (Kiefer, 2001, 2005; Martin et al., 2006; Pulvermüller et al., 1999, 1996; Sim & Kiefer, 2005). However, in contrast to earlier findings within the concrete concept class, we found feature-specific ERPs in response to visual abstract concepts also in right fronto-temporal electrodes of Cluster 5. This difference might be due to differential conceptual representations of the two concept classes (concrete vs. abstract) or might reflect interindividual differences in neuroanatomy of different samples. Moreover, although care must be taken with regard to EEG and spatial localization, the source of the fronto-temporal electrode cluster may be located in the anterior part of the fusiform gyrus, as it already has been indicated by a previous fMRI study (Harpaintner et al., 2020). Furthermore, it cannot be ruled out that the source of the ERPs is located in the temporal pole, a prominent candidate for a hub region (Patterson et al., 2007), although the previous fMRI study using the same stimulus material did not observe differential activity in this region. Note that we did not perform source analyses because of the low signal-to-noise-ratio in the context of the relatively small ERPs in the present study and because our primary focus was the neural time course of abstract concept processing. Focusing that, our results suggest that differential ERP effects in response to motor and visual abstract concepts emerge 178 ms after target presentation indicating rapid access of modal features during conceptual processing. However, later feature-specific effects beyond 300 ms might reflect post-conceptual processes as already outlined above. At this point, we want to highlight the fact that the clusters showing the most significant differences between the processing of motor and visual abstract concepts are the clusters, in which differential effects emerge prior to 300 ms after target onset, further supporting the idea that the results reflect early semantic access to motor and visual information.

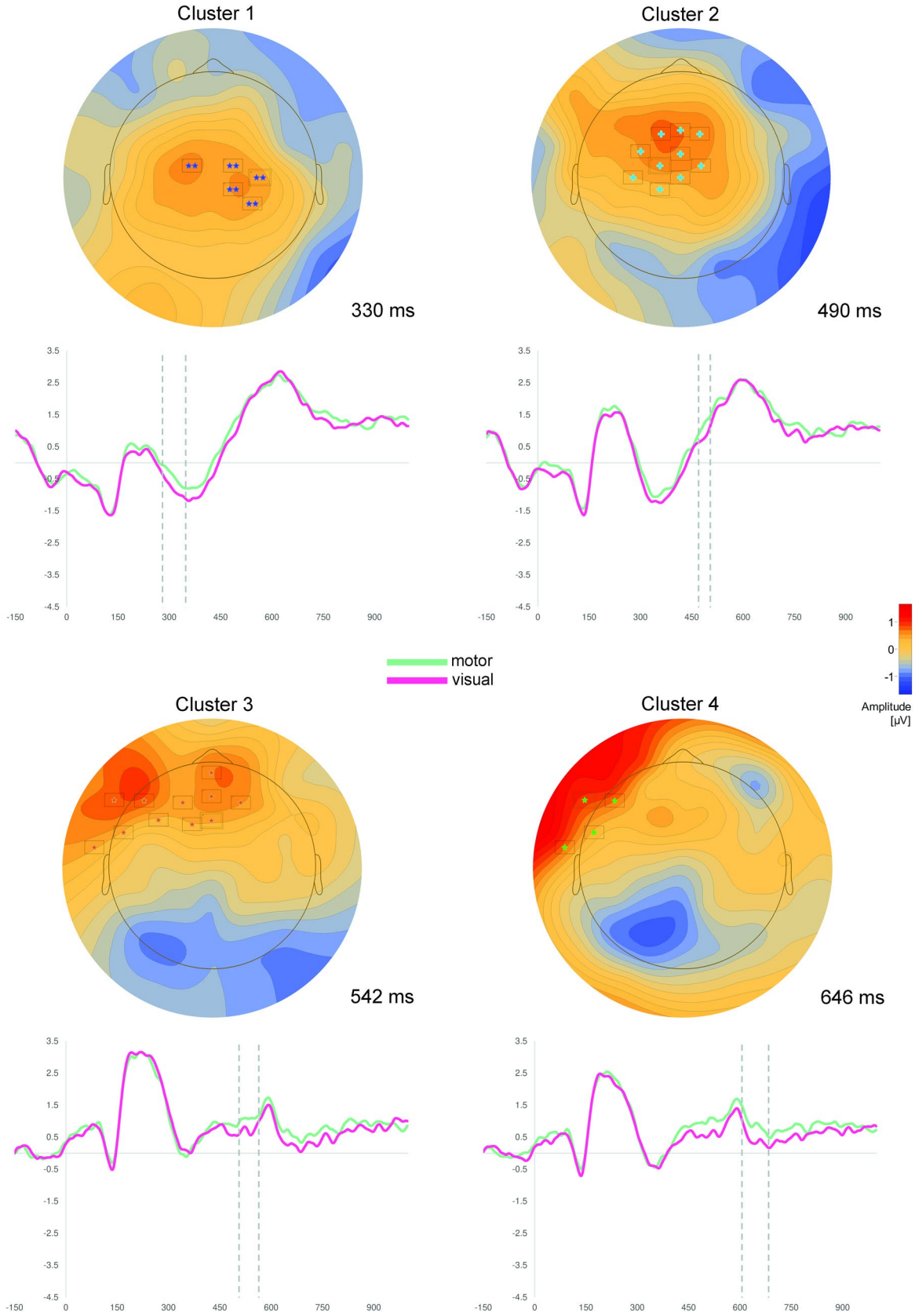
Experiment 2

In contrast to the first experiment, participants of Experiment 2 were asked to perform a deep conceptual decision task, in which the semantic relation between a context word and subsequent motor and visual abstract concepts had to be determined. We expected that feature-specific processing would be boosted during a deep conceptual decision task, which demands retrieval of conceptual information. This task-dependent modulation should be evident by earlier feature-specific ERPs in the deep task as compared to the shallow lexical decision task (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008).

Methods

Participants

Thirty-three native German-speaking undergraduate students from Ulm University participated in Experiment 2. Participants were healthy, right-handed (Oldfield, 1971) and had normal or corrected-to-normal vision. None of them reported a history of neurological or psychiatric disorders. Again, participants did not take part in a previous study of our laboratory using the same stimuli/procedure. Due to excessive artifacts in the EEG recordings, five participants were excluded from the EEG analysis. Final EEG analysis thus included data of 28 (M_{age} = 23.4 years, range = 19–29 years, 14 females) participants. Analyses of


Cluster 1
330 ms
Cluster 2
490 ms
motor
visual
Amplitude [μV]
Cluster 3
542 ms
Cluster 4
646 ms

◂**Fig. 1** Results of cluster permutation tests of Experiment 1. Depicted are clusters, which show significantly more positive scalp potentials for motor compared to visual abstract concepts. Above: Topographic map of each cluster at the time point of the highest *t*-value across all electrodes. Only electrodes with significant *t*-values ($p < .05$) at the specific time point are depicted (for all electrodes see Table 2). Below: ERPs averaged over all electrodes of the respective cluster. Dotted lines indicate the significant time window of the cluster

behavioral data included only 27 participants, because the data of one participant got lost due to a technical error. Participants gave written informed consent and were paid 17 Euros or course credits for participation.

Stimuli

The same 32 motor and 32 visual abstract concepts of Experiment 1 were used as stimuli for Experiment 2. Additional 64 abstract concepts (see Online Resource 2 for the full set of verbal stimuli) of our previous property listing study (Harpaintner et al., 2018) characterized by a low portion of generated motor and visual properties (e.g., "thirst"; $M_{motor/visual} < 12\%$) served as filler words (not further analyzed). For each motor and visual abstract concept, we selected a semantically related concrete context noun (matching condition; e.g., "bride–beauty"), and for every filler word we determined a semantically unrelated context noun (non-matching condition; e.g., "candle–thirst"), respectively. Thus, all critical motor and visual abstract words were presented in the contextual matching condition. Context words were chosen out of four concrete word categories: action (e.g., "sailing"), location (e.g., "store"), object (e.g., "candle") and person (e.g., "bride"). Context words were matched across conditions with regard to the respective word category and their word length. Furthermore, word length of motor and visual abstract words as well as the filler words was matched.

