Institute of Psychology

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# A Holistic Reading of Grounded Cognition: Embodiment from Life to Mind

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By

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Affidavits following §7 section 2 No. 9 of the doctoral regulations from the German Sport University Cologne, July 9th 2024:

Hereby I declare:

The work presented in this thesis is the original work of the author except where acknowledged in the text. This material has not been submitted either in whole or in part for a degree at this or any other institution. Those parts or single sentences, which have been taken verbatim from other sources, are identified as citations.

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## Summary

This dissertation contributes to the discussion on the format of mental representations. To do this, a theoretical analysis of different positions serves to clarify underlying distinctions between approaches. This consequently produces a new formulation of grounded cognition, an embodied approach to mental representations. This new formulation has fewer theoretical weaknesses and is rife for interdisciplinary integration. We perform such an integration with the predictive processing framework. This analysis and consequent integration produce a clear position on the format of mental representations called analog representations. It is fleshed out with various interdisciplinary supporting literature and a host of mechanisms from grounded cognition research.

The theoretical analysis in this dissertation contrasts cartesianism with holistic monism. Cartesianism, which is dominant in cognitive science and most other life sciences, neglects the inherent complexity giving rise to natural phenomena. Here, it is argued, that, despite the usefulness of this approach in many regards, it is an impediment to grounded cognition research. Firstly, because grounded cognition straddles opposing epistemological and ontological positions. This intra-theoretical tension undermines its theoretical stability. Second, because reductionist strategies and practices, when applied to complex systems, will fail to deliver explanations with natural kinds. Under the uncontroversial assumption that mental representations are the product of a complex system, the reductionist approach is therefore ill-fitting.

First, three central approaches to cognition and mental representations are presented, Standard Cognitive Science, Grounded Cognition, and Life-Mind Continuity, along with their commitments to cartesianism and holistic monism. Next, it is assessed whether grounded cognition is committed to holistic monism, or whether one finds cartesian stowaways implicit in its theories. Such a stowaway is identified and consequently tested in **Article I** and **Article II**. The details of cartesianism and holistic monism are then detailed, allowing, consequently to identify these in grounded cognition theorizing. Next, in **Article III**, a reading of grounded cognition is formulated which discards the cartesian stowaways, and in **Article IV** this reformulation is integrated with the life-mind continuity approach. Future directions, implications, and limitations are discussed in conclusion.

## Zusammenfassung

Diese Dissertation leistet einen Beitrag zur aktuellen Debatte über das Format mentaler Repräsentationen. Zu diesem Zweck wird eine theoretische Analyse der dominierenden Positionen durchgeführt, die die grundlegenden Unterschiede zwischen den verschiedenen Ansätzen herausarbeitet. Dies mündet in einer neuen Formulierung des Grounded-Cognition-Ansatzes. Diese Neufassung weist weniger theoretische Schwächen auf und eignet sich für eine interdisziplinäre Integration, die in dieser Dissertation vorgenommen wird. Die Analyse sowie die daraus resultierende Integration ermöglichen die Beantwortung der Frage nach mentalen Repräsentationen und zeigen, dass es sich dabei um analoge Repräsentationen handelt. Analoge Repräsentationen zeichnen sich dadurch aus, dass sie viele Merkmale ihrer Referenten beibehalten, wie beispielsweise deren Struktur oder Form. Diese Neufassung wird durch eine Vielzahl interdisziplinärer Literatur sowohl theoretisch als auch empirisch gestützt.

Die theoretische Analyse wird durch den Kontrast zwischen den philosophischen Ansätzen des Cartesianism und des Holistic Monism geleitet. Der Cartesianism, der in den Kognitionswissenschaften und den meisten anderen Lebenswissenschaften vorherrscht, vernachlässigt mit seiner Betonung auf Reduktionismus die inhärente Komplexität natürlicher Phänomene. Unter der weitgehend akzeptierten Annahme, dass mentale Repräsentationen das Ergebnis eines komplexen Systems sind, erweist sich der reduktionistische Ansatz daher als ungeeignet. Erstens, weil Grounded Cognition gegensätzliche epistemologische und ontologische Positionen enthält: Anstatt einer holistischen Epistemologie, die mit der monistischen Ontologie von Grounded Cognition korrespondiert, weist es eine reduktionistische Epistemologie auf. Dieser intra-theoretische Widerspruch gefährdet die theoretische Kohärenz. Zweitens können reduktionistische Strategien und Methoden, wenn sie auf komplexe Systeme angewandt werden, keine Erklärungen anhand von „natural kinds“ liefern, was ein wichtiges Ziel wissenschaftlichen Fortschritts ist.

Zu Beginn dieser Dissertation werden drei zentrale Ansätze zur Kognition und mentalen Repräsentation vorgestellt: (1) Standard-Kognitionswissenschaft, (2) Grounded Cognition und (3) Life-Mind-Continuity, sowie deren jeweilige Verknüpfung mit Cartesianism und Holistic Monism. Anschließend wird untersucht, ob Grounded Cognition implizit cartesianische Elemente enthält. **Artikel I** und **Artikel II** identifizieren diese Elemente und prüfen sie sowohl theoretisch als auch empirisch. Die Charakteristika des Cartesianism und des Holistic Monism werden folglich spezifischer ausgearbeitet, um ihren Einfluss auf Theorien der Grounded Cognition zu bestimmen. In **Artikel III** wird schließlich

eine Formulierung von Grounded Cognition entwickelt, die diese reduktionistischen Annahmen verwirft. **Artikel IV** erweitert diese Neufassung, indem sie sie in die Life-Mind-Continuity-These integriert. Dadurch werden die Erkenntnisse der Grounded-Cognition-Forschung in eine evolutionär und biologisch plausible Theorie eingebettet. Abschließend werden zukünftige Forschungsrichtungen, Implikationen und Limitationen diskutiert.

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**Article I:**

Friedrich, J.; Fischer, M.H.; Raab, M. (2024). Physical Invariants in Abstract Concept Grounding – The Physical World in Grounded Cognition. *Psychonomic Bulletin and Review* 31, 2558–2580

**Article II:**

Friedrich, J.; Raab, M.; Voigt, L. (2025). Grounded cognition and the representation of momentum: abstract concepts modulate mislocalization. *Psychological Research*, 89, 51

**Article III:**

Friedrich, J.; Fischer, M.H.; Raab, M. Issues in Grounded Cognition and how to solve them – The Minimalist Account. *Journal of Cognition*, 8(1), 31.

**Article IV:**

Friedrich, J.; Fischer, M.H. (under review). Higher-Level Cognition under Predictive Processing: Structural Representations, Grounded Cognition, and Conceptual Spaces. *Minds and Machines*

"There's so much distance between the fundamental rules and the final phenomena, that it's almost unbelievable that the final variety of phenomena can come from such a steady operation of such simple rules. It's not complicated, it's just a lot of it."

– Richard Feynman, *Take the World from Another Point of View* (1973)

"Living systems are cognitive systems, and living as a process is a process of cognition"

– Humberto Maturana, *Biology of Cognition* (1970, p. 4)

# 1. Introduction

The central goal of cognitive science is understanding how *cognition* works. Central to this endeavor is certainly the construct of mental representations. For example, thinking about whether to drink from a bottle, involves a mental representation of the concept of drinking, of a bottle and so on. This is also evident in a variety of definitions of cognition which suggest mental representations as central in cognitive science. The Stanford Encyclopedia of Philosophy states: "cognitive states and processes are constituted by the occurrence, transformation and storage (in the mind/brain) of information-bearing structures (representations) of one kind or another" (Pitt, 2022). Similarly, in a discussion on "What is Cognition?" (Bayne et al., 2019), different experts voice their definition of cognition: Timothy Bayne argues that all cognition has a few central features, the foremost of which, according to him, "concerns concepts. Thinking, reasoning, perceiving, imagining, and remembering are cognitive processes to the extent that they involve the use of concepts." (p. 603). In the same discussion, David Byrne argues "Taking the cognitive approach entails asking questions about what information is (in some way) represented by an individual" (ibid., p. 609). The suggestion here is that at the center of the study of cognition is the mental representation of concepts. Mental representations are everywhere, and one of the central discussions about the topic of mental representations concerns their format. When representing the concept of drinking from a bottle, how does this representation manage to bear this meaning?

A multitude of theories has been put forth addressing this topic, and a goal of this dissertation is to comprehensively navigate and evaluate them. These theories are vastly different, underwritten not only by contrasting approaches to cognitive science research, but also to knowledge generation, and even having completely different foundational views on nature itself. These foundational views and the resulting downstream consequences in the scientific process inform the theories deeply, impacting not only the explicit content, but also the assumptions implicit in the kinds of explanations they produce. I show here, an examination of these theories' assumptions about the brain and nature produces insights comprehensive enough to significantly alter the current discussion about them, because it uncovers not only the specific positions of each theory but illuminates the deep chasm between them.

The foundational approach taken here, starting with the foundational worldview underlying each theory allows to strip back shallow differences, and to compare theories from a joint shared position. The here-presented meta-theoretical analysis therefore reshapes the discussion of their more surface-level postulates because foundational constructs can be aligned across surface-level theoretical boundaries. Beyond, this foundational approach manages to explicate the place of higher-level cognition on a continuum spanning from the simple basal emergence of cells to the sophisticated abilities of human cognition.

In this analysis of theories of cognition, I will focus on three predominant approaches to understanding the format of mental representations that have surfaced in past theories. The most common two can be characterized as *Standard Cognitive Science* (SCS), and the framework often framed as its antagonist, the *Grounded Cognition* (GC)[1] approach. SCS postulates a cartesian approach, meaning that it posits mental representations unlike anything found in nature (symbolic representation, rule-based logic, etc.). GC is often portrayed as its opposition because it has a distinctly non-cartesian postulate: mental representations involve the same format as that underlying action and perception. Yet, in the following, I argue that GC, in its departure from SCS, has harbored stowaways in the form of assumptions stemming from its cartesian worldview. These assumptions are not located in explicit postulates, rather they are implicit, residing in the types of theories GC proposes and the characteristics of the constructs which populate them. This leaves GC in a split, with the assumptions underlying its explanations differing from the assumptions inherent in the types of theories it produces (see Figure 1B). It is therefore necessary to identify and remove such *cartesian stowaways* in GC. In order to do this, it will be useful to view GC through the lens of the third predominant position, the *Life-Mind Continuity* (LMC) approach. LMC is, in fact, arguably the more direct counterpart to SCS, because it argues for universal principles underlying the emergence of life and cognition. Here, it serves as a useful perspective for examining GC's cartesian stowaways by extracting differences in their theories and constructs. I describe a reading of GC based on LMC, which allows GC to depart fully from implicit cartesian commitments, by uncovering cartesian stowaways. A GC without cartesian stowaways is aligned in its explicit and implicit theoretical commitments and assumptions, making it more theoretically coherent. Additionally, a central feature of LMC is that it is biologically plausible, because it builds directly on what is known from nature. Therefore, the non-cartesian reading of GC, which this analysis produces, will also be biologically plausible, a beneficial characteristic because it incurs theoretical parsimony. This dissertation intends to 1) demonstrate that GC harbors cartesian stowaways (sections 1-4), 2) describe and identify these cartesian stowaways within GC theories (sections 5-10), and 3) consequently describe a formulation

[1] This distinction reduces a vast and nuanced space into a dichotomy to facilitate discussion. Yet these two streams have been fairly distinct, for which reason they also have many names such as being called the *classic computational theory of cognition* versus the *empirical* approach (W. M. Ramsey, 2007) or the *componential computational theory of mind* versus *embodied cognitive science* (M. L. Anderson, 2014) among others. Also, GC will be treated as mostly similar to the term embodied cognition, the overlap is large enough in the discussion of mental representations that this distinction will be irrelevant. In those mentions where it is relevant, it will be explicitly stated.

of GC without them, that aligns fully with LMC approaches like the free-energy principle (sections 11-15).