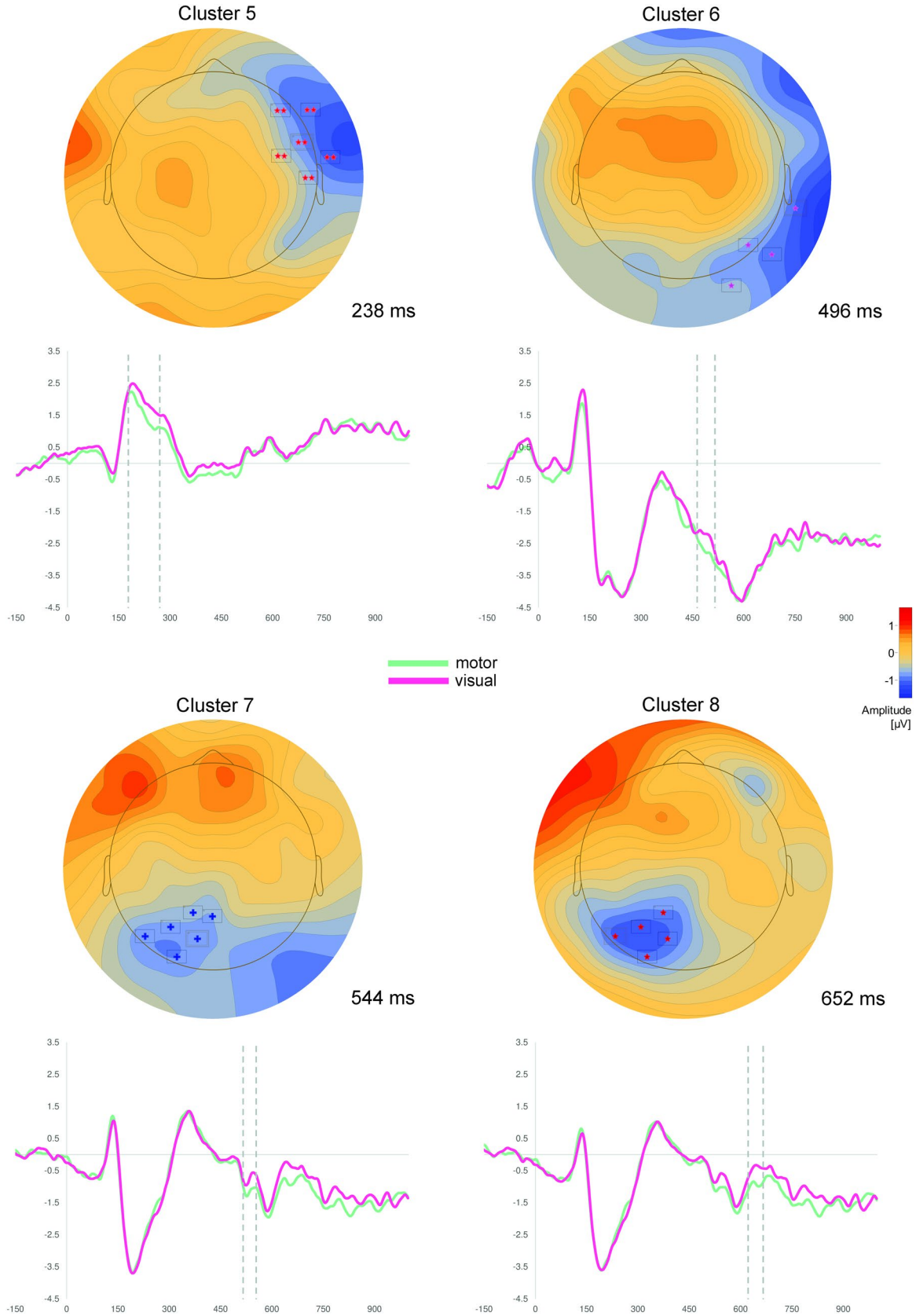
In order to test whether relatedness between context and abstract words differs significantly between visual and motor words, we quantified relatedness by performing a Latent Semantic Analysis (LSA; for further details see Günther, Dudschig, & Kaup, 2015) with the help of the R package "LSAfun" (Günther & Günther, 2018). The LSA uses linguistic co-occurrences based on large corpora and assesses the degree of the occurrence of words in similar contexts (Landauer & Dumais, 1997). Note that we were not able to obtain cosines based on the used corpora ("dewak.100 k. lsa.rda")[1] for five/three of the word pairs in the motor/visual condition, respectively. Comparing the cosines of the remaining word pairs with help of Welch's two sample *t*-test yielded no significant differences between the motor ($M = 0.32$, $SD = 0.20$) and visual ($M = 0.38$, $SD = 0.16$) conditions ($t(50.43) = -1.11$, $p = 0.27$) indicating that the two critical lists of word pairs were comparable with regard to relatedness. Possible confounding influences related to differential degrees of relatedness between the conditions on ERPs were therefore unlikely.

A pilot study with ten participants (not participating in the present study) using the same conceptual decision task as the main experiment (see procedure) and the subsequent univariate repeated measures ANOVA (motor vs. visual vs. filler) yielded significant differences in mean RTs between the conditions ($F(2, 18) = 6.28$, $p < 0.05$). According to a *post hoc* test (Bonferroni test), this difference was due to slower reaction times in response to filler words ($M = 740.50$ ms) as compared to visual abstract concepts ($M = 693.75$ ms, $p < 0.05$). Importantly, mean RTs in response to motor ($M = 713.42$ ms) and visual abstract concepts did not differ significantly ($p = 0.47$). A further ANOVA yielded no significant differences with regard to mean ERs between the conditions ($F(2, 18) = 1.70$, $p = 0.21$). Results thus confirmed that the critical conditions (motor vs. visual abstract concepts) were comparable with regard to their difficulty as measured by RTs and ERs. Note that the absence of significant differences in mean RTs and ERs further supports the claim that relatedness of the context words and the critical abstract words did not differ between the conditions.

Procedure

Experiment 2 was designed as a deep conceptual decision task, in which 64 critical motor and visual abstract words as well as 64 abstract filler words paired with 64 matching and 64 non-matching context nouns, respectively, were presented to the participants. The total number of 128 trials was randomly presented in four blocks of 32 trials each, separated by breaks. Words were presented as white letters (font size: 16 point character height) on a black background in the middle of the screen (viewing angle about 3° horizontally and 1°vertically). Each trial started with a fixation cross of 500 ms duration followed by the context noun lasting for 400 ms. After a clear screen of 500 ms, the abstract target word was presented for 400 ms. Participants had to decide as fast and accurately as possible whether the two words were semantically related or not, and were instructed to press a key with their right index finger in case of related word pairs and another key with their right middle finger in case of unrelated word pairs, respectively. The assignment of the conditions to reactions with the right index or middle finger was counterbalanced. The screen remained blank until a response was given. After another clear screen lasting for 500 ms, three hash marks lasting for 500 ms indicated

[1] Obtained from the University of Tübingen. Freely available under https://www.lingexp.uni-tuebingen.de/z2/LSAspaces/


Cluster 5
238 ms
Cluster 6
496 ms
motor
visual
Amplitude [μV]
Cluster 7
544 ms
Cluster 8
652 ms

◂**Fig. 2** Results of cluster permutation tests of Experiment 1. Depicted are clusters, which show significantly more positive scalp potentials for visual compared to motor abstract concepts. Above: Topographic map of each cluster at the time point of the highest *t*-value across all electrodes. Only electrodes with significant *t*-values ($p < .05$) at the specific time point are depicted (for all electrodes see Table 2). Below: ERPs averaged over all electrodes of the respective cluster. Dotted lines indicate the significant time window of the cluster

a pause between the trials. A training with 12 word pairs not used in the main experiment preceded the experimental session.

EEG recording, signal extraction, data analysis

EEG data regarding the two critical conditions (motor and visual abstract concepts) were recorded and analyzed similarly as described in Experiment 1. Again, the number of artifact-free EEG segments did not differ significantly between motor ($M = 28.07$, $SD = 2.33$) and visual ($M = 28.96$, $SD = 1.77$) abstract concepts ($t(27) = 1.60$, $p = 0.12$).

Behavioral data, RTs and ERs, were analyzed using Statistica 13.1 (StatSoft, Tulsa, USA). For RT analysis, only trials with correct conceptual decisions were included. Outlier trials (± 2 *SD*) were excluded from the RT analysis. Individual mean RTs and ERs in response to motor, visual and filler abstract words were compared using repeated measures of analyses of variance (ANOVA). Level of significance was defined as $p < 0.05$.

Results

Behavioral data

Mean ER of the deep conceptual decision task was 5.79% ($SD = 2.56\%$), which shows that participants performed the task carefully. A univariate repeated measures ANOVA revealed significant differences in mean ER between motor and visual abstract concepts and filler words, respectively ($F(2, 52) = 8.97$, $p < 0.001$). According to a *post hoc* test (Bonferroni test), this difference was due to lower ERs in response to filler words ($M = 3.41\%$, $SD = 2.91\%$) as compared to motor ($M = 9.26\%$, $SD = 6.85$, $p < 0.001$) and visual ($M = 7.06$, $SD = 4.71$, $p < 0.05$) abstract concepts. Importantly, ERs did not differ significantly between motor and visual abstract concepts ($p = 0.36$).

A further univariate repeated measures ANOVA revealed a similar pattern with regard to mean RTs. Significant differences between the conditions were found ($F(2, 52) = 16.79$, $p < 0.001$), but again, a *post hoc* test (Bonferroni test) revealed that differences were due to slower RTs in response to filler words ($M = 884.89$ ms, $SD = 208.46$ ms) as compared to motor ($M = 827.27$ ms, $SD = 151.99$ ms, $p < 0.001$) and visual ($M = 805.48$ ms, $SD = 149.23$ ms, $p < 0.001$) abstract concepts. Mean RTs in response to motor vs. visual abstract concepts did not differ significantly ($p = 0.39$).

Electrophysiological data

Cluster permutation tests revealed significant differences between the processing of motor vs. visual abstract concepts in five clusters (Table 3, Figs. 3, 4).

Cluster A, which encompassed mostly frontal electrodes in the time window between 72 and 146 ms, and Cluster B, which was fronto-centrally located in the time window from 644 to 746 ms, were characterized by more positive scalp potentials in response to motor vs. visual abstract concepts.

The reversed polarity effect (visual > motor) was found in three clusters located more posteriorly and more lateralized to the left hemisphere: Cluster C and D showed overlapping temporo-parietal electrodes in the time windows from 22 to 94 ms and from 256 to 316 ms, while Cluster E encompassed more occipitally located electrodes between 464 and 802 ms.

Discussion

Processing of motor and visual abstract concepts within a deep conceptual decision task in Experiment 2 again yielded differential feature-specific ERP effects. However, unlike in Experiment 1, ERP effects already emerged at about 22 ms after target presentation. Motor abstract concepts were specifically associated with significantly more positive potentials in fronto-(central) clusters, whereas the processing of visual abstract concepts was specifically related to more positive scalp potentials in temporo-parietal and occipital electrode clusters.