This dissertation will proceed as follows (for overview, also see Table 1). To begin, I outline the SCS, GC, and LMC approaches. Next, I view GC from the perspective of LMC. If GC harbors cartesian stowaways from SCS, these will be in conflict with LMC and thereby uncovered. Identifying and evidencing one such stowaway would warrant a full analysis of the foundational assumptions of GC theorizing. The cartesian stowaway which this LMC perspective uncovers is that GC has limited the types of representations which can ground concepts, neglecting representations of physical invariants. In **Article I** and **Article II**, this stowaway is analyzed and consequently tested, providing theoretical and empirical evidence in favor. These articles demonstrate that GC does indeed harbor cartesian stowaways, which motivates the need to rid GC of these cartesian stowaways, warranting a full analysis of its assumptions. It also demonstrates a weakness of the cartesian approach generally, motivating the need to align GC with LMC. In order to identify all cartesian stowaways, and consequently rid GC of them, I consequently assess cartesianism in its entirety. First, its most foundational aspects, the worldview underlying cartesian approaches to science (based in Euclidean geometry), then research strategies it produces (proceeding by decomposition and localization), and finally, most specifically, the types of theories produced by these strategies (boxes-and-arrows theories), are described. With this clear picture depicting the deep chasm between these approaches across different levels of the research process, I progress to a comprehensive assessment of these assumptions in SCS', LMC's, and GC's theories. This not only leads to the conclusion that GC is heavily shaped by these cartesian stowaways, but also the need to generate a reading of GC without them. In **Article III**, a non-cartesian reading of GC, the 'minimalist account', is then produced. Next, in **Article IV**, the strength of this account is demonstrated as it is aligned with the LMC theory of predictive processing. Summarizing, in this dissertation, I motivate and formulate a non-cartesian and biologically plausible, description of the format of mental representations, which is supported by – and extends – converging literatures on predictive processing, grounded cognition, structural representations, and others. For a full overview of the articles and their role in this aim, see Table 1.

The endeavor undertaken here is a timely and necessary step. It is only now possible, because the relative novelty of LMC did not allow to look at GC 'from the outside'. With no alternative theory, it is exceedingly difficult to recognize implicit assumptions. GC originated from severe theoretical shortcomings of SCS (e.g., Harnad, 1990; Searle, 1980). At the time, only the very radical ecological approach (e.g., Gibson, 1979) could serve as a contrast[2]. Recently though, the advent of prediction-error minimization approaches offers a different view of cognition, which is nonetheless compatible enough to allow assessing GC's implicit assumptions. Furthermore, while GC has made progress, its general postulates are still mostly in line with the theoretical positions of its central theories from before 2000 (Barsalou, 1999; Lakoff & Johnson, 1980). Around that time, the seminal study which formed the vanguard of predictive coding in the mainstream (Rao & Ballard, 1999) was published. Since then, prediction-error minimization theories like the Free-Energy Principle have not only been formulated and developed, but also become leaders in their fields (Hohwy, 2020; Poth, 2022). It may be that GC is now between one old and one new world and is rife for detailed theoretical comparison.

[2] Although it may be argued that connectionism (e.g., Rumelhart et al., 1986) also constitutes a contrast to SCS, it is still mostly committed to the vast majority of theoretical details in SCS (O'Brien & Opie, 2006; Smolensky, 1988). Also, it must be acknowledged that some early work on LMC indeed predates even much of the SCS discussed here (e.g., Maturana, 1970; Maturana & Varela, 1980), yet it is uncontroversial to state that the majority of work on this came later with the mid-1990s' surge of work on A-Life (e.g., Godfrey-Smith, 1994; Wheeler, 1997).

**Table 1**
*Listing of the Articles in this dissertation and their respective role in argumentation*

| Sequence | Article Title | Role in Dissertation Argumentation |
|---|---|---|
| **Article I** | Physical Invariants in Abstract Concept Grounding – The Physical World in Grounded Cognition | Identification of a cartesian stowaway in GC – Theoretical evidence |
| **Article II** | Grounded cognition and the representation of momentum: abstract concepts modulate mislocalization | Identification of a cartesian stowaway in GC – Experimental evidence |

- Articles I and II together demonstrate that GC harbors a cartesian stowaway, motivating a full analysis of GC to identify cartesian stowaways.
- They also demonstrate that these cartesian stowaways prevent GC from incorporating new evidence, constituting a theoretical weakness. This motivates the consequent LMC-formulation of GC

| Sequence | Article Title | Role in Dissertation Argumentation |
|---|---|---|
| **Article III** | Issues in Grounded Cognition and how to solve them – The Minimalist Account | A formulation of GC without cartesian stowaways, i.e., a holistic version |
| **Article IV** | Higher-Level Cognition under Predictive Processing: Structural Representations, Grounded Cognition, and Conceptual Spaces | Because the minimalist account is holistic, it can be transplanted onto other, biologically plausible, LMC theories, like predictive processing |

- This transplantation produces a description of the format of mental representations under predictive processing and GC which is holistic and in line with LMC.

Before progressing to examining these approaches, it is important to note that many terms used in this dissertation like 'complexity' or 'self-organization' are often associated with ecological approaches like the dynamical hypothesis (Gelder, 1998), radical embodiment (Chemero, 2013), or enactivism (Hutto & Myin, 2012). These ecological approaches are loaded with a host of other, more radical, theoretical addenda such as denying mental representations. The current discussion and subsequent use of the insights gained from complexity science should not serve to suggest allegiance to these other radical implications of such approaches. Furthermore, a short note on terminology. The respective terms introduced above (SCS, GC, LMC) can be classified varyingly as theories, frameworks, approaches or models, depending on how they are used. This use is not consistent in literature, and they also carry different names in different texts. For current purposes I have used these three names, SCS, GC, LMC because they are common and simultaneously specific. Furthermore, I will call them theoretical approaches. This captures their breadth, as I discuss the general practices throughout the respective field. Therefore, I am not focusing on one specific theory, unless stated otherwise (such as when mentioning the 'free-energy reading of LMC'). Similarly, I will use the term *phenomenon* in line with the APA definition of the term: "an observable event or physical occurrence." The term is intentionally vague in order to capture any sort of thing which one intends to explain with a theory (cf. Bogen & Woodward, 1988; Haig, 2013). It is now possible to begin looking at these different theoretical approaches.

### 1.1. Standard Cognitive Science

SCS relies on the central motif of the computer metaphor, in which the brain is viewed as a computer. This corresponds to a view of cognition which argues that cognition is computation using algorithms over logic (e.g., Gallistel & King, 2009; Newell, 1980). More than a guiding metaphor, this view is central to SCS, so much that it is often simply called the computational approach (e.g., Edelman, 2008; Shagrir, 2006). The computer metaphor argues that the brain has the structure of, and functions like, a computer, and often it is argued that because the brain literally computes, it is also literally a computer (Maley, 2022). Specifically, a computer is made up of dedicated modules, such as a hard drive which acts as long-term information storage, a RAM module which stores intermediate calculations, or a CPU which executes sequences of arithmetic logical operations. The computer's total function is then made up of these. Each module performs only its specific tasks (e.g., the CPU cannot act as long-term storage). Computations, i.e., the processes performed by a computer, are sequential steps in which input is transformed into symbols, which are transformed by algorithms to produce other symbols which are transformed into output (D. A. Patterson & Hennessy, 2017). SCS postulates the same structure and functions in the brain. It argues for a *modular* architecture where perception, cognition, and action constitute modules in the brain which are distinct from each other and are each in turn made up of individual modules. Accordingly, in the module for cognition, there is e.g., a "language faculty" exclusively responsible for language production and comprehension, or a long-term memory separate from working memory (e.g., Tooby & Cosmides, 1992). Beyond consisting of encapsulated modules, these also interact uni-directionally, in which cognition is distinct from and sandwiched between perception and action, and each of module is connected to the others via a one-way path, such that perception has no influence on action and vice versa (Hurley, 2001; Marr, 1982). This is especially argued for perception, which is assumed to be fully encapsulated such that visual perception is unaffected by other modalities (e.g., auditory perception), and by higher-level cognition (e.g., Firestone & Scholl, 2016; Fodor, 2001). Furthermore, in this view, just as the hardware of the computer is independent from its software, the body has no special role, and is functionally (at least to cognition) equivalent to any other object in the world (Wheeler, 1997).

The format of mental representations under SCS also takes inspiration from the computer. If the brain works using algorithms to process information (Gallistel & King, 2009; von Neumann, 1958; Pylyshyn, 1984), correspondingly, the format of mental representation should be discrete and amodal symbols (e.g., Carello et al., 1984). Some views go as far as arguing that if neurons are digital, because they are either on or off, i.e., firing or not firing, cognition must also be digital, just like a computer working over 1s and 0s (e.g., Edelman, 2008). I return to the notion of digital computation later. Perhaps the most successful program of SCS is the Language of Thought Hypothesis (Fodor, 1975; Quilty-Dunn et al., 2022). This approach argues that cognition is made up of a language (sometimes called 'mentalese') made up of symbols, analogous to words. These have, for example the format of "ON(cat, mat)" to describe the state that a cat is lying on a mat. Cognition then involves the transformation of such structures via algorithms.

SCS is argued to be a cartesian *dualist* approach as its roots. Cartesian dualism originates from Descartes who postulated the existence of a non-physical substance, which can be called the mind or a 'soul', distinct and separate from the body (Blackburn, 2008; Wheeler, 2015). In modern cognitive science, these esoteric roots are reigned in, and a cartesian approach to cognitive science argues that the mechanisms which underpin cognition are qualitatively different from those which underpin perception or action (Foglia & Wilson, 2013). One of the foremost theories underpinning the cognitive revolution, Chomsky's linguistics, explicitly classifies itself as cartesian (Chomsky, 1966) and Jerry Fodor, one of the flagbearers of the SCS approach calls his theory "neocartesian" (Fodor, 1983, p. 2). SCS is cartesian because nowhere in nature could one find symbols. Even within the body, the symbol-based cognition is distinct and qualitatively different from the processes and abilities underlying perception or action. This is captured by Pylyshyn (1980), who explicates that there is a difference in kind between human cognition and the kinds of phenomena in nature, speaking to "the fundamental distinction between 1) behavior governed by rules and representations, and 2) behavior that is merely the result of the causal structure of the underlying biological system." (p. 112).[3] Despite most research in cognitive science and

[3] The discontinuity of this process is often justified arguing that the ability for language (and thereby sophisticated cognition) evolved not gradually over time, but rather by a single 'great leap forward' in the form of a genetic mutation (Berwick & Chomsky, 2017).

psychology not explicating adherence to a computer metaphor or explicitly proposing a language of thought, SCS is usually called the classic or standard approach (W. M. Ramsey, 2007; L. A. Shapiro, 2019) because the cartesian dualism is so wide-spread that it constitutes the default. For example, one seminal textbook on cognitive psychology describes SCS' modularity as a "key assumption" (Eysenck & Keane, 2020, p. 8) throughout cognitive psychology generally. Therefore most works, on closer inspection of their theoretical frameworks, do have the lingering assumptions of cartesian dualism (Cisek, 1999; Mudrik & Maoz, 2015).

### 1.2. Grounded Cognition

As GCs details are discussed in depth in all four of the articles in this dissertation, I will discuss here only those points necessary to proceed until then.

In contrast to SCS, GC research argues that mental representations of concepts consist of the same representations which are used to guide action and perception (Fischer & Coello, 2016; Glenberg, 1997). In place of words in a language of thought, GC puts forth re-activations in sensory and motor systems. For example, when considering the concept of a CHAIR the format of this mental representation is the same as that evoked when perceiving a chair or acting with it, such as seeing, touching, moving, sitting on, or throwing the chair (Barsalou, 1999; J. J. Prinz, 2005). This supported by vast evidence from brain (e.g., Dobler et al., 2024; Harpaintner et al., 2020; Pulvermüller, 2005) and behavior (e.g., Boroditsky & Ramscar, 2002; Kaschak et al., 2005; Pecher et al., 2003). The two central theories in GC are *perceptual symbol systems* (Barsalou, 1999; Barsalou & Wiemer-Hastings, 2005) and *conceptual metaphor theory* (Johnson, 2010; Lakoff, 2014; Lakoff & Johnson, 1980). More recently, other theories have provided novel perspectives such as the *Affective Embodiment Account* (Vigliocco et al., 2014) or the *Words as Social Tools* approach (Borghi & Binkofski, 2014), which extend these notions. These extensions typically include novel types of representations which can ground concepts, such as language, social metacognition, and emotions (Muraki & Pexman, 2024; B. Winter, 2022). Additionally, beyond the postulates of specific theories, recent synthesizing work on GC has increasingly argued that, while many mental representations will rely on perception- and action-based mental representations, many others are also represented by language (Dove et al., 2022; Muraki et al., 2023). It is argued that especially abstract concepts, such as DEMOCRACY, are defined by intangible features which therefore by definition cannot be grounded in perception or action, making the use of language critical.

Where the SCS approach above exhibited dualism in the format of its mental representations, GC posits *monism*. As mentioned above, under the cartesian dualist view, cognition has different qualities than those found elsewhere in human behavior, biological organisms, or most generally, nature (Favela & Chemero, 2023; Gefei, 2023). Monism describes the position that all things are made up of the same material, and that the mind is not distinct from mechanisms from nature, but rather a progression and continuation of the same principles (Godfrey-Smith, 2021; H. Robinson, 2023). In the current context, the format of mental representations in GC is identical to the format posited for perception and action.[4] This is also evident in the literature, where GC is commonly framed as the direct opposition to cartesian approaches (e.g., Cuccio & Gallese, 2018; Johnson, 1987; Lakoff & Johnson, 1999). Additionally, while the modularity assumption divides cognition into different faculties, GC has been portrayed as bridging these separate faculties because it argues that the same substrate underlies all of them (Glenberg, 2010).

### 1.3. Life-Mind Continuity

LMC argues that the emergence of life corresponds to the emergence of mind (i.e., cognition)[5]. Specifically, the fundamental principles that drive the development of living organisms also drive the development of cognitive abilities (Godfrey-Smith, 1994; E. Thompson, 2010). The stark difference between this approach and typical cognitive science, and the fact that it is not repeated in any of my articles, means it demands a more detailed explanation than the other approaches.

To arrive at the fundamental principles that drive life and cognition, it is necessary to look at what the process of living entails. Already Schrödinger (1944) identified, in his aptly titled essay "What is life?", that biological organisms maintain their structure over time, in resistance of the second law of thermodynamics which states that all systems tend toward entropy. He argued therefore that living systems are characterized by their ability to maintain organization over time[6]. If the particles that make up a human were organized differently, in the overwhelmingly vast majority of other constellations it would immediately become a pile of sludge instead of a living human. One can conclude that for a

[4] It may be argued that language violates this, but this is not necessarily so. Firstly, the theories applying language, portray it as a tool or device which is exploited by the embodied mind. Therefore, in examining their position vis à vis monism, it can nonetheless be argued they a priori assume that cognition involves the same features as other perception and action, irrespective of what additional artifacts human minds conjure to aid them in cognition. Second, language is often conceptualized as nonetheless relying on embodied mechanisms like inner speech (e.g., Borghi & Fernyhough, 2022), therefore the format is nonetheless not the format of a symbol.

[5] It can here be noted that, any theory of cognition under LMC must therefore also apply to life and vice versa. This incurs great benefit on a meta-theoretical position, because this means that joining these two phenomena (life and mind) into a single framework constrains each. The necessity for constraints on cognitive and psychological theories has been recently emphasized as a critical focus for future theoretical development (Craver & Darden, 2013; Eronen & Bringmann, 2021).

[6] Even earlier, Spencer (1864) had already emphasized the importance of organization in living systems.

system to remain alive, and therefore to remain organized and resist entropy, it must react timely to environmental features which threaten this organization (Friston, 2013; Kauffman, 1993; Maturana & Varela, 1980; Morowitz, 1968). These threats include those classically viewed as such, e.g., predators, but also more menial everyday threats to organization such as external temperature or energy demands. A useful method for a system to achieve an adaptive and timely reaction to environmental threats comes from cybernetics, where the *good regulator theorem* states that "any good regulator of a system must be a model of that system" (Conant & Ashby, 1970). Cybernetics therefore argues that to enable appropriate and timely response, the system must be (or have) a model of itself and its environment. This is not a direct mirroring, but rather that the organism carries the relevant semantic information (Kolchinsky & Wolpert, 2018), like a key which is a model of a lock (Shepard, 1981). One can take a bacteria which has evolved to move left when there is food to the left (as opposed to moving randomly) as an example of being an abstract model of the environment (Karl, 2012; Kirchhoff, 2018).

The life-mind continuity thesis proposes then that this same principle should underlie cognition. In evolutionary development, organisms progressed from being a model of the environment in their phenotype to having a model in the form of a nervous system. Continuing the cybernetic solution, this approach argues that the brain acts as the central regulator for the system (Conant & Ashby, 1970; Wiener, 1948). The brain then attempts to, instead of being a model of its environment, carry a – now much more flexible – model. Specifically, cognition is the product of aiming to maintain a correspondence between the internal states of an organism and the external environment. For example, reacting to anticipated outside temperature changes (e.g., approaching nightfall) by reducing perspiration. Yet, such an account may be perceived as deflationary and intuitively unsatisfying because, while this reading may provide a satisfactory description of *what* cognition is, it tells little about *how* it does this.

The *free-energy principle* is a framework, within the LMC approach, that specifies these cybernetic insights from the past and describes how such imperatives lead to cognition (Friston, 2010; Friston et al., 2023). It states that cognition involves maintaining the model such that the discrepancy between the model and the environment, here called prediction error, is minimized over the long term. This gives rise to predictive coding[7] schemes like *predictive processing*. For this reason, the free-energy principle also

[7] The host of names associated with these frameworks may leave some readers confused. Predictive coding, hierarchical predictive coding, prediction-error minimization framework, predictive processing, action-oriented predictive processing, active inference, Bayesian brain approaches and the free-energy principle all share many central tenets to the point that they are exchangeably used. There is no convention regarding this terminology, but for the course of this dissertation, I will use the term *Free-Energy Principle* to describe the notion of life self-organizing in order to carry a model of the environment. The free-energy principle uses the mechanisms of the framework called *predictive processing* when applied

aligns with many other Bayesian[8] prediction-error minimization frameworks. How to connect this principle with the cognition one knows from everyday life requires looking at how the imperative to maintain homeostatic balance by prediction-error minimization is scaled up. When stating that a system maintains its organization, one can describe this as the need to revisit certain, desirable, states of homeostatic balance (e.g., a body temperature around 36°C or a heart rate roughly between 40 and 200 beats per minute). These states become predicted, and therefore desirable, giving rise to higher-order goals. The everyday cognition one knows are then goals serving the prediction of revisiting these states in the long term. For example, hunger gives rise to a higher-order goal (in the form of a prediction) of satiation by eating. This triggers action to minimize such a prediction-error. For example, the action produced by this prediction is to go to the supermarket, buy food, return home, and cook (Pezzulo & Cisek, 2016). Similarly, going for a run (which brings the body out of homeostatic balance, and therefore further away from the desirable states) also serves the goal of maintaining homeostasis, because in the long run it improves health or because it helps to get to know the neighborhood, thereby reducing future prediction-error (Clark, 2018; Van de Cruys et al., 2020).

LMC is, just like GC and in contrast to SCS, monistic (Friston et al., 2020). It emphasizes at its core, that cognition is not qualitatively different from other processes in human behavior, biological organisms generally, or even most generally, all moving particles (Friston et al., 2023; Wiese & Friston, 2021). It must be clarified here, that the phenomenon under investigation (human cognition) is evidently different, as a human's ability to perform complex cognitive operations is different from a

to cognition. The conclusions I draw are not limited to either of these two frameworks, but rather to most hierarchical predictive coding frameworks.

[8] A short note on the role of 'Bayesian' in this context: Bayes' theorem allows to get insight into an unknown probability distribution, which is critical for the brain, which is solely supplied with stimulation at a variety of sensory receptors. Unlike e.g., neural networks which are supervised (a network is trained by providing it supervision in the form of a number of 'correct' answers, and then applying this trained network to novel datasets), the brain must arrive at a picture of the world with solely internal 'guesswork'. One metaphor equates the brain with a person locked in a control room of a machine, tasked with controlling this machine. This control room, without windows, has access to the outside only via blinking lights and certain levers and buttons. This person must then understand a mapping between the flashing lights and the relation with the levers. In order to arrive at this mapping, such a person is likely to use as a point of departure an idea of what could be outside, and compare this to the inputs they are getting (Dennett, 2013, ch. 23). In Bayesian terms, this person in the control room is getting data (i.e., flashing lights) and has some hypothesis about what could be outside the machine causing these (i.e., the actual state of the world). Formally, with solely the three probability distributions of 1) the data generally $P(d)$, 2) the probability of my beliefs given the data $P(h|d)$, and 3) the probability of my hypothesis $P(h)$, I can glean insight into the probability of my data given what I believe $P(d|h)$, i.e., what is outside (the control room or brain). On the Bayesian brain reading, this corresponds to the ability to gain insight into the actual state of the world by inverting the $P(h|d)$ (cf. Hohwy, 2013, ch. 2). This discussion pertains to the notion of perception as inference (cf. Gregory, 1980; Helmholtz, 1866). The role of Bayesian probability is not further pertinent to the ensuing discussion.

woodpecker's. Yet, the life-mind continuity hypothesis argues that these qualitative differences arise from a progressive increase in scale of the same basic principles, not in kind.

## 2. A Life-Mind Continuity Reading of GC

The stance underlying SCS is dualism (for its amodal symbols as the representational format, algorithmic logic, etc.) and underlying GC and LMC is monism (for their postulates of higher-level human cognition in line with basic perceptual or action; Robinson, 2023). Yet, such an *ontology* (a position on what exists in the universe) produces an *epistemology* (a position on what constitutes knowledge). An epistemological position, in turn, produces the theory and methodology of a research domain (Bhaskar, 1975; Crotty, 2020).