Results of Experiment 2 mostly parallel results of Experiment 1, even though feature-specific ERP effects emerged earlier in Experiment 2 than in Experiment 1. The very early emergence of differential effects in Cluster C 22 ms after target presentation might reflect priming processes, in which the preceding context word preactivates certain abstract concepts leading to fast access to modal information during processing of the abstract target concept. Furthermore, this earlier onset of feature-specific effects is in line with previous work on concrete concepts demonstrating earlier feature-specific activity in modality-specific brain regions during deep conceptual tasks (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008). This early onset further suggests that visual and motor information is rapidly accessed during conceptual processing. However, since other clusters (in particular clusters B and E) covered protracted and therefore also late periods, semantic elaboration, imagery or spreading

Table 3 Results of cluster permutation tests for Experiment 2

Polarity	Cluster[a]	Electrodes within cluster	Time window	*p*-value
Motor > visual	A	AF7, FP1, FPz, AFz, AF3, F5, FP2, AF4, Nz	72–146 ms	< .01
	B	FP1, FPz, AFz, AF3, F1, Fz, FCz, F10, T8, FT8, AF8, FP2, AF4, F6, FC6, FC4, F2, FC2, Nz	644–746 ms	< .005
Visual > motor	C	TP9, P7, TP7, T7, FT7, FC5, C5, P5, PO3, CP3, C3, FC3, FCz, FC1, CP1, Cz, FC2, CP2	22–94 ms	< .005
	D	P7, TP7, C5, P5, PO3, P1, CP3	256–316 ms	< .05
	E	TP9, P9, O9, O1, P7, TP7, C5, P5, PO3, PO1, P1, CP3, CP1, Iz, Oz, O2, PO4, PO2, Pz, P2, CPz	464–802 ms	< .005

[a]Reported clusters were sorted by polarity and ordered by time window (early → late)

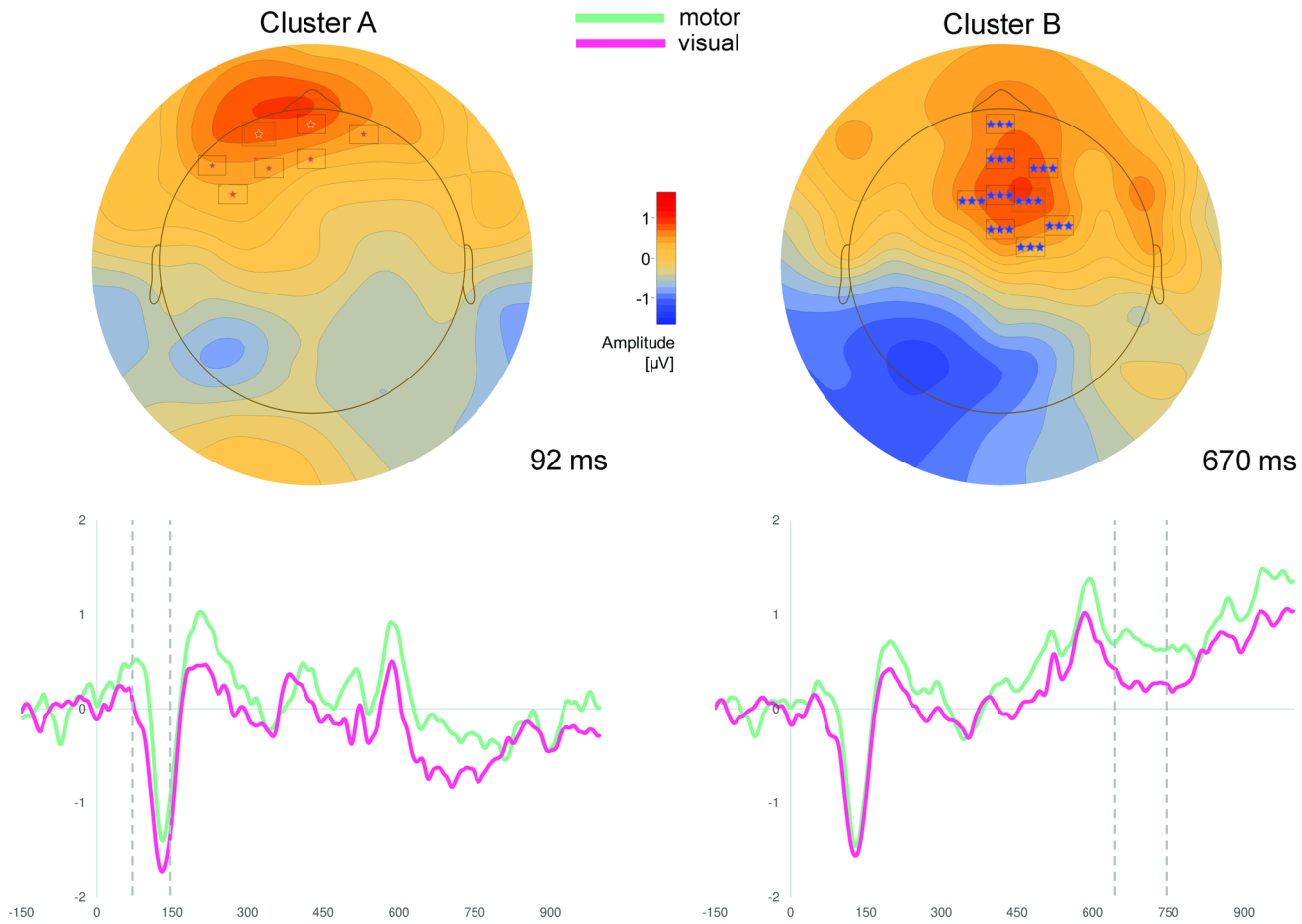


Fig. 3 Results of cluster permutation tests of Experiment 2. Depicted are clusters, which show significantly more positive scalp potentials for motor compared to visual abstract concepts. Above: Topographic map of each cluster at the time point of the highest *t*-value across all electrodes. Only electrodes with significant *t*-values ($p < .05$) at the specific time point are depicted (for all electrodes see Table 3). Below: ERPs averaged over all electrodes of the respective cluster. Dotted lines indicate the significant time window of the cluster

activation processes might also take place, after initial conceptual access.

Regarding the present topographic pattern, the deep conceptual decision task seems to shift effects toward the right hemisphere leading to more lateralized ERP effects in Cluster B as compared to those of Experiment 1. Comparing Cluster 1 of Experiment 1 and Cluster A of Experiment 2, which both reflect relatively early motor feature effects, Cluster A (Experiment 2) primarily includes left frontal electrodes. The deep conceptual decision task seems to shift early motor feature effects toward the left frontal scalp as seen in Cluster A, while later effects of Experiment 1 were found at more centrally located electrodes as seen in Cluster 1. Different locations of Clusters A and 1 might be the result

of different neural generators within the motor cortex with Cluster A being related to more left lateralized premotor regions compared to Cluster 1. However, as already indicated above, care must be taken with regard to the localizational value of EEG data rendering the latter considerations highly speculative. Beyond that, as in Experiment 1, the polarity, topography as well as the time course of differential ERP effects of Experiment 2 are comparable to those of earlier studies examining the processing of concrete concepts (Kiefer, 2001, 2005; Martin et al., 2006; Sim & Kiefer, 2005; Trumpp et al., 2014). Taken together, results of Experiment 2 suggest i) that motor and visual abstract concepts are processed in different neural circuits (see Experiment 1), and ii) that the deep conceptual decision task enhanced feature-specific processing of abstract concepts as indicated by earlier feature-specific effects as compared to Experiment 1.

General Discussion

The present work investigated the time course of the semantic processing of motor and visual abstract concepts using ERPs. Firstly, we asked whether feature-specific ERP effects for motor and visual abstract concepts would be similarly observed as for concrete concepts. Secondly, we assessed whether possible differential ERP effects would emerge in early (between 150 and 300 ms) or in later time windows. Such early ERP effects most likely reflect semantic access and not post-conceptual processing. Thirdly, we tested whether processing of abstract concepts is prone to conceptual flexibility and assessed whether a deep conceptual decision task leads to earlier feature-specific ERP effects compared to a shallow lexical decision task, similar to observations in concrete concepts.

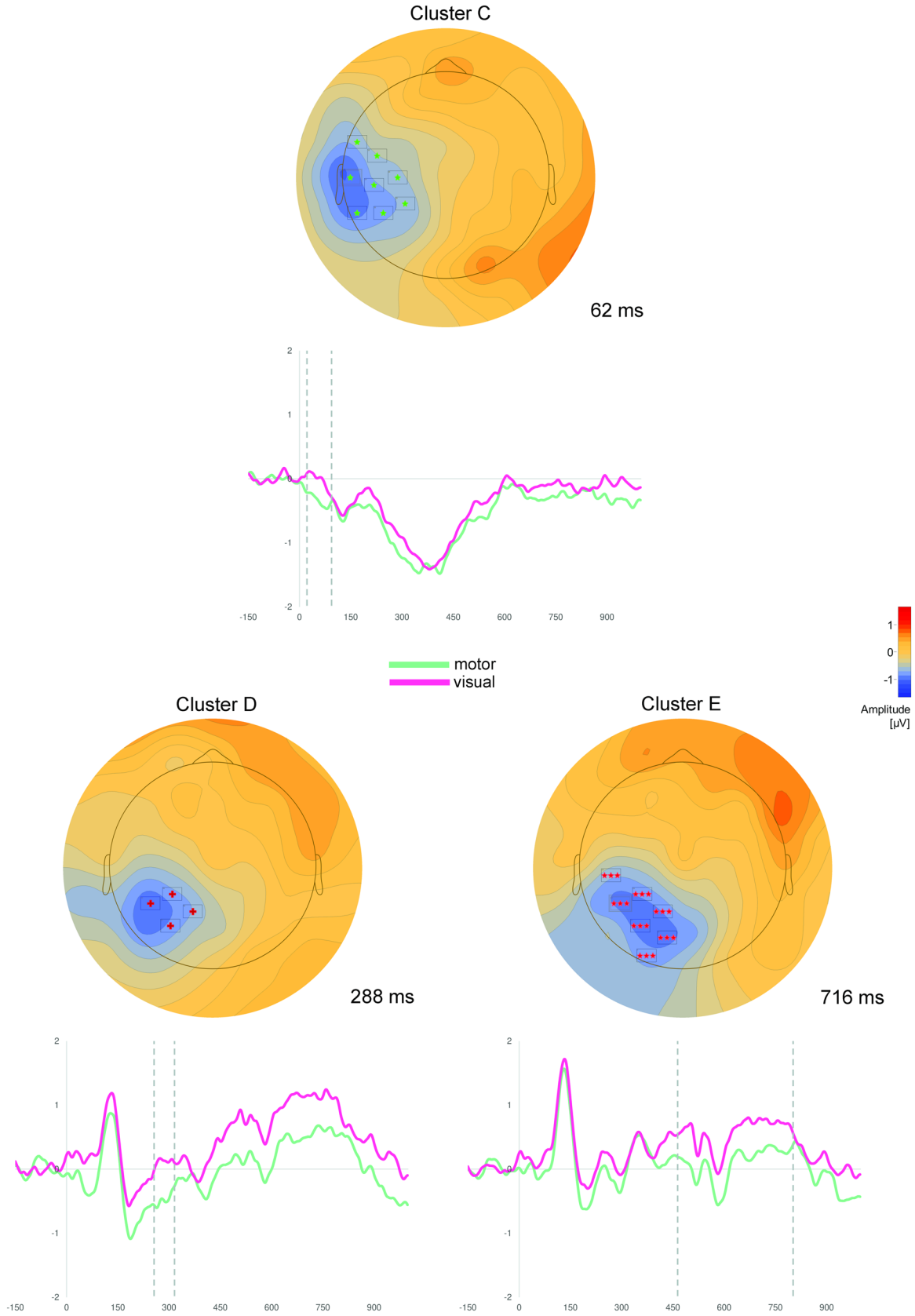
ERP analyses of Experiment 1, in which participants had to perform a shallow lexical decision task, revealed feature-specific effects in fronto-central, parieto-occipital and fronto-temporal scalp regions emerging 178 ms after target onset and extending to later time windows until 680 ms. Experiment 2, a deep conceptual decision task, yielded differential scalp potentials in fronto-central, temporo-parietal and occipital electrode clusters 22 ms after target onset, with some of these clusters covering protracted and therefore also late periods.