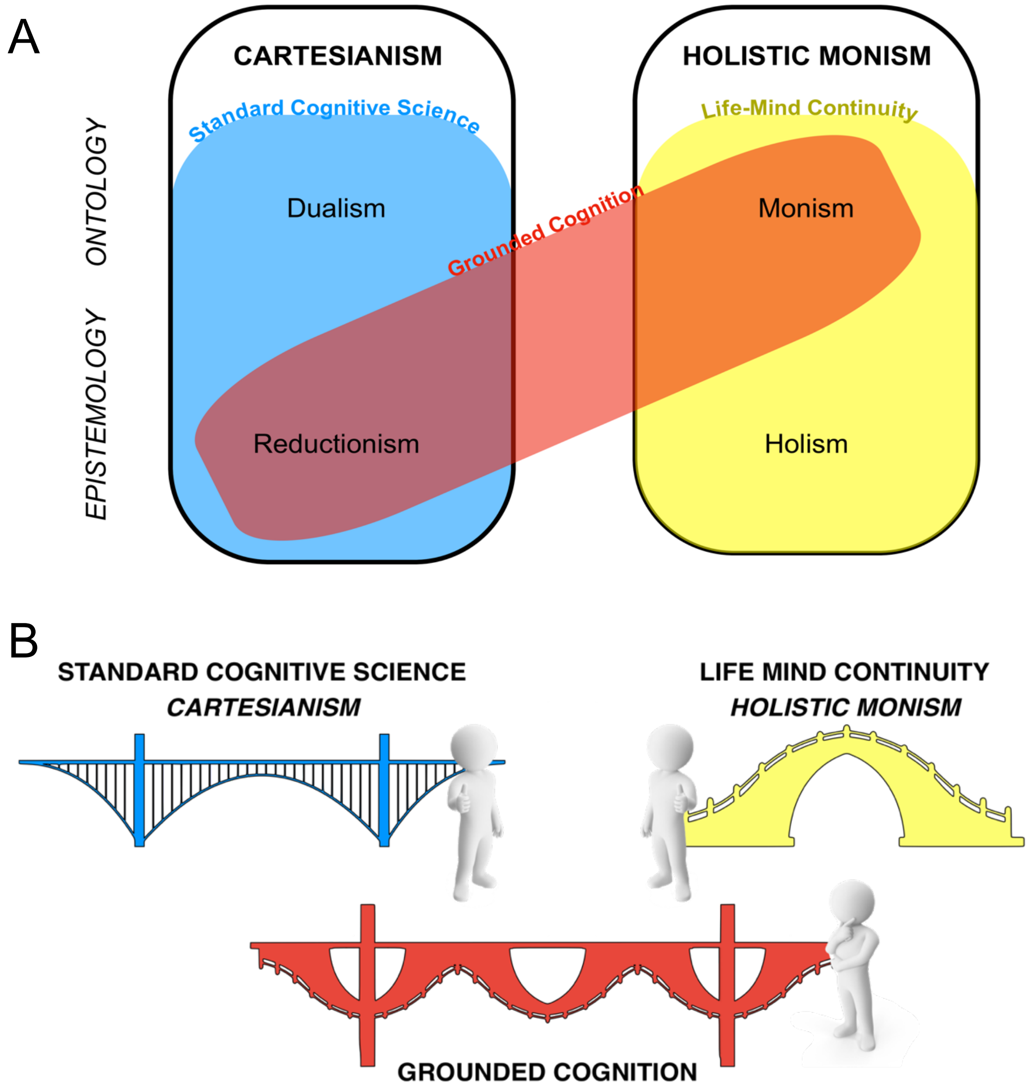
Dualism's corresponding epistemological position is called *reductionism*, which is consequently also the epistemology underlying SCS (M. L. Anderson, 2014; E. Thompson, 2010). The reductionist epistemological position states that to understand a given phenomenon (e.g., cognition) it should be divided into parts which are then understood in isolation and later added together to understand the more general phenomenon[9]. In fact, René Descartes, beyond contributing the mind-body dualism, also argued that science should progress by reductionism, and this practice is called *Cartesian Reductionism* (Overton, 2002). Here, the general position of dualist ontology and reductionist epistemology will therefore be named for Descartes: *Cartesianism*. On the other hand, monism produces the epistemology *holism*, which emphasizes the need to view phenomena as a whole. It argues that reducing a phenomenon to its constituent components loses the many important interactions between parts which constitute phenomena, especially in the life sciences (Nagel, 2007; Sarkar, 1998). Therefore, I will use *cartesianism* (Dualism and Reductionism) and *holistic monism* to describe the general set of ontological and epistemological positions that build on one another and that underlie the two streams of research, SCS and LMC, respectively. The theme central to this dissertation is where GC is situated within these, and

[9] The epistemological (or also called mechanistic) reductionism I speak of here is not to be confused with ontological reductionism. Ontological reductionism states that explanations of phenomena should involve more fundamental sciences. It would therefore attempt to explain psychological phenomena by neuroscience, neuroscience by biology, and so on (Bickle, 1998; Oppenheim & Putnam, 1958). As Crick put it: "the ultimate aim of the modern movement in biology is to explain all biology in terms of physics and chemistry" (Crick, 1966). Although if one takes the position that mental states are nothing over and above a brain state (i.e., ontological reductionism), it is likely that one arrives at a description of these phenomena with few isolated components (i.e., an epistemological reductionism), this is not necessarily so. For example, Jerry Fodor who is a dedicated epistemological reductionist, is explicitly against ontological reductionism (Fodor, 1974).

especially not only in the explicit constructs it posits, but also the assumptions reflecting its epistemology that underlie the constructs and theories which they populate.

**Figure 1**

*Two schematic depictions of the meta-theoretical tension in GC.*




*Note.* 2A (top) portrays the epistemological and ontological assumptions of the three theoretical approaches. SCS, coded as blue, aligns squarely with cartesianism in both its dualist ontology, as well as its reductionist epistemology. Similarly, LMC, coded as yellow, aligns with holistic monism in its monistic ontology and holistic epistemology. GC, coded as red, on the other hand, straddles both; having a monistic ontology and a reductionist epistemology. Second, 2B (bottom) metaphorically depicts the consequences of lacking the full commitment to either approach. Both LMC and SCS are depicted as different approaches, that because they are coherent in their assumptions, arrive at viable frameworks in different ways (here depicted as different methods of building stable bridges). GC, on the other hand, is not coherent in its approach, choosing different aspects of both, generating instability. GC's theories are therefore unviable (here, an unstable bridge) because they are not coherent.

### 2.1. Identifying a Cartesian Stowaway

GC is, on its surface, much more aligned with holistic monism. Yet, as mentioned above, it still retains some cartesian stowaways, suggesting that it may still, below the surface, be wedded to SCS. To motivate the later holistic monism reading of GC, it is first necessary to identify whether GC retains cartesian stowaways. If this is the case, there is sufficient reason to perform a full analysis of GC's epistemological commitments. With the aim of this first step, assessing the degree to which GC carries cartesian stowaways, it is useful to look at it through the lens of LMC, which reflects true holistic monism. If GC is seen to violate the basic postulates of LMC, this suggests a cartesian stowaway. To assess this, we can look to the topic of *physical invariants*, which are unchanging features of physical motion. The mental representations of these are called *invariant representations*. Specifically, does GC allow for grounding in invariant representations?

The limits of GC are conventionally set at the body, yet, this may be an implicit cartesian assumption. It is cartesian because the ontological position of dualism is based on modularity, and the limiting of grounding substrates to within the body reflects a dualist position (Favela & Amon, 2023). While SCS draws an impenetrable line between modules, GC draws this line at the body, but in both cases a line is drawn. SCS places a privileged locus in the brain, and GC in the body, but the underlying practice is nonetheless that of one specific milieu. The postulation of a distinction such that perceptions of bodily states are privileged, and external states are inaccessible to the grounding mechanisms therefore constitutes a cartesian stowaway. It is also implicit, meaning this postulate was not based on research. It originates, not from testing which has arrived at these limits, but rather from implicit boundaries produced by ontological assumptions.

### 2.2. Evidence of a Cartesian Stowaway

Why should physical invariants be investigated so closely? This possibility is supported from a theoretical argument from fields adjacent to GC. The basic premise of grounded cognition is the assumption that the description of cognition is not necessarily confined to brain-states (Clark, 2008). Other, similar fields have treated the limits of cognition more liberally. Indeed, GC is just one of four well-known challenges to SCS. In literature on *4E cognition* (embedded, enacted, embodied, and extended)[10], with GC often being synonymous with embodied cognition. Another of these E's is *extended cognition*. It does not just argue that cognition involves the body, instead, it argues: Cognition extends into the environment (Clark & Chalmers, 1998; Rowlands, 2010). Work in this field typically involves the integration of temporary environmental features into the cognitive system. For example, experienced Tetris players do not figure out whether a candidate shape fits into a certain place with internal cognitive processing, but rather externalize this cognitive process by rotating the shapes on the screen (Kirsh & Maglio, 1994). Grounding concepts is, admittedly, a more permanent process than solving problems by using the environment as a scaffold. Yet, extended cognition demonstrates that there is no a priori reason to draw a limit to grounding at the skin. Especially, as other work has already demonstrated that the unchanging features of the environment shape the experiential grounding of concepts (M. H. Fischer, 2012; Myachykov et al., 2014).

This suggestive evidence further underlines that there is little justification, if one takes the GC approach, to exclude the possibility of grounding in physical invariants. In fact, GC's basic argument is that cognition is not purely symbol-based and brain-bound, and that it instead exploits the perceptual and action information arriving at its sensory receptors (Clark, 2008). It does not follow from this statement, that cognition must then instead be skin-bound. In fact, to my knowledge there are no papers or positions on where to draw the limit. There is no mention of grounding outside of body-based representations in any of the classic theories. To my knowledge, except for Talmy's (1988) work on force dynamics which is absent from any modern accounts, and a series of unpublished experiments (Madden & Pecher, 2007), physical forces have been absent from GC theorizing. The totality of grounding substrates classically encompasses the sensorimotor system, interoception, emotion, and social relations. This absence is also not justified. The seminal introduction of perceptual symbol systems, which argues that mental representations consists of simulations mentions physical invariants when arguing in favor of the ability to simulate generally (Barsalou, 1999, p. 589). Yet, despite evidently arguing that it is possible to simulate physical invariants, and stating that simulation is how concepts are mentally represented, the possibility that simulations of physical invariants play a role in concepts is not mentioned. The decision to limit representations for grounding to the body in this and other seminal texts, was therefore not explicit. This contrasts with the view in LMC approaches, though, which make no such a priori exclusions. These attributes of GC literature therefore suggest, firstly, that there is no

[10] I refer to 4E cognition here, despite being aware of other formulations such as 6E (e.g., McCauley, 2023), 7E (e.g., Johnson, 2018), or 8E (e.g., Pelkey, 2023) cognition. 4E is the most typically used (Newen et al., 2018), and as the notion of extended cognition is present in all formulations of #E cognition, it is irrelevant which is chosen.

evidence from GC literature excluding the possibility, and second that it in fact aligns well with its central postulates. Its quiet exclusion therefore, is suggestive of a cartesian stowaway.

In the free-energy principle reading of LMC, predictions are generated using a rich model of the internal and external world. This means that not only, e.g., interoceptive sensations (Seth & Friston, 2016) or motor execution can be simulated (Adams et al., 2013), but also the external world, such as simulations of gravity (Jörges & López-Moliner, 2017; Torricelli et al., 2022). Indeed, there is a vast literature on the models of physical laws which humans apply to interact with the world (for full discussion see **Article I**; McIntyre et al., 2001; Zago et al., 2008). Beyond the free-energy principle, it seems plausible, when assuming that life and cognition are one continuum, that physical laws, which are critical for effective interaction with the environment in all life forms, should be represented. Therefore, an LMC reading clearly suggests that physical invariants are on par with bodily representations[11].

If demonstrated, this expansion of grounding substrates has important implications. It suggests that grounding substrates, and therefore potentially all of GC theorizing, is unnecessarily constrained by cartesian stowaways. This would consequently warrant a deeper investigation into the potential other implicit cartesian stowaways in GC. To test this, the first two articles of this dissertation will be concerned with the notion of physical invariants. We begin with **Article I** which summarizes the state of research, demonstrating that there is ample theoretical support for the notion that mental representations are grounded in physical invariants. Consequently, we transfer this theoretical possibility into an empirical test in **Article II**. In 4 experiments we assess whether the abstract concept of SUCCESS is grounded in the physical invariant momentum.

[11] Of course, bodily sensations are likely more important, because they are much more relevant for survival. Yet, they do not reflect distinct categories.

# 3. Article I: Physical Invariants in Abstract Concept Grounding – The Physical World in Grounded Cognition

Friedrich, J.; Fischer, M.H.; Raab, M.

In: *Psychonomic Bulletin and Review* 31, 2558–2580 (2024)

**Abstract**

Grounded cognition states that mental representations of concepts consist of experiential aspects. For example, the concept 'cup' consists of the sensorimotor experiences from interactions with cups. Typical modalities in which concepts are grounded are: The sensorimotor system (incl. interoception), emotion, action, language, and social aspects. Here, we argue that this list should be expanded to include physical invariants (unchanging features of physical motion; e.g., gravity, momentum, friction). Research on physical reasoning consistently demonstrates that physical invariants are represented as fundamentally as other grounding substrates, and therefore should qualify. We assess several theories of concept representation (simulation, conceptual metaphor, conceptual spaces, predictive processing) and their positions on physical invariants. We find that the classic grounded cognition theories, simulation and conceptual metaphor theory, have not considered physical invariants, while conceptual spaces and predictive processing have. We conclude that physical invariants should be included into grounded cognition theories, and that the core mechanisms of simulation and conceptual metaphor theory are well-suited to do this. Meanwhile conceptual spaces and predictive processing are very promising and should also be integrated with grounded cognition in the future.

Keywords: embodiment, physical invariants, concepts, predictive processing

# 4. Article II: Grounded cognition and the representation of momentum: abstract concepts modulate mislocalization

Friedrich, J.; Raab, M.; Voigt, L.