The behavioral data of both experiments yielded comparable mean ERs (Experiment 1 & 2) and mean RTs (Experiment 2) for motor and visual abstract concepts, thus paralleling results of our earlier pilot studies (Harpaintner et al., 2020). The comparable behavioral data pattern for both subcategories of abstract concepts rules out the possibility that differential scalp potentials were due to differences in task difficulty. In a similar vein, the comparable high mean numbers of artifact-free EEG segments for motor and visual abstract concepts in Experiment 1 and 2 ensure that differences in ERPs were not due to differences in signal-to-noise ratios across conditions.

Topography of feature-specific effects

Regarding the present electrophysiological results of Experiment 1, ERPs in response to motor and visual abstract concepts showed differential polarity patterns in fronto-central, parieto-occipital and fronto-temporal scalp regions. Paralleling the topographic results of the first experiment, Experiment 2, a deep conceptual decision task, yielded differential feature-specific ERP effects in fronto-central, temporo-parietal and occipital electrode clusters. However, comparing the first and the second Experiment, it is noticeable that Cluster B of Experiment 2 shows more lateralized ERP effects than the first experiment. The underlying causes must remain speculative, but the deep conceptual decision task seems to shift effects toward the right hemisphere. Different topographic patterns of Cluster 1 of Experiment 1 and Cluster A of Experiment 2, with Cluster A being located more left lateralized at frontal electrodes, might further reflect different neural generators within the motor cortex for the two clusters. Even though the underlying causes, here too, must remain speculative, the deep conceptual decision task seems to shift effects of Cluster A to more left lateralized premotor regions as compared to Cluster 1.

The feature-specific ERP effects in response to motor and visual abstract concepts are largely comparable to earlier EEG studies, which investigated the processing of concrete concepts: Similar to concrete motor concepts (Hauk & Pulvermüller, 2004; Kiefer, 2001, 2005; Popp et al., 2016; Pulvermüller et al., 1999, 1996; Trumpp et al., 2014), abstract motor concepts were associated with relatively more positive potentials over frontal and central scalp regions, whereas abstract visual concepts, similar to concrete visual concepts (Kiefer, 2001, 2005; Martin et al., 2006; Pulvermüller et al., 1999, 1996; Sim & Kiefer, 2005), were specifically related to more positive potentials over parieto-occipital as well as over temporal scalp regions. Although the spatial resolution provided by the EEG must be interpreted with caution (Nunez, 1981), the topography of the present feature-specific effects is nevertheless in line with findings of a previous neuroimaging study using the same set of abstract concepts as stimuli (Harpaintner et al., 2020). This fMRI study revealed that the processing of motor abstract concepts was associated with an enhanced BOLD signal in frontal and parietal motor regions, similarly as the execution of real movements. The processing of visual abstract concepts, instead, was related to enhanced activity in temporal and occipital visual brain areas, similar as the observation of object pictures. Furthermore, numerous fMRI studies on concrete concepts linked


Cluster C
62 ms
2
1
0
-1
-2
-150
0
150
300
450
600
750
900
motor
visual
1
0
-1
Amplitude
[μV]
Cluster D
288 ms
Cluster E
716 ms

◂**Fig. 4** Results of cluster permutation tests of Experiment 2. Depicted are clusters, which show significantly more positive scalp potentials for visual compared to motor abstract concepts. Above: Topographic map of each cluster at the time point of the highest *t*-value across all electrodes. Only electrodes with significant *t*-values ($p < .05$) at the specific time point are depicted (for all electrodes see Table 3). Below: ERPs averaged over all electrodes of the respective cluster. Dotted lines indicate the significant time window of the cluster

the processing of motor concepts to an increased activity in fronto-central motor regions (Hauk, Johnsrude, & Pulvermüller, 2004; Hauk & Pulvermuller, 2011; Kemmerer, Castillo, Talavage, Patterson, & Wiley, 2008; Pulvermüller, Cook, & Hauk, 2012; Pulvermüller, Kherif, Hauk, Mohr, & Nimmo-Smith, 2009; Raposo, Moss, Stamatakis, & Tyler, 2009; Rüschemeyer, Brass, & Friederici, 2007; Tomasino, Weiss, & Fink, 2010; Willems, Hagoort, & Casasanto, 2010), whereas the processing of visual concepts was associated with an increased activity in the occipital and temporal lobe (Devlin et al., 2002; Perani et al., 1995; Simmons et al., 2007).

Whereas the topography of the rather late clusters of Experiment 1 comparing visual vs. motor abstract concepts is highly compatible with previous electrophysiological and neuroimaging findings, Cluster 5 showing differential feature-specific ERPs in right fronto-temporal electrodes requires detailed consideration. As already discussed above, this topographic difference compared to findings on concrete concepts might be due to differential conceptual representations of concrete vs. abstract concepts or might reflect interindividual neuroanatomical differences of samples. Based on findings of our previous fMRI study (Harpaintner et al., 2020), the fronto-temporal electrode cluster might also reflect activity in the anterior part of the fusiform gyrus. Referring to recent hybrid models (Kiefer & Pulvermüller, 2012; Patterson et al., 2007), Cluster 5 might also be based on an increased activity in the temporal pole, which has been considered a prominent candidate for a hub region (Patterson et al., 2007), although our previous neuroimaging study did not reveal differential activity in this region (Harpaintner et al., 2020). Finally, the fronto-temporal electrode cluster might be the result of a paradoxical localization based on the direction of the electrical current flow originating from the left fusiform gyrus, a phenomenon characteristically obtained with regard to the N400 component. Even though the maximum of the N400 is typically observed at right parieto-central electrodes, its neural sources constantly trace back to the left fusiform gyrus and the left medial temporal lobe (Kutas & Federmeier, 2011). A similar mechanism might also have taken place with regard to Cluster 5.

Time course of feature-specific effects

Cluster permutation tests revealed significant differences between the processing of motor vs. visual abstract concepts emerging 178 ms after target onset for Experiment 1. The start of differential ERP effects was earlier in Experiment 2, demonstrated by Cluster C, in which modality-specific effects emerged 22 ms after target onset. As already discussed above, this very early emergence of differential effects in Cluster C might be a result of priming processes, caused by the context word preceding the abstract target word. Furthermore, the earlier onset of differential effects in Experiment 2, in which a retrieval of conceptual information is demanded, is in line with previous work on concrete concepts demonstrating earlier feature-specific activity in modality-specific brain regions during deep conceptual tasks (Papeo et al., 2009; Popp et al., 2019; Sato et al., 2008). Most importantly, the differential onsets of the first and second experiment speak in favor of conceptual flexibility by showing that ERP effects were modulated by task.

Earlier studies (Adorni & Proverbio, 2012; Barber et al., 2013; Bardolph & Coulson, 2014; Palazova et al., 2013; West & Holcomb, 2000; Wirth et al., 2008), which examined the time course of the processing of abstract concepts, were particularly limited to the comparison of concrete vs. abstract concepts. A key finding of these studies was that specific electrophysiological effects, like the emotion related early posterior negativity effect (Palazova et al., 2013) or congruency effects (Bardolph & Coulson, 2014), occur later in abstract concepts than in concrete concepts (Borghi et al., 2017). This result pattern led some researchers to conclude that ERP effects reflect mental imagery instead of lexico-semantic processes (Adorni & Proverbio, 2012; Barber et al., 2013; Borghi et al., 2017). As outlined in the introduction section, late ERP effects might reflect post-conceptual imagery processes and therefore do not preclude the existence of amodal conceptual representations, which are accessed earlier. For that reason, only demonstration of early sensorimotor activity during a conceptual task, reflecting access to conceptual representations rather than post-conceptual processes, can be taken as unequivocal evidence for grounded cognition theories (Kiefer & Pulvermüller, 2012).

However, abstract and concrete concepts differ with regard to a variety of variables such as familiarity, word frequency or age of acquisition, rendering a direct comparison difficult. Furthermore, as discussed in the introductory section, abstract concepts are highly heterogeneous with regard to their semantic content and should not be considered as uniform conceptual category (Kiefer & Harpaintner, 2020). Making use of a theory-driven approach and comparing electrophysiological responses to specific subgroups of abstract concepts with a known feature composition, we showed that abstract concepts are associated with both, early

and relatively late feature-specific ERPs. The early emergence of differential scalp potentials in both Experiments 22 and 178 ms after target onset, dependent on the task, suggests that effects reflect rapid conceptual access of motor and visual information. After initial conceptual access, however, post-conceptual processes such as imagery, semantic elaboration or spreading activation might take place, as indicated by the subsequent clusters showing feature-specific ERPs in later time windows.

Implications for theories of conceptual representations, limitations and further directions

The findings of Experiment 1 and 2 are difficult to reconcile with traditional amodal theories of conceptual representation, which assume the representational format of concepts, especially of abstract concepts, to be independent of original modality-specific experiential information (Anderson, 1978; Collins & Loftus, 1975; Fodor, 2001; Mahon & Caramazza, 2009; Pylyshyn, 1980). The early onset of feature-specific ERPs furthermore invalidates the argument of amodal theories that differential effects, often found in brain imaging studies, explicitly rely on later imagery or elaborative processes or spreading activation. Instead, our results suggest distinct feature-specific conceptual processing circuits for abstract concepts implemented by the grounding of conceptual representations in perception and action. In line with grounded cognition theories (Barsalou, 2008; Borghi et al., 2017; Ghio et al., 2016; Kiefer & Barsalou, 2013; Kiefer & Harpaintner, 2020; Pulvermüller & Fadiga, 2010), our findings indicate that motor and visual abstract concepts, similar to concrete concepts, are processed in distinct brain areas (see also Pulvermüller & Henningsen, this issue). Together with our earlier fMRI study (Harpaintner et al., 2020), which provides precise anatomical information for the presently observed feature-specific effects, the results of this ERP study suggest that abstract concepts are represented in modality-specific sensorimotor brain areas, even if they lack a clear physical referent. Our results furthermore support theoretical considerations of grounded cognition theories that access to conceptual knowledge is highly flexible (Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020) by showing that feature-specific ERPs are differentially affected by task demands in Experiment 1 and 2. Overall, the present results are consistent with hybrid theories of conceptual representation proposing that conceptual knowledge is based on an interaction between modality-specific, multimodal and amodal conceptual hub areas (Fernandino et al., 2016a; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016b; Garagnani & Pulvermüller, 2016; Harpaintner et al., 2020; Kiefer & Harpaintner, 2020; Kuhnke et al., 2020; Popp et al., 2019; Simmons & Barsalou, 2003).

As EEG studies only provide correlational data, methods that render causal conclusions possible are inevitable in order to show that sensorimotor information is necessary for the processing of abstract concepts. Further work making use of transcranial magnetic stimulation (Pulvermüller et al., 2005a; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017), behavioral interference paradigms (Shebani & Pulvermüller, 2013; Vermeulen, Corneille, & Niedenthal, 2008) or investigating brain-lesioned patients (Dreyer et al., 2015; Neininger & Pulvermüller, 2003; Trumpp et al., 2013a) seems mandatory in order to shed light on the functional relevance of modality-specific representations for the processing of abstract concepts.

It is noteworthy that we only investigated the processing of motor and visual abstract concepts, even though the feature composition of abstract concepts seems to be much richer and highly heterogeneous (Barsalou & Wiemer-Hastings, 2005; Binder et al., 2016; Harpaintner et al., 2018; Kiefer & Harpaintner, 2020; Lynott & Connell, 2009, 2013; Muraki et al., this issue; Troche et al., 2014; Troche et al., 2017; van Dantzig et al., 2011). Future work should examine abstract concepts, which are characterized by different modal features, in order to complete the picture. It is likely that other subgroups of abstract concepts, like abstract concepts with a strong link to emotions, social constellations, mental states or verbal associations, elicit ERPs with other topographies, polarities and time courses as compared to the present study.

In conclusion, the results of the present ERP experiments demonstrate differential ERP effects for motor and visual abstract concepts, whose topography parallels ERP effects of concrete motor and visual concepts (Hauk & Pulvermüller, 2004; Kiefer, 2001, 2005; Martin et al., 2006; Popp et al., 2016; Pulvermüller et al., 1999, 1996; Sim & Kiefer, 2005; Trumpp et al., 2014). A previous fMRI study (Harpaintner et al., 2020) with the same stimuli localized the neural sources of these feature-specific effects in corresponding modality-specific brain areas. Most importantly, the present study extends these earlier findings by providing information about the time course of abstract concept processing. Both the shallow lexical decision task and the deep conceptual decision task were associated with feature-specific ERPs in relatively late time windows indicating that post-conceptual processes such as imagery, semantic elaboration or spreading activation might be involved in the processing of abstract concepts. However, the emergence of differential scalp potentials before 300 ms with effects as early as 22 and 178 ms after target onset favors the assumption of grounded cognition theories that motor and visual information is also rapidly accessed in corresponding modal brain regions during conceptual processing. The fact that differential ERPs occurred earlier in the deep as compared to the shallow task furthermore indicates that the processing

of abstract concepts is prone to conceptual flexibility supporting another important notion of the grounded cognition framework.

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Author contributions MH contributed to conceptualization, methodology, software, formal analysis, investigation, data curation, writing original draft, visualization. NMT involved in conceptualization, methodology, supervision. MK participated in conceptualization, methodology, software, resources, writing review & editing, supervision, project administration, funding acquisition.

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Compliance with ethical standards

Conflicts of interest The authors declare no conflict of interest, financial or otherwise.

Ethics approval Procedures for all Experiments (1–2) were approved by the Ethical Committee of Ulm University and adhere to the tenets of the Declaration of Helsinki.

Consent to participate Participants gave written informed consent to participate.

Consent to publish Participants gave written informed consent to publish their data.

Availability of data and material The full sets of verbal stimuli are provided as Online Resources. Additional datasets during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

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3. General discussion and future directions

The present work aimed to provide evidence for the grounding of abstract concepts in the sensory and motor systems as predicted by refined grounded cognition theories. In particular, this dissertation addressed important research gaps in the investigation of abstract concept organization in semantic long-term memory in modality-specific brain areas. Previous research lacked systematical investigation regarding the probable heterogeneity of the semantic content of abstract concepts, the neural substrate of specific subgroups of abstract concepts, the role of a priori determined sensorimotor features in their representation, the time course of brain activity during their processing and conceptual flexibility in the abstract concept domain.

For this purpose, I made use of a property generation task, the high spatial resolution of the fMRI and the excellent temporal resolution of the EEG. The property generation task indicated that the content of abstract concepts is highly heterogeneous and that different abstract subgroups, defined by the dominance of certain conceptual features, exist. The existence of differential subgroups of abstract concepts was further supported by the results of the fMRI study, which found differential brain activity in response to abstract concepts with dominant motor vs. dominant visual features, overlapping with activity patterns observed during real world hand movements and object observation (pre- and postcentral gyrus vs. fusiform and lingual gyrus). Furthermore, the ERP studies demonstrated that differential sensorimotor brain activity reflects late post-conceptual processes and, most importantly, early access to conceptual representations, as indicated by feature-specific ERPs in early and later time windows. Finally, the task-dependent modulation of ERPs (shallow lexical decision task vs. deep conceptual decision task) supported the notion of conceptual flexibility as assumed by grounded cognition approaches.

Hence, in accordance with assumptions of grounded cognition approaches, the present dissertation confirmed the existence of different subgroups of abstract concepts (study I), demonstrated distinct neuroanatomical conceptual representations of motor and visual features in corresponding sensorimotor brain regions (study II), which are accessed early, thus ruling out that differential effects are based on post-conceptual processes solely (studies IIIa + IIIb), and indicated that abstract concept representations are highly flexible depending on the degree of depth of conceptual tasks (studies IIIa + IIIb). These findings, their implications for competing theories of semantic memory organization and for theoretical considerations regarding putative differences in concrete vs. abstract concept representations as well as limitations of the present studies are outlined in detail in the following sections. I conclude with suggestions for future investigations in the domain of abstract concepts and proposals for possible practical implications of my research.

3.1. Heterogeneous feature composition of abstract concepts

The majority of previous studies on the representation of abstract concepts contrasted them as a homogeneous conceptual category with concrete concepts and therefore neglected the multifaceted nature of the semantic content of abstract concepts (e.g., Wang et al., 2010) as indicated to some extent by previous rating and property generation studies (e.g., Barsalou & Wiemer-Hastings, 2005). The latter studies are of particular importance as they provide the basis for the theory-driven experimental two-step approach described earlier, which led to the most conclusive findings in the concrete concept domain. This two-step approach is characterized by the identification of specific conceptual subsets based on rating or property generation studies and subsequent (neuroscientific) comparisons of different subgroups.

The situation is further complicated due to the fact that previous studies taking the heterogeneity of abstract concepts into account were partly based on a very small number of stimuli. For instance, one of the first and most influential property generation studies examining the semantic content of abstract concepts (Barsalou & Wiemer-Hastings, 2005) was based on the analysis of nine words, of which only three were abstract, thus reducing the generalizability of the results.

Therefore, the property generation task comprised in the present dissertation investigated the feature composition of abstract concepts in a large set of 296 stimuli. In this study, participants generated a substantial proportion of verbal associations but also affective, introspective, social and sensorimotor properties supporting the notion that the feature composition of abstract concepts is highly heterogeneous. The result pattern found here fits well into the picture of previous evidence gained by rating and property generation studies, which implied that different conceptual knowledge aspects are of different importance depending on the individual (abstract) concept (Barca et al., 2017; Barsalou & Wiemer-Hastings, 2005; Binder et al., 2016; Ghio et al., 2013; Lynott & Connell, 2009, 2013; Troche et al., 2014; Troche et al., 2017; van Dantzig et al., 2011; Wiemer-Hastings et al., 2001). The differential dominance of certain features furthermore implied the existence of several subgroups of abstract concepts providing an important prerequisite for the comparison of motor and visual abstract concepts in the two subsequent studies (Harpaintner et al., 2020a; Harpaintner et al., 2020b). If the assumption of one large homogeneous abstract conceptual category were correct, the absence of any differential effects in the present experiments would have been likely. Instead, the present fMRI and ERP studies revealed differential BOLD-signals and scalp potentials in response to the two conceptual abstract subgroups. These differential effects are difficult to reconcile with earlier approaches, which treated abstract concepts as an undifferentiated conceptual category, and emphasize the existence of multifaceted feature types in abstract concepts.

3.2. Distinct representations of conceptual motor- and vision-related feature information in abstract concepts

Based on the results of the property generation task, the present work furthermore aimed to shed light on the neural substrate of specific subgroups of abstract concepts and to determine whether sensorimotor areas are involved in their representation. As already indicated above, previous neuroimaging studies mainly contrasted abstract concepts as a whole against concrete concepts (e.g., Wang et al., 2010). In addition to the theoretical questionability of this approach, it also revealed highly inconsistent results: While some of these studies indicated a predominance of left hemispheric language regions in abstract concept representation (Desai et al., 2011; Sakreida et al., 2013), some other studies implied that modal brain regions play an important role as well (Kiehl et al., 1999).