In: *Psychological Research* 89, 51 (2025)

**Abstract**

Literature on grounded cognition argues that mental representations of concepts, even abstract concepts, involve modal simulations. These modalities are typically assumed to reside within the body, such as in the sensorimotor system. A recent proposal argues that physical invariants, such as momentum or gravity, can also be substrates in which concepts can be grounded, expanding the assumed limits of grounding beyond the body. We here experimentally assessed this proposal by exploiting the representational momentum effect and the abstract concept of success. If success is grounded in the physical invariant momentum, the representational momentum effect should be larger for successful targets. We tested this hypothesis across four experiments (three pre-registered). In a surprising finding, we find hints that large trial numbers may hinder being able to find a representational momentum effect, which should be further investigated in future research. Regarding the central hypothesis, although only one experiment found statistically significant support, the effect tended toward the same direction in the three others as well. In order to draw robust conclusions about the results, we performed a mini meta, which aggregates the effects and inference statistics across the $N = 271$ participants. Across the four experiments, this effect was statistically significant, suggesting evidence in favor of the central hypothesis. These results should be interpreted with caution as there was inconsistency across experiments, suggesting the magnitude of the effect is small, and when asked who they believe moved faster, participants did not reliably indicate the successful target.

*Keywords:* embodied cognition, representational momentum, biomechanical movement, physical invariants, invariant representations

## 5. The Role of Invariant Representations

In these two articles we investigated the possibility of grounding concepts in physical invariants. We began in **Article I** by looking to past literature on physical invariants and their representation in the brain. This past literature suggests a rich representation of physical invariants in which not only the movement, but also the kinetic force which generates movement of objects, is represented. With this overview in hand, we investigated whether the central theories of GC (perceptual symbol systems and conceptual metaphor theory) could nonetheless explain how physical invariants could come to represent concepts. Indeed, they could not, because they were too inflexible and their postulates too specific. In contrast, two other theories, predictive processing and conceptual spaces, were able to explain the grounding in physical invariants. This theoretical argument was supported in **Article II** by experimental evidence in which the representation of momentum (a physical invariant), as measured by a moving target's representational momentum, was modulated by this target's description as either successful or as a failure. We find that that the abstract concept SUCCESS is grounded in the metaphoric representation of momentum.

First, these articles suggest that it is possible to ground concepts in invariant representations. Specifically, we find evidence for what we termed in **Article I** as the strong version of our proposal, that invariant representations can even ground abstract concepts. These two papers constitute an important development, as it is not common that novel grounding substrates are uncovered. It crucially incurs also the addition of kinetic force into the representation of concepts. Indeed, the empirical test, which exploits the *representational momentum effect* (cf. Freyd, 1987; Hubbard, 2019), manages to depict this kinetic force. According to this reasoning, because the forward movement of the stimuli used was identical across conditions, the observed forward bias in response in the SUCCESS condition is based in the underlying force propelling the stimuli. This finding suggests important consequences for applications in e.g., offside or pilot training. Yet, especially relevant for basic research is the theoretical implication that cognition exploits more of the information available to it than previously considered. Cognition does not just use the body, but also the physical features outside of the body.

This is broadly in line with the extended cognition views described above, and forms part of a recently posited "ecological turn" in cognitive sciences (Rasczaszek-Leonardi, 2016, 2023), which departs even further from SCS than GC. SCS has historically argued that the environment is impoverished and perception is poor, and that a sandwiched (see above, Hurley, 2001) cognition in the format of symbols is required to reconstruct this environment (e.g., Chomsky, 1980). On this reading, "all the essential action" (S. Gallagher, 2015, p. 97) takes place in the brain. On the other hand, in the ecological turn, especially 4E cognitive sciences are increasingly accepting and emphasizing the environment (and even artificial intelligences; Loock, 2025; White et al., 2025) as a constituent of cognition. Ecological approaches distribute the action, arguing that the environment is rich, and perception is privy to this rich information. Therefore, cognition must not reconstruct the environment, but oppositely, exploits the vast information available in it (Gibson, 1979). The evidence in favor of invariant representations in concept grounding aligns with this second, ecological description, and demonstrates how cognition has access to many features of the environment and readily uses these.

# 6. Aligning Epistemology and Ontology in GC

Second, in the larger context of grounded cognition theories and of this dissertation, the evidence in favor of invariant representations in concept grounding uncovers a cartesian stowaway in GC. Specifically, grounded cognition, despite its monistic stance assumes a modular division between internal and external. Such a modular division aligns with cartesianism, and contrasts with the LMC approach which is thoroughly aligned with holistic monism. Furthermore, the ability for predictive processing and conceptual spaces to account for invariant representations (cf. **Article I**) is not the result of wise premonition, but rather that these theories do not have GC's shortcomings. Therefore, not only does this cartesian stowaway constitute evidence of meta-theoretical tension, but also demonstrates shortcomings, that cartesian theories are closed off from new evidence.

These articles therefore suggest that GC should discard its cartesian stowaways and adopt the epistemology corresponding to its monist ontology, holism. For one, GC's combination of a monistic ontology in combination with a holistic epistemology, is dissonant and this constitutes a threat to the integrity of the theory (see Fig. 1). Second, the articles above suggest a more basic insight that touches on the role of assumptions generally and the need for theories of cognition to be biologically plausible to avoid being closed off from new evidence. I now shortly look at these conclusions in more detail and the consequences that these arguments carry for GC research, motivates a deeper reading of the reductionism-holism dichotomy, which will allow to identify and discard cartesian stowaways.

## 6.1. Why GC should align with Holism

Two basic reasons motivate the need for GC to be aligned with monism. The first reason to align GC with holism is that it is axiomatic that the approach one takes in attempting to formulate a theory (i.e., its epistemological stance) should align with what one believes to exist in the world (i.e., ontological stance; Bhaskar, 1975; Crotty, 2020). This is because the methods should be positioned such that they can generate the type of knowledge that the epistemology is interested in, and its epistemology should in turn be built on the most basic assumptions about the phenomena in question (Crotty, 2020). If one, for example, takes a realist position (in which there is an objective, unchanging reality outside of a researcher), the research program one develops will attempt to cancel out the influence of the investigator, by using e.g., quantitative techniques, as opposed to qualitative. This is very different if one assumes that all reality is only created relative to the investigator, in which one would make explicit one's subjective view and interpretation (Guba & Lincoln, 1994).

In the case of GC, there is no such coherence, because the theories contain the monist assumption that cognition is like all other parts of nature, yet simultaneously, its research practices, stemming from reductionism, investigate cognition under the assumption that it is unlike other natural phenomena. Such a state of theory, with inherent contradictions, will struggle to generate a coherent research program.

The second reason to align is that the theorizing of GC (as well as of SCS) has severe limitations because this epistemological position, reductionism, is in tension with what is known generally about biological systems. In other words, perhaps this epistemology has the shortcoming that it is not biologically plausible (Gilbert & Sarkar, 2000; Lyon, 2006). In fact, GC departed from SCS for good reasons, and these reasons include the fact that cognition likely evolved to support and coordinate action in an environment, making an evolutionarily discontinuous amodal symbol system, as posited by SCS, unlikely (Glenberg, 1997; Lakoff & Johnson, 1999). The distance between reductionist theories and the natural phenomena which they aim to explain, is in itself a weakness.

An example of the weakness introduced by biological implausibility found in a historically-minded look at SCS' central motif, the computer metaphor. The computer metaphor is not the first time that a currently-popular technological development has served to influence scholars' model of the mind. Half a century before the inception of the computer metaphor, the telephone exchange was believed to be an accurate model of cognition, two hundred years before that, it was clockwork, before that, the hydraulics underlying fountains, and for Aristotle and others at the time, it was a theatre (Cobb, 2020; Draaisma, 2000). This fact, that throughout history, scholars have used en-vogue technological developments as models of cognition (cf. also Gigerenzer & Goldstein, 1996), displaces the computer metaphor from its singular place as a model of cognition. Adherence to the computer metaphor therefore presumes the extraordinary circumstance that the current scholars are the privileged few that live during the invention of the final culmination of technological advancements (cf. Brette, 2022; Richards & Lillicrap, 2022)[12]. While the computer metaphor's unlikeliness is the result of a very obvious departure from what is known about biological systems, the detrimental consequences resulting from theories' failure to be biologically plausible is perhaps best demonstrated in the replication crisis.

### 6.2. The Detriments of a Reductionist Epistemology

The replication crisis involved many well-known effects in research failing to replicate (Camerer et al., 2018; Open Science Collaboration, 2015)[13], causing a loss of confidence in findings and widespread acknowledgement of need for reform. Many of the proposed reformations targeted more rigorous methodology, more vigilance of questionable research practices, or changes in incentive structures[14] (Cumming, 2014; Koole & Lakens, 2012; Zwaan, 2021). Yet, many argued that these failed replications rather signaled a *theory crisis* (e.g., Morawski, 2019; Oberauer & Lewandowsky, 2019). Specifically, it can be argued that these failures to replicate are caused by reductionism, which is inherently in violation of the complexity of natural phenomena, like psychological states. The reductionist approach to empirical testing of theory is formulated by Fodor: "It would be hoped that sufficient information about initial states, together with a viable theory of actions, would, in principle, permit the theorist to compute the pattern of motions that will realize a given action on a given occasion." (Fodor, 1968, p. 43). In other words, if one knows the beginning state, a theory should be sufficient to predict the consequent phenomena.

Widespread failures to replicate may suggest that reality deviates from this idealized scenario. Opponents of this reductionist approach to theory testing argue that typical research practices (including the methodological reformations proposed in response to the replication crisis described above), are operating under the assumption that research investigates *stable effects*, static and universal phenomena to be tapped into (see Fig. 2A), as opposed to changing, context-dependent phenomena which emerge from many interacting components (see Fig. 2B; Brandt et al., 2014; Yarkoni, 2020). This illusion of stable effects favors and even encourages a harmful methodological orthodoxy (see the discussion of

[12] Underlying the computer metaphor is also a general unlikelihood: scholars have fallen prey to the fallacy that current technological innovations depict cognition many times over. It seems unlikely that this time it would be different.

[13] Although often the discussion of the replication crisis focuses on psychological research, it is similarly prevalent in other fields like medicine (Hillary & Medaglia, 2020; Hope et al., 2021) or cognitive science (Huber et al., 2019; Miłkowski et al., 2018; for a recent multi-lab non-replication see Paul et al., 2025).

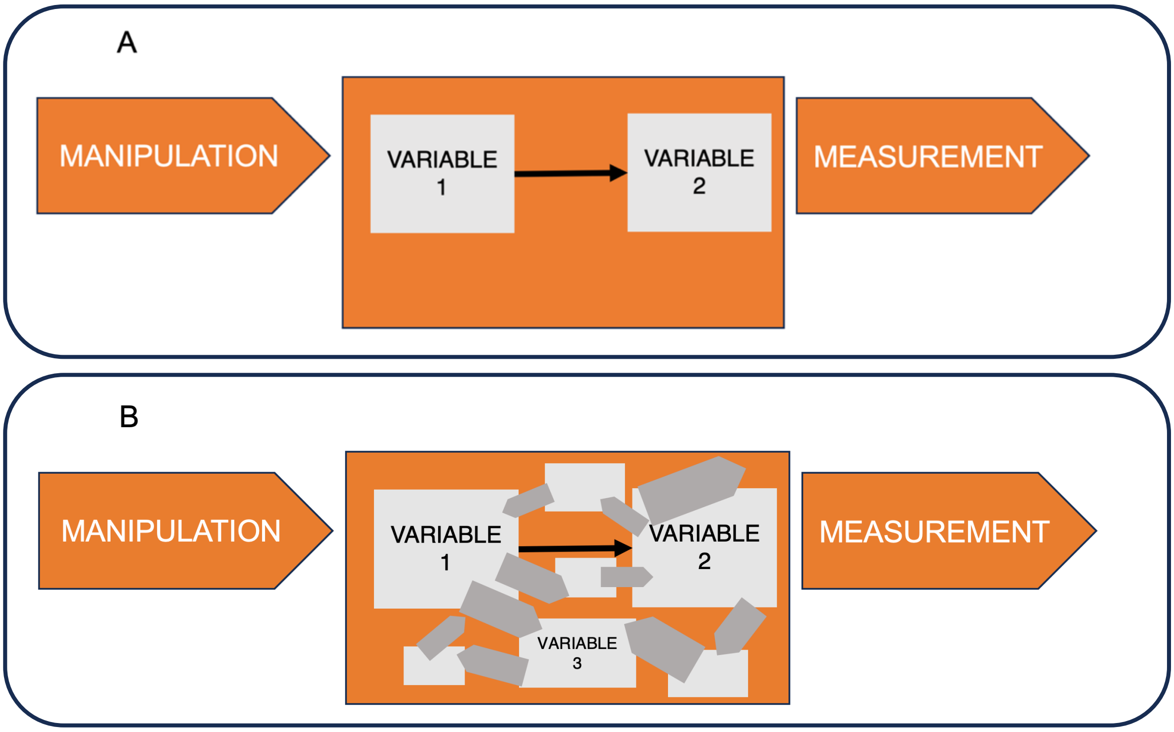
[14] The upcoming discussion of the replication crisis focuses on the theoretical discussion, which does not intend to signal that these other responses are not valid. Unquestionably, the replication crisis vitally signaled the need for reform of these factors. They form critical pillars in the scientific community's response to this crisis and tap into real, important empirical shortcomings of the field.

*statistical rituals* in Gigerenzer, 2018), in which there is a rigorous adherence to methodological stringency which is ignorant of a much more substantive lack of knowledge about underlying mechanisms. This has led some to even describe the dogmatic emphasis on methodological rigor as "indigenous epistemology" (Flis, 2019; see also the description of psychology as "cargo cult science" by Feynman, 1998) or worse as disqualify it as a science (Bezerow, 2012).

This reductionist approach, assuming stable effects, is contrasted with the holistic assumption of complexity, which argues that all empirical findings are fragile and dependent on many factors within a person and the context (Feest, 2024). The replication crisis, it is argued under the holistic assumption, results from neglecting the critical insight that the vast majority of psychological phenomena are particular and fragile. While other sciences may have an unchanging phenomenon to tap into, the life sciences can offer no such reliability. Acknowledging the complexity of phenomena, the inability to replicate is not surprising, as theories are necessarily too general to capture the innumerable particularities of a psychological phenomenon (S. B. Klein, 2014; Wiggins & Christopherson, 2019).

**Figure 2**

*A schematic depiction of the distinction between stable effects and complexity*




*Note.* In the stable effects assumption (A, top), a non-replication is caused by a theory being incorrect. In the complexity assumption (B, below), the non-replication could be caused by any number of other intervening variables. In the in-text example of old age cues reducing walking speed, variable 1 would be the activation of the concept of old age, while variable 2 would be the behavior schemas stemming from old age which in turn affect the measurement. Adapted from Feest (2024).

To demonstrate this dissonance between complex phenomena and reductionist approaches in cognitive science, one can look to arguably the most prominent 'victims' of the replication crisis: modal priming experiments (Körner et al., 2016; Oberauer & Lewandowsky, 2019). Typical studies in this field aim to demonstrate that concepts are grounded in sensorimotor representations by activating a concept and then measuring in some way whether a participant is more predisposed to perceive or act in line with the concept. One failed replication involved testing whether the concept of OLD AGE is grounded in the sensorimotor system, with the hypothesis that participants walk slower when primed with cues associated with old age. Yet, such a hypothesis is targeting a complex phenomenon. There is significant particularity in its testing, and at each step a replication can fail. The replication must ensure firstly, that the concept of old age is primed, that this prime activates the behavioral schemas associated with old age, and that these schemas are those that one expects (Stroebe & Strack, 2014). A non-replication may fail to evoke the concept of old age for a variety of reasons, or the concept of old age is active, but the participants, due to e.g., regional cultural norms, do not have a stereotype of elderly persons as slow (see Fig. 2B). In both these cases, the theory, postulating that concepts are grounded in the sensorimotor system, is not tested and the replication uninformative in that regard. Therefore, it can be argued that the inability of such a replication to find the same effect is not diagnostic of its inexistence, but rather that the authors found contextual effects or boundary conditions (Derksen & Morawski, 2022; Irvine, 2021).

This suggests that the connection between theoretical constructs and empirical testing is not sufficiently specific about the entirety of all variables relevant in evoking a hypothesized finding (Stanford, 2009). Yet, specifying all influencing variables of an experiment (and its replication) seems an insurmountable challenge. Among the reasons that have been provided for the above-described non-replications are a difference in the method used to measure walking speed (Doyen et al., 2012), or that an experiment was not performed in cubicles (Dijksterhuis, 2013). With innumerable such miniscule details, good theories in the reductionist tradition seem far out of reach. Indeed, unless Fodor had a distinct talent for assessing research questions in their amenability to cubicle-testing, the reductionist approach does not align with these lessons from the replication crisis. It is possible to conclude that "Theories in the Social and Behavioral Sciences Will Always Be Vague, Weak, and Unfalsifiable" (Sanbonmatsu et al., 2025, p. 6), or one may reconsider the epistemology underlying this, reductionist, approach.

The assumption of stable effects is reductionist because it acknowledges no (or few) components outside of the few theoretical constructs, that impact an experimental effect (Feest, 2024; Morawski, 2022). In place of the actual myriad intertwined causal pathways that underlie a person's walking speed, it assumes two isolated variables uni-directionally connected. The lessons, as presented here, suggest that a mismatch between the complexity of the phenomena under investigation and the assumptions which reductionist research makes, namely of few simple relations, is to blame for the replication crisis. These are failures of the theories to align with the holism demanded by the complexity of nature. GC is suffering from the same issues, and they must be addressed[15].

## 7. Reductionism in Science

Having now clearly delineated the negative effects of cartesian stowaways, and the detriments of reductionism generally, the need for GC to adopt a holistic epistemology is clear. To do this, I examine the assumptions of reductionism in-depth. Due to the deep differences between these approaches, this will be necessarily foundational and transdisciplinary. With this in hand, we can progress to the epistemological position of reductionism itself. Then, the research strategies and practices which result from a reductionist epistemology are presented. Then, these are identified in a case study of a reductionist theory, and the implicit assumptions that underlie it. By taking such a foundational approach, the specific instances presented consequently become more evident (cf. Crotty, 2020). This will lead naturally to GC's cartesian stowaways. See Table 2 for an overview.

### 7.1. The Reductionist Worldview

Reductionism is based on the assumption that its phenomena are constituted of *simple systems* (simple does not mean they are not complicated, i.e., difficult to understand; Den Hartigh et al., 2017), meaning their parts are conceptualized as being independent and related to each other by one-directional causal relations where one component affects another but is typically not affected by it. A simple system is, for example when a sphere rolls down an incline in a perfect vacuum (Mazzocchi, 2008). In simple systems such as this, the number of relevant constructs required to describe this phenomenon are few, including just gravity pulling the sphere down, the angle of incline, and so on. On the other hand,

[15] Another popular solution to dealing with the complexity of psychological phenomena, in contrast to the one taken in this dissertation, is to implement formal modeling (e.g., Glöckner & Betsch, 2011; Oberauer & Lewandowsky, 2019; Sanbonmatsu et al., 2025). This position acknowledges the issues with current theories, but commits to reductionism, arguing that the complexity can be captured not by verbal theories but by formalized models. Although this surely addresses many problems and is a valuable endeavor, it still relies heavily on assumptions to bridge a gap between verbal theories and the phenomena. It assumes, for example, that the concepts in a theory are natural kinds. Therefore, the current state of knowledge is (and, some argue, will always be) too incomplete to begin with formalization (Eronen & Bringmann, 2021; Eronen & Romeijn, 2020; Maatman, 2021).

holism assumes that natural phenomena are the result of *complex systems*. These involve interdependent components, that interact in reciprocal feedback loops. Complex systems are typically 'more than the sum of their parts', meaning that the whole system exhibits novel dynamics or behaviors which are not immediately visible from the attributes or behaviors of their constituent components, a feature called *emergence* (P. W. Anderson, 1972; Francescotti, 2007). For example, the intricate patterns of snowflakes are not immediately discernible when looking at the behavior of single ice particles. Similarly, looking at the brain, made up of many highly interdependent components (neurons), it is not immediately discernible that it should give rise to behavior, consciousness, or societies (Guevara et al., 2020; Singer, 2007). Such feedback loops, giving rise to emergence, are also responsible for generating *nonlinearity*, when the behavior of a system (i.e., output) is not directly proportionate to the force acting on it (i.e., input). Irrespective of how to investigate natural phenomena, or what constitutes a good theory of natural phenomena, it is widely accepted that the vast majority of phenomena in the life sciences are the result of complex systems (Camazine et al., 2020; Erdi, 2008; Guastello et al., 2008; Kauffman, 1993; Krakauer, 2024; Mitchell, 2011; Sanbonmatsu & Johnston, 2019; Simon, 1962; Weaver, 1948).

Descending the 'Hierarchy of the Sciences' to its most basic discipline (Fanelli & Glänzel, 2013; Lewes, 1853), one can frame the two distinct epistemologies in mathematical terms, captured as the difference between Euclidean and non-Euclidean geometry. Euclidean geometry isolates idealized relations, emphasizing straight and neat lines, as found in simple polygons likes squares, triangles, curves and circles (Mainzer, 2007). It can be found in man-made structures, such as a skyscraper, which can be described by a simple rectangle reaching from the ground to the sky. Euclidean geometry has arguably formed the core of scientific reasoning since its inception thanks to its value as a system for generating idealized mathematical relations (Prigogine & Stengers, 1984). Yet, it has been increasingly pointed out that such idealized relations are not representative of interacting components at scale. Life sciences typically analyze phenomena which are the product of many components in reciprocal interaction. Because these show novel, emergent, behaviors, they are not reflections of the idealized relations which gave rise to them at their smallest scale. Accordingly, complex systems can be described as producing non-euclidean geometry. Nature has very few neat straight lines, and the shapes of clouds, trees, or coastlines for example, hardly align with any conventional polygon (Mandelbrot, 1967, 1983; D. W. Thompson, 1917). It is therefore unfitting for many domains of science, especially in the life sciences, where interdependent components are the norm, to align with Euclidean geometry (Krakauer, 2024; Mitchell, 2011; Poincaré, 1905)[16]

To understand the resultant scientific practices of these worldviews, take the pool table example by Weaver (1948). A reductionist science is focused, and excels at, explaining the events on a pool table when only a single billiard ball is moving on it. The basic rules, as described by classical mechanics, are after all, known. When scaling this up to two or three billiard balls, it is only with great difficulty, due to the many interactions between them, that the movements on the table can be described by these rules. Yet, this calculation becomes intractable at only ten or twenty billiard balls, because of potentiating interactions, making the understanding of the pool table impossible. Now, take a hypothetically immense pool table with hundreds of billiard balls. This billiard table is suddenly possible to be described again. Yet, out of reach for reductionist methods, it is imperative to change perspective. In fact, despite the object of interest remaining the same, the variables which describe it change. It is no longer useful, in order to understand the events on the pool table, to examine the cause-effect relations between single billiard balls. Rather, one could analyze the system by, e.g., measuring the average number of collisions per minute per billiard ball. This would tell us something about the pool table as a whole. The same holds for the life sciences, where basic idealized rules capture little of the story of what happens to particles at scale. In fact, here, the recognition of looking at different variables is even more relevant because of the emergence of novel behaviors at scale, as if the billiard balls started coordinating (cf. Pessoa, 2017). There are many lessons for theories in cognitive science that can be gleaned from this distinction (cf. Den Hartigh et al., 2017; Favela, 2020), but first and foremost this demonstrates the important change in perspective that occurs when recognizing that a system is complex, as opposed to simple.