In contrast to this, we adopted a theory-driven approach frequently used in the domain of concrete concepts by comparing specific conceptual subgroups, which were determined based upon results of a property generation task. Using this approach in a fMRI study revealed that the processing of motor and visual abstract concepts is associated with differential activity patterns in modality-specific brain areas overlapping with brain activations obtained during hand movements and object observation: While motor abstract concepts were related to an enhanced activity in pre- and postcentral gyrus, visual abstract concepts were related to an increased activity in fusiform and lingual gyrus. The existence of distinct representations of conceptual motor- and vision-related feature information was further supported by the two ERP studies, which both yielded differential scalp potentials in response to motor vs. visual abstract concepts. Topographically, motor abstract concepts were related to more positive potentials over frontal and central scalp regions, whereas visual abstract concepts were related to more positive potentials over parietal, occipital and temporal scalp regions.

The present result pattern parallels evidence found within the concrete concept domain, in which concrete concepts with different feature compositions constantly elicited differential activity patterns in distinct modal brain regions. While concrete concepts with a predominance of motor features were constantly related to peak activities in primary and premotor regions (de Zubicaray, Arciuli, & McMahon, 2013), concrete concepts with a predominance of visual features were frequently related to peak activations in the ventral visual stream (Simmons et al., 2007). Moreover, the topography of scalp potentials in both ERP studies in the present work were largely comparable to patterns found in concrete concepts. While concrete motor concepts were associated with relatively more positive potentials over fronto-central scalp regions (Hauk & Pulvermüller, 2004; Kiefer, 2001, 2005; Popp, Trumpp, & Kiefer, 2016; Pulvermüller, Lutzenberger, & Preissl, 1999; Pulvermüller, Preissl, Lutzenberger, & Birbaumer, 1996; Trumpp et al., 2014), concrete visual concepts were associated with relatively more positive potentials over parieto-occipital and temporal scalp regions (Kiefer, 2001, 2005; Martin, Hauk, & Pulvermüller, 2006; Pulvermüller et al., 1999; Pulvermüller et al., 1996; Sim &

Kiefer, 2005). The observed topography of feature-specific ERP effects in the present ERP studies thus parallel evidence found in concrete concepts and furthermore complement spatial information gained by the fMRI study, even though the spatial resolution of the EEG must be interpreted cautiously (Nunez, 1981).

At the same time, the present results are in line with the few studies demonstrating an involvement of the sensorimotor system in the processing of abstract concepts (Dreyer & Pulvermuller, 2018; Moseley, et al., 2012; Vigliocco, et al., 2014; Mason & Just, 2016; Wilson-Mendenhall, et al., 2012). Compared to these studies, which inferred the contribution of sensorimotor features post-hoc on basis of the observed neural activity patterns, feature compositions of the present stimuli were determined a priori based on property listings. The present studies also provide evidence for a considerable generalizability of findings by using a larger number of stimuli compared to previous studies (Wilson-Mendenhall et al., 2012). The generalizability is further enhanced by demonstrating distinct representations of conceptual motor- and vision-related feature information in abstract concepts using two different neuroscientific methods, which capture brain activity in a complementary fashion.

3.3. Early lexico-semantic vs. late post-conceptual processes

One major argument held against grounded cognition approaches concerns the time course of brain activity during conceptual processing: Differential effects in neuroimaging studies were often attributed to post-conceptual processes, such as imagery, semantic elaboration or spreading of activation (Mahon & Caramazza, 2008), which do not reflect access to conceptual representations, but later concomitant or auxiliary processes. These late auxiliary processes therefore do not rule out amodal representations of concepts, which are thought to be accessed earlier.

While some evidence regarding the time course of brain activity is available for the processing of different subgroups of concrete concepts, corresponding evidence in the abstract concept domain was non-existent. Instead, previous research focused on the comparison of concrete vs. abstract concepts. This contrast often revealed later effects when processing abstract compared to concrete concepts (Borghi et al., 2017). For instance, congruency effects (Bardolph & Coulson, 2014) or the emotion related early posterior negativity effect (Palazova et al., 2013) were found to be temporally delayed in abstract concepts. This delay and the absence of earlier electrophysiological effects sometimes led to the conclusion that later post-conceptual processes are more relevant in abstract concepts and, building on this, that amodal representations are more likely in this concept class (Adorni & Proverbio, 2012; Barber et al., 2013; Bechtold, Ghio, & Bellebaum, 2018; Borghi et al., 2017).

Even though differential ERPs in late time windows were observed in the present ERP studies, the emergence of relatively early feature-specific scalp potentials clearly oppose the

latter assumptions. Dependent on the depth of the conceptual task, differentials ERPs in response to motor vs. visual abstract concepts emerged 178/22 ms after target onset in study IIIa/b, respectively. Again, the present results are in line with evidence obtained by studies, which used the same approach and contrasted different subgroups of concrete concepts. Comparable, they found differential modality-specific ERPs about 150 ms after target onset (Hauk & Pulvermüller, 2004; Hoenig et al., 2008; Kiefer et al., 2011; Proverbio et al., 2007; Pulvermüller et al., 2000). Moreover, to the best of my knowledge, the combination of the present ERP and fMRI results is the first one to demonstrate early sensorimotor activity in abstract concept processing. The present findings, thus, rule out an exclusive involvement of post-conceptual processes, when modality-specific circuits are accessed during abstract concept processing. Instead, the differential scalp potentials in relatively early time windows indicate access to modal conceptual representations and can be considered as unequivocal evidence favoring grounded cognition approaches (Kiefer & Pulvermüller, 2012).

3.4. Flexibility of conceptual representations

Traditionally, it is assumed that concepts are represented stable and that retrieval of conceptual information is situationally invariant and independent of context factors (Collins & Loftus, 1975). Challenging this view, grounded cognition approaches propose that conceptual processing is highly flexible (Kiefer & Pulvermüller, 2012), thus assuming a strong dependence on bottom-up and top-down factors, such as psycholinguistic variables or task demands (Hoenig et al., 2008; Muraki et al., 2020b; Popp et al., 2019a; Pulvermüller, 2018; van Dam et al., 2012).

In order to test the notion of conceptual flexibility, study III of the present dissertation made use of two different conceptual tasks, which differed with regard to the requested depth of conceptual processing. While study IIIb comprised a deep conceptual decision task (determining the semantic relatedness of two words) demanding retrieval of conceptual information, study IIIa merely required retrieval of lexical information in a shallow lexical decision task (word vs. pseudoword decision). Besides differences in the requirement of semantic retrieval, the conceptual and lexical decision task also differed with regard to relational processing (single word vs. relational words) and response mode (go/no-go response mode vs. two alternative forced choice). Note that all of these factors contribute to the fact that study IIIb required deeper semantic processing as compared to study IIIa.

Results demonstrated that feature-specific ERP effects emerged earlier (22 ms after target onset) in study IIIb compared to study IIIa, in which differential effects occurred 178 ms after target onset. Again, the present results are in line with results found by previous studies investigating the processing of concrete concepts, where more pronounced/earlier feature-specific activation of modal brain areas was found during deep conceptual tasks (as compared

to more shallow tasks; Papeo et al., 2009; Popp et al., 2019a; Sato et al., 2008). Most importantly, the present results support theoretical assumptions about conceptual flexibility made by grounded cognition approaches by demonstrating that differential ERPs were modulated by task (Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020). Note that conceptual flexibility per se is in principle compatible with amodal theories as some of their representatives recognize the theoretical value of flexible conceptual representations (e.g., Tyler & Moss, 2001).

3.5. Implications of the present results for theories of semantic memory organization

3.5.1. Amodal vs. grounded cognition vs. hybrid approaches

Traditional amodal approaches of semantic memory organization propose that conceptual knowledge is represented independently of the motor and perceptual systems (Anderson, 1978; Collins & Loftus, 1975; Fodor, 2001; Mahon & Caramazza, 2009; Pylyshyn, 1980). Furthermore, the majority of their representatives (e.g., Visser et al., 2010) assume that heteromodal association cortices (sometimes called amodal semantic hubs) serve as anatomical seats of conceptual information. In these amodal hub regions (e.g., temporal pole), all kind of concepts, regardless of their feature composition or concreteness/abstractness level, are considered to be processed similarly leading to almost identical neural activation patterns. Additional engagement of modality-specific brain areas is, if at all, explained by secondary auxiliary processes based on passive spreading of activation (Mahon, 2015a, 2015b) or imagery processes (Machery, 2007). These auxiliary processes are thus thought to reflect post-conceptual processes only, which are not causally involved in conceptual processing and take place after a putatively amodal concept had been accessed (Mahon & Caramazza, 2008).

Contrasting these theoretical considerations, grounded cognition approaches assume modality-specific brain systems, which include regions associated with perceptual, motor, mental, introspective and emotional processes, to represent feature-specific conceptual information (Barsalou, 2008; Borghi et al., 2017; Ghio et al., 2016; Herbert et al., 2011; Kiefer & Barsalou, 2013; Pulvermüller & Fadiga, 2010). Importantly, these newer approaches of semantic cognition propose that modality-specific brain systems contribute causally to conceptual representation and that experience-dependent (partial) reinstatement of modal brain areas during concept processing reflects processes going beyond post-conceptual auxiliary processes. Sensory and motor brain activity is considered to reflect direct access to feature-specific conceptual knowledge, which is flexibly recruited dependent on bottom up (e.g., psycholinguistic variables) and top-down (e.g., task demands) factors (Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020).

Considering these theoretical assumptions, results of the present studies are difficult to reconcile with traditional amodal approaches of semantic memory organization, as they did not reveal unitary processing of motor and visual abstract concepts. While the property generation task did not formally allow concluding about the validity of the competing approaches, the demonstration of modal properties by participants' listings and the identification of different subgroups of abstract concepts provided an important prerequisite for the validity of the grounded cognition approach. The property generation study furthermore provided an important requirement for the comparison of motor and visual abstract concepts in the two subsequent studies, which clearly speak in favor of grounded cognition approaches by demonstrating differential representations of conceptual motor and visual features: The fMRI study revealed distinct modality-specific neural correlates in response to motor vs. visual abstract concepts. These results were further complemented by both ERP studies, which demonstrated differential feature-specific ERP effects for the two abstract subgroups. The unitary processing of all kind of conceptual information in a heteromodal association cortex, in contrast, would have led to similar brain activation patterns and to comparable ERPs in response to motor and visual abstract concepts.