### 7.2. The Reductionist Epistemology

As the pool table example demonstrates, whether one believes that a phenomenon comprises a simple or a complex system, has consequences for the knowledge that constitutes understanding of the system. Reductionism is a position which aims to understand phenomena by breaking it down into its

[16] It should be mentioned that in less antique times, even very fundamental findings, such as Einstein's theory of relativity, which relies on the non-euclidean Riemannian space, depart from Euclidean geometry. In fact, this non-euclidean nature underlies what Dirac (1979) describes as the singular excellence of the theory. Speaking of Einstein and the theory, he says: "His entire procedure was to search for a beautiful theory, a theory of a type that nature would choose" (p. 14) and "Anyone who appreciates the fundamental harmony connecting the way Nature runs and general mathematical principles must feel that a theory with the beauty and elegance of Einstein's theory has to be substantially correct." (p. 13).

parts, i.e., reducing systems into their components (Nagel, 2007; Sarkar, 1998). This reflects the goal of understanding each component on its own, and afterwards adding all components together to arrive at an understanding of the system in general. Reductionism is, across most sciences, and historically, the default epistemology. It is the foundation of the (Euclidean-based) analytic method that, since the 18th century has been commonly applied to wrangle natural phenomena into scientific theories (Heylighen et al., 2007). In contrast, holism aims to understand phenomena by looking at the system in general (Gilbert & Sarkar, 2000; Özpolat et al., 2025)[17]. These respective positions are the direct consequence of different assumptions about the simplicity or complexity of the system producing the phenomena under investigation. Now, what are the specific strategies produced by reductionism, assuming natural phenomena as being simple systems?

### 7.3. The Reductionist Research Strategies

The first common strategy in reductionist research is to proceed by *decomposition*, which involves breaking a phenomenon down into constituent parts, either its physical parts or the individual processes that comprise it (Bechtel & Richardson, 2010). As demonstrated above, when assuming one is investigating a simple system, the understanding of single components will sum up to constitute an understanding of the system as a whole. This thinking guides the reductionist research strategies. In cognitive science, for example, decomposition can be found in common experimental tasks. The logic of these is often that cognition is made up of independent abilities that add together to constitute cognition. For example, the Stroop task is argued to be a measure of "selective attention" (e.g., Lavy & van den Hout, 1993; or "inhibitory control"; Aïte et al., 2018). Underlying the Stroop task is the assumption that "selective attention" exists independently of, and can be measured independently of, other similar constructs (like "cognitive flexibility"). The holist, on the other hand, would argue that the measure of performance on a Stroop task (typically reaction time or accuracy; Scarpina & Tagini, 2017) does not reflect an isolated ability. There are no components with clean edges that make up the behavior of a person in any environment, because even the system producing a Stroop task measurement is made up of a broader cognitive system that dynamically adapts to specific contexts. Therefore, the holist would argue response categories cannot be traced back to a single construct. Another reductionist assumption underlying the use of the Stroop task is that also in real life cognition is made up additively of such independent components. Therefore, such a performance measure on a stroop task will transfer to other

[17] Again, this is an overly simplified explanation to demonstrate the dichotomy, there are middle-ground positions (e.g., Burnston, 2021).

situations which also requires e.g., "selective attention". The holist would argue that, even if "selective attention" could be measured independently, the construct lacks usefulness because any real-life behavior is a function of many interacting features within and outside a person that also do not interact in linear ways.

The second common strategy is to proceed by *localization* (Bechtel & Richardson, 2010). Localization describes the strategy of mapping specific phenomena or abilities to specific, compartmentalized, locations (such as brain regions) or systems (e.g., a "visual system"). These strategies pervade typical scientific practice, including cognitive science (Silberstein, 2021), with some even proposing cognitive science itself should be replaced by cognitive neuroscience (Bickle, 1998, 2003). Underlying this practice is the assumption that the decomposed system's components are located in single locations. By localizing a construct to a location, with time one may arrive at a full map in which single regions and arrows between them can describe a phenomenon. The strategy of localization gives rise to sentences such as: The amygdala is "a critical structure for the expression and *perception of fear* and the *development of fear conditioning* [and] *appetitive processes* [...]. Recent research in humans has explored the amygdala's contributions to more complex processes, such as *social interaction* [...], *social judgments* (e.g., trustworthiness, stereotyping) [...], and *decision-making* [...]." (citation brackets are replaced by ellipses for brevity, emphasis mine; Gupta et al., 2011, p. 1). Localization can also be found in one of the central methods of cognitive neuroscience in which damage to a brain region (i.e., a subtracted component) is correlated to changes in cognitive processing (a subtracted ability), thereby allowing to localize abilities to brain regions (Shallice, 2015, p. 318; Eysenck & Keane, 2020). This *subtraction assumption* presumes that a single ability reduces to a single location. Yet the holist would argue that brains of patients who have suffered a stroke show remarkable ability to compensate for damaged areas (Grefkes & Ward, 2014). For example, brains of people born without hearing reuse the auditory cortex for other abilities (Glick & Sharma, 2017). The practice of localization, and implicit belief in the usefulness of locating theoretical constructs in the brain, has led some to describe cognitive science as a "new phrenology" (M. L. Anderson, 2014; Uttal, 2001, 2013).

### 7.4. The Reductionist Research Practices

These more general strategies result in a few research practices characteristic of reductionism. Typically, reductionist theories consist of few constructs with direct, one-directional causal relations between them. Before proceeding to discuss this more specifically and its potential shortcomings, it is necessary to discuss shortly the nature of constructs generally.

It is, of course, impossible to criticize theoretical constructs wholesale. Constructs are extraordinarily useful because they allow to divide phenomena and their analysis into categories with clear boundaries (e.g., reductionism vs. holism, as done in this dissertation). Constructs, as well as their surrounding theories, are necessary because they "serve as foundational units of scientific activity and enable scientists to make progress by not being overwhelmed by the blooming, buzzing confusion of the world." (Dubova & Goldstone, 2023, p. 656). A critically important question is, what properties of the phenomenon are reflected in the theory and its constructs? It will become evident that some constructs manage to "carve nature at its joints", meaning to capture natural categories, while others do not. Navigating these constructs and their distinctions requires vigilance and failing to do so successfully can have detrimental consequences.

Some constructs are characterized by their ability to be useful, as opposed to capturing natural categories. *Pragmatic kinds* are such constructs, conceived because they are reliable and predictive (Fried, 2017). For example, in research on personality, the construct of "conscientiousness" may be a pragmatic kind because it is useful to predict a person's subsequent behavior at university, despite conscientiousness not being a clearly defined construct in nature. That this construct is a pragmatic kind is evident because persons described as conscientious need not share any characteristics beyond their ability to be hardworking, self-controlled, etc. (Roberts et al., 2014; Zachar, 2002). It is therefore clearly a man-made and socially agreed-upon category. On the other hand, a *natural kind* is a construct which captures a distinction that exists as such in nature. Natural kinds are often described as existing, whether humans would know it or not (Bird & Tobin, 2024). It is therefore a construct which captures a true state of things in nature, and manages to "carve nature at its joints". For example, because $H_2O$ is a natural kind any liquid that does not have two hydrogen and one atom molecule will not be water, creating a natural category[18].

An important ramification in the pragmatic-natural distinction is that pragmatic kinds are constructs that do not postulate anything about the underlying properties, their existence is solely predicated on their definition (i.e., in the case of conscientiousness, a person's affinity to be hardworking, self-controlled, etc; Roberts et al., 2014). When reductionist theories decompose phenomena into constructs, this practice, regardless of whether useful, is not necessarily problematic. What leads to problems is when mistaking a pragmatic for a natural kind, called an *illusory essence* (Brick et al., 2022). When phenomena are complex, there are no few, simple natural kinds that compose a

[18] Personality traits have also been framed as natural kinds (e.g., McCrae et al., 2004) although such a view is today much less received.

phenomenon. Therefore, theories are populated nearly exclusively by pragmatic kinds, making reductionism's decomposition and localization ineffective as it decomposes a socially created category into more socially created categories. Such a practice is at risk of detaching fully from the actual natural causes and heading down a false line of research (cf. discussion of conceptual clarity in **Article III**). This produces a veritable issue for the reductionist program: One intends to arrive at natural kinds at some point, yet this seems unlikely if natural phenomena are made of complex systems. So, what do reductionism's theories look like, and do they run this risk?

**Table 2**

*The world and research according to Reductionism from the most general worldview to most specific in the features of its theories*

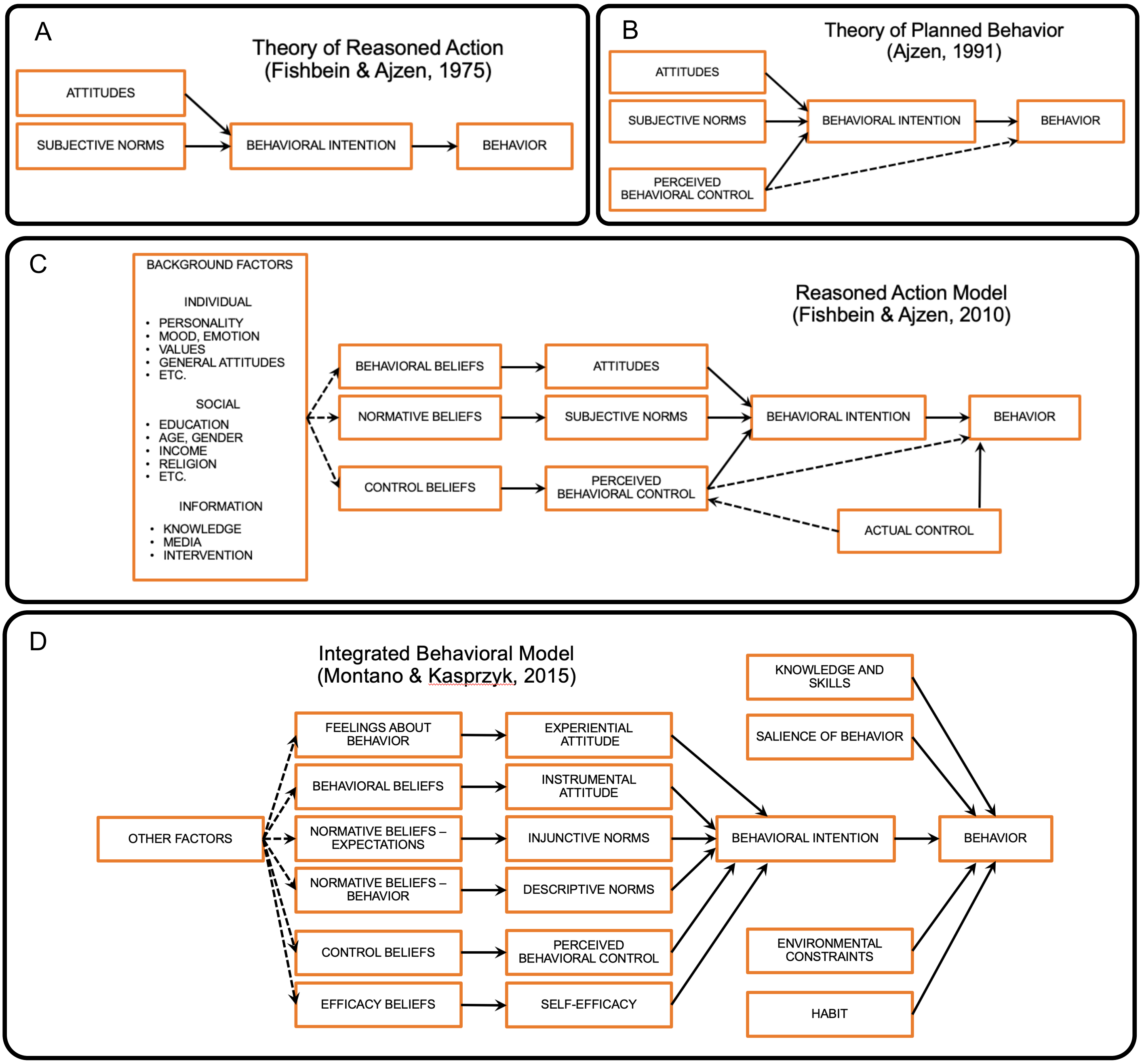
| Term | Meaning | Example |
|---|---|---|
| Simple Systems | Independent additive components underlie natural phenomena | A sphere rolling down an incline in a perfect vacuum |
| Euclidean Geometry | Straight lines reflecting idealized reductions | A square or sphere |
| Decomposition & Localization | Divide causes of phenomena into distinct components, localize these to biological or causal categories | Inhibitory control, measured by a stroop task<br>Subtraction assumption |
| Boxes-and-Arrows Theories | Theories that describe phenomena using few constructs related to each other by few one-directional causal relations | Theory of Reasoned Action, Planned Behavior, and others |

The constructs and surrounding theories, to which decomposition and localization give rise, are sometimes described as being a *boxes-and-arrows* approach (Datteri & Laudisa, 2014; Korb et al., 2016; Pessoa, 2017). This approach describes that reductionist theories often explain phenomena by positing few constructs which are connected by one-directional causal relations. The schematic depiction of these then often involves these constructs in the shape of boxes, and connected by arrows. Although such an approach excels at generating an explanation, just as Euclidean geometry, it may be better thought of as a display of idealized relations than natural kinds (Sanbonmatsu et al., 2025). Indeed, boxes-and-arrows theories rarely posit constructs that are natural kinds.