Obtained information about the time course of brain activity during the processing of motor and visual abstract concepts furthermore invalidated the argument of amodal approaches that a potential involvement of modal brain areas in conceptual processing leads back to secondary post-conceptual processes only. Instead, the emergence of differential scalp potentials in response to motor vs. visual abstract concepts within 200 ms after target onset indicates relatively early access to conceptual representations, clearly opposing the assumption that differential effects exclusively trace back to post-conceptual processes, such as imagery, semantic elaboration or spreading of activation. The fact that the time course depended on the depth of the conceptual task additionally supported the notion of conceptual flexibility made by grounded cognition approaches and opposed amodal approaches assuming conceptual stability (e.g., Collins & Loftus, 1975). As already indicated above, not all amodal approaches support the notion of conceptual stability (Devlin et al., 1998; McClelland & Rogers, 2003; Ralph et al., 2017; Rogers et al., 2004). For instance, the Controlled Semantic Cognition Approach (Ralph et al., 2017) assumes an interplay between two separate systems responsible for semantic representation and control. According to this approach, semantic representations are located in anterior temporal lobe, while task- and context-dependent conceptual flexibility is realized by an interaction with semantic control regions located in lateral and ventromedial prefrontal cortex, among others. Note, however, that the present results are still incompatible with these latter approaches as they also assume concepts to be represented in an amodal format in a unitary conceptual system independent of sensory and motor brain systems.

Thus, the present results clearly oppose amodal approaches of semantic cognition and are rather in line with grounded cognition approaches. The present results are furthermore in line with hybrid approaches of conceptual representation, which assume an interaction between modality-specific, multimodal and amodal hub areas, even though the latter areas were not the subject of this dissertation (Fernandino et al., 2016a; Fernandino et al., 2016b; Garagnani & Pulvermüller, 2016; Kiefer & Pulvermüller, 2012; Kuhnke et al., 2020; Muraki et al., 2020a; Patterson et al., 2007; Popp et al., 2019a; Simmons & Barsalou, 2003; Wang et al., 2020). In accordance with these sometimes called *hub-and-spokes* models, the present results indicated modality-specific conceptual feature representation as proposed in the notion of *spokes.* Evidence regarding the involvement of typical *hub* regions in the processing of motor and visual abstract concepts, however, is limited in the present data: The conjunction analysis of the fMRI study, which aimed at identifying regions underlying general abstract concept processing, yielded common activity in posterior temporal cortex, which is considered a potential hub region (Gold et al., 2006; Hoffman et al., 2012; Price, 2000). However, no common activity in other prominent candidates in the anterior temporal lobe (Patterson et al., 2007) or inferior parietal cortex (Binder & Desai, 2011) was found. Additionally, Cluster 5 of study IIIa might reflect increased activity in the temporal pole, even though the spatial resolution of the EEG must be interpreted with caution (Nunez, 1981) and no similar activity pattern was observed in the fMRI study, possibly due to susceptibility effects, which attenuated the MR signal in this region. Also, note that the present studies focused on differences in the processing of subgroups of abstract concepts and not on their commonalities, rendering conclusions about hub regions involved in integrational processes and general semantic binding difficult.

Taken together, the present results are most clearly compatible with assumptions of grounded cognition approaches, ranging from the notion of modality-specific conceptual representation to the notion of conceptual flexibility. Furthermore, even though evidence with regard to hub regions is scarce in the present data, possibly due to methodological limitations, results are in principle reconcilable with modern hybrid multi-level approaches. Considering the available literature, also from the domain of concrete concepts, in which the existence of hub areas was indicated, it appears plausible that these hub regions also play a role in abstract concept representation. In order to clearly favor one of the two approaches (grounded cognition vs. hybrid approaches), future studies should be designed to be sensitive with regard to both, *spokes* and *hubs*.

3.5.2. Concrete vs. abstract concept representation

For a long time, the debate about the representation of abstract concepts was dominated by the idea of a representational dualism stating that the representational format of abstract

concepts differs essentially when compared to the format of concrete concepts. Particularly, the Dual Coding Theory (Paivio, 1986), which proposes that the representation of abstract concepts relies on a verbal-symbolic code only, while concrete concepts are represented through a verbal-symbolic and a visual imagery code, inspired a huge amount of studies to adopt this dualistic view by contrasting abstract concepts as a whole undifferentiated with concrete concepts. Advocates of this view often take the so-called *concreteness effect*, a processing advantage for words referring to concrete concepts as compared to words referring to abstract concepts (e.g., Fliessbach et al., 2006; Marschark & Paivio, 1977), as evidence for the validity of the representational dualism. However, the assumption that this processing advantage leads back to the dual coding of concrete concepts has been repeatedly questioned (e.g., by the Contextual Availability Theory; Schwanenflugel et al., 1988). Additionally, existing empirical evidence obtained from neuroimaging experiments is highly inconsistent: On the one hand, some of these studies revealed neural patterns in line with the Dual Coding Theory by demonstrating that the processing of abstract concepts was predominantly associated with temporal regions typically involved in language processes, whereas the processing of concrete concepts was related to increased brain activity in modal areas (Wang et al., 2010). On the other hand, studies demonstrating the opposite pattern (greater engagement of modal areas during abstract concept processing) are also available (Kiehl et al., 1999).

Considering these inconsistent findings, the present dissertation abandoned the traditional approach of treating abstract concepts as a homogeneous conceptual category. Based on this theoretical assumption, the present property generation study gave insights into the feature composition of a large set of abstract concepts and yielded results highly incompatible with the Dual Coding Theory. Assuming that considerations of the Dual Coding Theory are correct, a much higher proportion of verbal associations in participants' listings would have been likely. Instead, participants generated a substantial amount of modal features, including emotional, introspective, social as well as sensorimotor features, in response to abstract concepts. By demonstrating that abstract concepts are characterized by a rich and heterogeneous semantic content predominantly based on modal feature categories, the present results parallel findings obtained from the domain of concrete concepts (Lynott & Connell, 2009, 2013; van Dantzig et al., 2011). The present fMRI and ERP studies also emphasized similarities rather than differences in the processing of abstract and concrete concepts: (i) Similar to concrete motor concepts (e.g., Hauk et al., 2004; Hauk & Pulvermüller, 2004), the processing of abstract motor concepts was related to enhanced brain activity in pre- and postcentral gyrus and to relatively more positive potentials over fronto-central scalp regions. (ii) Similar to concrete visual concepts (e.g., Sim & Kiefer, 2005; Simmons et al., 2007), the processing of abstract visual concepts was associated with an increased BOLD-signal in fusiform and lingual gyrus and with relatively more positive potentials over parieto-

occipital and temporal scalp regions. (iii) Similar to findings from studies investigating the processing of concrete concepts (e.g., Popp et al., 2019a), the present studies found task-dependent differential feature-specific effects in relatively early time windows.

Summing up, the present results are strictly in line with findings obtained from studies, which investigated the processing of concrete concepts. However, concrete and abstract concepts might still hold differences, especially with regard to their feature composition. As shown by the regression analysis of study I, higher abstractness ratings went hand in hand with a high proportion of emotional/introspective features, while higher concreteness ratings were related to higher proportions of sensorimotor features. These different feature compositions, though, do not speak against a similar modal representational format of concrete and abstract concepts in various modality-specific brain regions as suggested by grounded cognition approaches. Additionally, as the present studies only investigated the processing of specific abstract concepts, which were associated with certain modal features, conclusions about other subgroups of abstract concepts are hard to draw. It might be possible that highly abstract concepts as *superconductivity*, strongly linked to verbal associations, are predominantly represented in language or amodal hub regions as implied by the Dual Coding Theory. Importantly, possible differences would not only apply to the comparison with concrete concepts but also to the comparison with other subgroups of abstract concepts (e.g., motor abstract concepts). At this point, it might also be noteworthy that an accumulating amount of evidence points out to the fact that concreteness/abstractness constitutes a highly continuous spectrum instead of a categorical variable (Wiemer-Hastings et al., 2001). Some authors (Mkrtychian et al., 2019; Myachykov & Fischer, 2019) even argue that, dependent on the context, the same concept may be either concrete or abstract, further questioning the clear-cut distinction made between concrete and abstract concepts. What all of the latter considerations have in common is that they cast doubt on the approach of simply contrasting the two putative clear-cut concept classes against each other, as it has been done under the notion of representational dualism.

3.6. Limitations of the present studies and future directions in investigating abstract concept representation

The present dissertation provides evidence for the grounding of abstract concepts in modality-specific systems as predicted by refined grounded cognition theories. However, as all of the studies presented here only provide correlative information with regard to the involvement of the visual and motor systems in abstract concept processing, statements about the functional relevance of motor and sensory systems in the representation of abstract concepts are hard to make. Investigating patients with brain injuries, TMS or behavioral interference/facilitation paradigms constitute important methods allowing for causal conclusions, as it already has

been demonstrated in the concrete concept domain (Klepp et al., 2017; Pulvermüller et al., 2005a; Trumpp et al., 2013a; Vermeulen et al., 2008) and in rare investigations of abstract concepts (Dreyer et al., 2015). Note that a behavioral interference study conducted in our laboratory using the same stimuli as studies II and III, which is not part of the present dissertation due to scheduling reasons, yielded first proof with regard to the functional relevance of the visual system in the processing of visual abstract concepts. Participants in this study were asked to perform a semantic decision task (abstract [visual vs. motor] vs. concrete word) while simultaneously performing a visual/motor interference task (1-back task including visual form pictures vs. hand movements). This experimental crossover double dissociation paradigm was used in order to investigate whether the interference tasks specifically impair the processing of visual vs. motor abstract concepts. While the motor interference task did not lead to any significant effects, the visual interference task, interestingly, led to faster reaction times (RT) when processing visual compared to motor abstract concepts (Fig. 3).

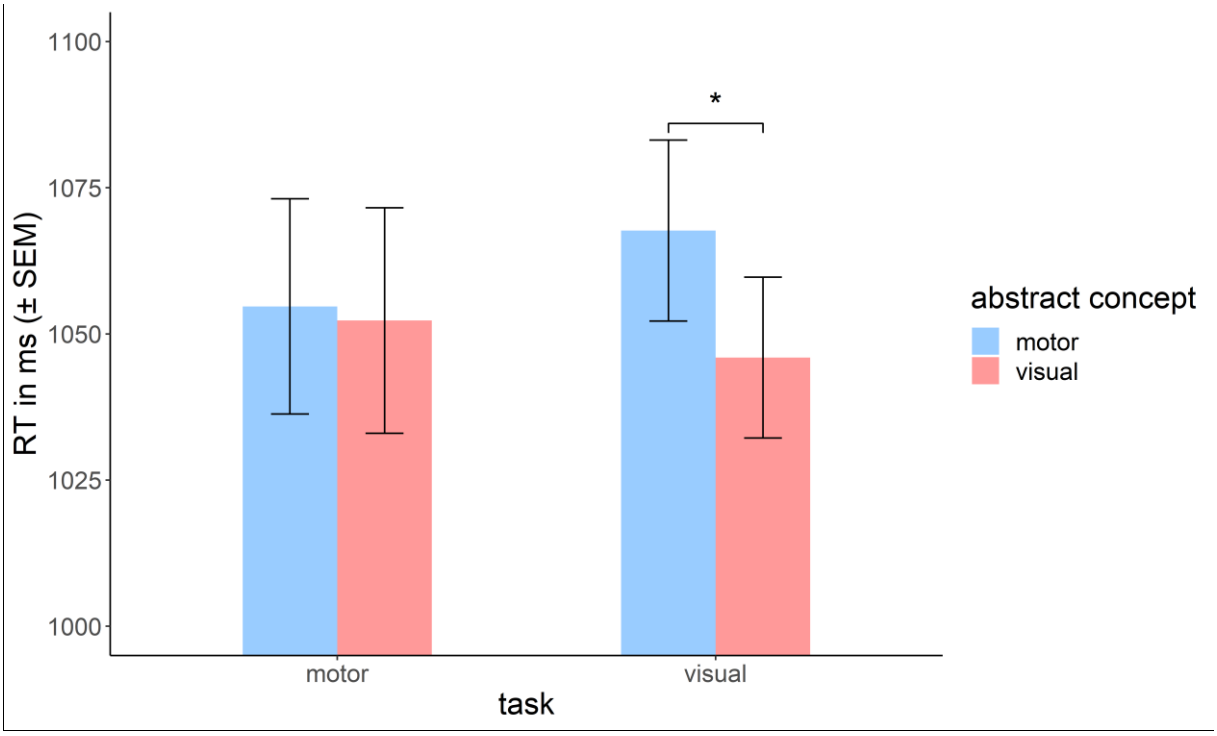

Figure 3. Mean reaction times (RT) in the semantic decision task of the behavioral interference study as a function of abstract conceptual subcategory (*abstract concept*) and (interference) task (*task*). Error bars represent standard errors of the mean (*SEM*).

Instead of the hypothesized interference effect, these results indicated that the visual task specifically facilitated the processing of abstract concepts of the same modality, which is rather compatible with the idea of a priming effect (for similar facilitation effects see Cao et al., 2016; Klepp et al., 2017; Klepp et al., 2019; Niccolai et al., 2017). Either way, the specific effect of the visual (interference) task on the processing of visual abstract concepts, but not on the

processing of motor abstract concepts, indicates a functional relevance of the visual system for the representation of visual abstract concepts (see Liepelt, Dolk, & Prinz, 2012 for further considerations regarding facilitation vs. interference effects). Future investigations using further methods that provide information about the functional relevance of modal brain areas in abstract concept processing (e.g., TMS, investigations of brain-damaged patients) are inevitable in order to validate core assumptions of grounded cognition approaches.

As already noted above, conclusions of this dissertation are limited to very specific subgroups of abstract concepts, as the present studies focused on the processing mechanisms of motor and visual abstract concepts. Other subgroups of abstract concepts, which are characterized by different modal feature compositions, might be represented in other modality-specific brain areas or, in the case of abstract concepts strongly related to verbal associations, even in language or amodal hub regions. Thus, in order to complete the picture, it is essential to examine a broad variety of subgroups of abstract concepts.

Future investigations might further benefit from another presentation modality as compared to the present studies (e.g., acoustically instead of visually), especially when contrasting abstract concepts strongly related to vision with abstract concepts related to other modal features. A simultaneous recruitment of the visual system by the written word form of stimuli and the visual feature dominance of visual abstract concepts could thus be avoided. Additionally, it might be worth considering that future work focuses on deep conceptual decision tasks. As demonstrated in the present ERP studies as well as in previous work (Cao et al., 2016; Klepp et al., 2017; Niccolai et al., 2017; Papeo et al., 2009; Popp et al., 2019a; Sato et al., 2008), this type of task leads to faster/more pronounced effects when compared to shallow lexical decision tasks. It furthermore appears reasonable to collect future data of property generation tasks as well as neuroimaging data in the same sample in order to use the individual proportions of generated properties as continuous predictors of potential modality-specific effects. This approach would also allow taking into account individual differences of conceptual feature compositions, which might arise from different experiences (Beilock et al., 2008; Hoenig et al., 2011; Kiefer et al., 2007; Lyons et al., 2010; Willems et al., 2010). Moreover, a simultaneous acquisition of neuroimaging and electrophysiological data in the same sample by combining the fMRI and the EEG might be a promising future approach in order to integrate spatial and temporal information of abstract concept processing. Finally, as the present studies provided first evidence regarding the representation of motor vs. visual abstract concepts in differential modal brain regions on basis of moderate sample sizes, further work should examine a larger number of participants in replication studies.

3.7. Further implications of the present findings

The present dissertation provides evidence for the grounding of abstract concepts in the sensorimotor systems as postulated by refined grounded cognition approaches, similarly as it has already been found in the concrete concept domain. By shedding light on mechanisms of human cognition only marginally explored in earlier studies, the present results are accompanied by practical implications in a wide range of fields of application. As abstract concepts had been considered to be learnt exceptionally hard when compared to concrete concepts (e.g., Paivio, 1986), it might be promising to complement teaching, which typically focuses on the achievement of linguistic knowledge based on theoretical assumptions of representational dualism, by approaches influenced by the grounded cognition framework (Glenberg, Goldberg, & Zhu, 2011; Macedonia, Hammer, & Weichselbaum, 2018). Students in elementary schools but also in secondary and language schools might profit from teaching, which places emphasis on sensory and motor interactions in the context of abstract vocabulary acquisition (Chen, 2006; Hashagen, Büching, & Schelhowe, 2009). For instance, additionally to verbal descriptions related to the unfamiliar abstract concept *justice*, teachers could provide experiential information by demonstrating pictures of the Goddess *Justitia* carrying typical symbolic items such as a sword, scales and a blindfold, thus enriching the abstract concept by sensorimotor information through metaphoric relations to concrete concepts (Lakoff & Johnson, 1980). Following Barsalou and Wiemer-Hastings (2005), students might further benefit from an excursion to the local court by directly enriching the concept by visual (e.g., the scene of a court hearing), motor (e.g., the swinging of the gavel) and emotional (e.g., guilt of the losing party) content. In addition, teachers could utilize social situations in everyday school life and use social aspects (e.g., fair reward of good behavior and punishment of bad behavior) to illustrate the concept of *justice*. Such teachers would take into account the present findings, which further validated refined grounded cognition approaches, by considering the importance of perceptions and motor interactions in the context of concept learning thus enabling the development of rich semantic knowledge exceeding knowledge solely based on verbal associations.

A related field, which might benefit from an optimal learning environment designed in accordance with functional mechanisms of human cognition, is neurological rehabilitation. Patients with semantic memory deficits due to amnesia or other neurological disorders could achieve faster success in regaining (abstract) conceptual knowledge if the rehabilitation environment enables rich sensorimotor experiences (Macedonia et al., 2018).

Another field that might profit from the present studies is the field of robotics (Cangelosi & Stramandinoli, 2018; Paul, Arkin, Roy, & Howard, 2016). As future robots will face the challenge of serving as housekeepers, co-workers and caregivers for handicapped persons, it seems particularly important for artificial cognitive agents not only to be able to deal with sentences describing concrete actions (e.g., *lower the stretcher*), but also with tasks related to

more abstract dimensions (e.g., *comfort the patient*; Cangelosi & Stramandinoli, 2018). In accordance with the present results, two main grounding mechanisms in the context of the design of artificial agents and abstract concept learning have been proposed (Cangelosi & Stramandinoli, 2018): (i) A mechanism, in which robots build up semantic knowledge by direct perception of their environment or by direct interaction with their surroundings (*direct grounding*); and (ii) another mechanism, which focuses on linguistic factors without direct sensory or motor experiences, such as word combinations (*grounding transfer*). Results of the present dissertation validate the importance of linguistic factors and verbal associations (study I), but, even more clearly, the significance of sensorimotor features in abstract concept representations (study I – III). Based on the present results, but also on consecutive studies, robotics might develop artificial agents capable of processing complex abstract conceptual information.

3.8. Conclusions

In summary, the present dissertation filled important research gaps that have been neglected in previous work by addressing the feature composition of abstract concepts, the neural substrate of specific conceptual subgroups and the role of sensorimotor features in their representation, the time course of brain activity during their processing and the notion of conceptual flexibility. In this respect, results of study I – III demonstrated the heterogeneity of the semantic content of abstract concepts, the existence of specific subgroups of abstract concepts, distinct modality-specific representations of conceptual motor and visual feature information, which are rapidly accessed, as well as task-dependent conceptual flexibility. Paralleling results gained in the domain of concrete concepts, the present work provides further important evidence in favor of refined grounded cognition theories, which assume abstract concepts to be grounded in the sensorimotor systems. Studies I – III consistently support the notion of a modality-specific structure of semantic memory, thus shedding further light on grounding mechanisms of conceptual representations, even in the case of concepts, in which a clear physical referent is missing. Hence, the present work extents already existing evidence in the field of concrete concepts by important insights in abstract concept representation and provides a major contribution to the scientific debate in cognitive science of how concepts are organized at a functional and neural level.

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