As an example of the shortcomings of the boxes-and-arrows approach, and by extension of reductionist theorizing, take the *theory of reasoned action* (Fishbein & Ajzen, 1975), one of the most well-known theories of behavior change. It posits that a person's propensity to engage in a new behavior depends on their intention to engage in this behavior, which in turn is predicted by their attitude towards it and their subjective norms (see Fig. 3a). This is a neat distillation, and its massive acceptance suggests it captures something important about behavior change (Albarracín et al., 2001). Yet, it had shortcomings (see e.g., Triandis, 1980), which later led to an amended version, the *theory of planned behavior* (Fig. 3b; Ajzen, 1991). In fact, it was amended a total of three times, each time in response to criticisms arguing it fails to capture a specific source of behavior change. This produced the *Reasoned Action Model* (Fig. 3c; Fishbein & Ajzen, 2011), and then finally the *Integrated behavioral model* (Fig. 3d; Montano & Kasprzyk, 2015). With noble intentions it grew from four constructs and three arrows in its first iteration to 19 constructs connected by 23 arrows in its last. Yet the final version has much redundancy and vagueness, such as positing the independent existence of the constructs of "Knowledge and skills", "control beliefs" and "self-efficacy" regarding the novel behavior. Even the most decomposition-inspired reductionist could not deny that self-efficacy or control beliefs regarding a novel behavior are unrelated to the skills to execute it. Yet, there are no arrows between any of these three. Such illusory essences can be found throughout the iterations. In fact, the final product is akin to attempting to describe the pool table with hundreds of billiard balls, with classical mechanics. The true interactions are too numerous, and idealized relations too far from the actual natural phenomenon. The subsequent attempt to capture the complexity of behavior change inflates the theory, illustrating its inability to capture the true web of causal relations. It is, of course, nonetheless highly commendable that the authors recognized the failure of the original theories to capture the many interrelated causes of behavior change, and amend their work.

**Figure 3**

*Four behavior change theories demonstrating boxes-and-arrows theories*




*Note.* Chronologically, from top left clockwise: The Theory of Reasoned Action (3A), which was later amended and called the Theory of Planned Behavior (3B). Containing further additions, the Reasoned Action model (3C). Most recently, the integrated Behavioral Model attempts to capture further complexity (3D). The progression serves to be a demonstrative example of the limits of boxes-and-arrows theories in capturing the complexity of the phenomena under investigation. The number of arrows progresses from 3 to 5 to 13 to 21. There are rumors of a fifth theory, but no journal would publish it on account of printing costs.

The reasoned action theories are not uniquely fallible in this regard. Such an issue will visit any boxes-and-arrows theory of behavior change because behavior change is the subject of a vast number of interconnected influences (Juarrero, 2000). The inamenability of such a complex phenomenon to be captured by decomposition and localization strategies, is demonstrated by looking to the "ABC of Behavior Change" (Michie et al., 2021). This book aims for a comprehensive listing of behavior change theories, and it lists some 83 theories. Each is useful in their own right, but unless one wants to make a risky bet (1/83 or 1.2% chance of correctness), it is safe to assume that none "carve nature at its joints". Of course, as with pragmatic kinds, such theories are not de facto useless[19]. It is only when believing these to go beyond pragmatic kinds, uncovering a category in nature, that this should incur any problems.

# 8. Assessing SCS, LMC, and GC

This example demonstrates the shortcomings and features of the theories that stem from reductionist research practices. Boxes-and-arrows postulate few discrete components in the causes of phenomena and postulates simplistic one-way causal relations, a basic structure that likely does not reflect the true underlying causes or categories. This expansive description of reductionism's practices can now be applied to the three central approaches. First, I examine SCS' research practices, demonstrating that it is thoroughly reductionist. Then, I continue to LMC and delineate the attributes of its constructs regarding reductionism. Finally, it is possible to examine GC's epistemological status, which should uncover any cartesian stowaways.

## 8.1. SCS' Scientific Practices

SCS is, predominantly, and proudly, reductionist (M. L. Anderson, 2014; Bechtel & Richardson, 2010; E. Thompson, 2010). Fodor makes explicit the assumed system underlying cognition: "modular cognitive systems are domain specific, innately specified, hardwired, autonomous, and not assembled" (Fodor, 1983, p. 37). This is a near-perfect listing of the opposites of those features which characterize

[19] Although here the focus is on the theory of reasoned action's (and its descendants') status as natural kinds, agnostic to their usefulness, one can also leverage a criticism against them based on their usefulness. A theory is only valuable if it makes specific predictions, which by definition means that it excludes other hypotheses. Yet the final theory has many variables that are vague. Additionally authors of these theories prescribe that one must be selective in choosing variables because "there is no one-size-fits-all approach" (Montano & Kasprzyk, 2015, p. 105). This presents the problem that the theory becomes a collection of many variables from which the researcher can pick-and-choose at leisure. This is a threat to scientific integrity because it masquerades as scientific, suggesting specificity, while allowing researchers nonetheless to cherry-pick based on intuition or worse, post-hoc data analysis.

complex systems, which are interaction-dominant, emergent, self-organizing, and soft assembled (M. J. Richardson & Chemero, 2014). Similarly, *standard computation*, the computational process envisioned in SCS is dependent and described by linear relations, while the kind of emergent computation produced by complex systems is described by nonlinearity (Forrest, 1990). This assumption naturally leads to a reductionist epistemology, again expressed by Fodor: "Since [...] behavior typically involves the simultaneous activity of a variety of distinct psychological mechanisms, the best research strategy would seem to be divide and conquer" (Fodor, 1983, p. 1).

Continuing, both decomposition and localization can be found in theorizing. For example, the ability to produce and understand language, is argued to be reducible to a single construct called the language faculty (Fitch et al., 2005; Hauser et al., 2002), relying on a specific innate structure called universal grammar (Chomsky, 1980; Pinker, 1995), and at times localized to specific locations in the brain such as the superior temporal gyrus (Poeppel, 2017). Also research taking SCS as a point of departure has these attributes. For example, in research on decision making, the classic theoretical base is the *serial model*. It decomposes the decision-making process into discrete steps executed in an ordered one-directional sequence: decision, choice, and execution (e.g., Newell & Simon, 1972; for an alternative view see, Raab, 2020; Voigt et al., 2023). It is therefore uncontroversial, and indeed explicitly stated by SCS theorists, that the field is committed to reductionism, making explicit that it views cognition as a simple system, producing modular explanations, in the form of boxes-and-arrows theories. It is therefore aligned in its epistemological and ontological positions, yet is, as argued above, biologically implausible.

### 8.2. LMC's Scientific Practices

The continuity between life and mind as posited by the free-energy principle aligns with reductionism's opposite, holism. LMC explicitly assumes that the phenomena it is investigating are complex systems. In fact, the attributes of complex systems (see above), are not only found in its theories, but placed centrally. LMC argues that self-organization is the primary mechanism underlying life and cognition, it places nonlinear dynamics front and center, and indeed argues that life and cognition are emergent features (e.g., Isomura et al., 2023; Millidge, 2021; see also Colombo & Palacios, 2021; Karl, 2012). Looking more specifically at its practices, the free-energy principle's constructs are natural kinds that are scaled up through interactions: it argues that all living organisms are (smaller or larger) collections of cells obeying the simple first principle of free-energy minimization. Similarly depicting its devotion to holism, LMC emphasizes 'organization' as being the factor distinguishing between living organisms and a pile of sludge, departing fully from decomposition and emphasizing interactions between particles (cf. Kauffman, 1993). There is therefore no decomposition or localization in LMC approaches.

Without decomposition or localization strategies, LMC also does not tend to produce boxes-and-arrows theories. In general, central to the LMC approach is a dissolution of theoretical boundaries in its theories. One finds myriad examples of equating traditionally distinct categories in LMC theories. The free-energy principle reading of LMC no longer distinguishes between faculties like action, perception, and cognition, or between physiology and behavior (Cisek, 1999; Pezzulo, Parr, & Friston, 2024; Pezzulo & Cisek, 2016). First, as described above, it does not draw a line between the internal and external world when creating a model from which to generate predictions. The hierarchical generative model is not picky in deciding whether a piece of information comes from outside or inside the skin, it will inform the model nonetheless. As all these categories have a familiar origin in a hierarchical generative model performing prediction-error minimization, there is no natural kind distinction between them (which is not to say they do not exist, just that they do not signal theoretically relevant distinctions). Second, the centrality of the dogma "perception as inference" (Friston, 2003; see also Gregory, 1980; Helmholtz, 1866) demonstrates the fluid distinction between perceiving the world and understanding it, because underlying any perception is a belief. Active Inference, also from the family of free-energy principle, emphasizes that actions serve to reduce the state of uncertainty in the world, casting both perception and action as inference (Brown et al., 2011; Pezzulo, Parr, & Friston, 2024), indeed even all of cognition (Pezzulo, 2012). Third, physiological changes are no different from behavior itself, with both being homeostatic control mechanisms: "When a perturbation away from desirable states is caused by events in the world (e.g. the appearance of a predator), we call that 'stimulus-response behaviour'. When the perturbation is caused by internal changes (e.g., a growing hunger), we call that 'goal-directed behaviour'. In both cases, the fundamental organization is a feedback system that controls the animal's state." (Cisek, 2021, p. 1). There is, therefore, not just a continuity between the origins of life and of cognition, but also between all categories that pervade the study of human cognition and behavior. These attributes of LMC approaches produce explanations that do not decompose or localize phenomena, and instead places continuous explanations throughout, even dissolving widely held constructs in favor of multi-dimensional underlying webs.

### 8.3. GC's Scientific Practices

While it is evident that SCS and LMC clearly fall into the category of reductionism and holism respectively, the central theme of this dissertation pertains to GC's cartesian stowaways. If GC produces theories with monist ontology, but with reductionist epistemology hiding in its strategies and practices, this would constitute meta-theoretical tension in the approach, and biological implausibility.

Firstly, GC tends to assume cognition to be a simple system. Firstly, this can be found in the fact that many lines of GC research also became victims of the replication crisis for the same assumption of stable effects explained above. One prominent example is the seminal ACE experiment by Glenberg & Kaschak (2002; also, Kaschak et al., 2005). This experiment failed to replicate, yet arguably because the important context effects from the original were not retained. These include factors like the type of words used, the amount of emphasis placed on a verb, or the timepoint of response (Teskey et al., 2024; A. Winter et al., 2022). Thus, its theories are in conflict with the complexity of these phenomena, and nonetheless, in non-replications it is argued that a null finding reflects their incorrectness. Furthermore, in the context of failing to replicate the ACE, Papesh (2015), in a paper critical of the existence of the ACE effect, displayed perhaps the clearest expression of the assumption that the research is examining stable effects. In a post-hoc Bayesian analysis of past research on the ACE, this author was required to estimate a prior which reflects the effect size one expects to find. This author chose the distribution $r$ = 1. This distribution is associated with testing fairly large effect sizes. A small effect size, as could be expected from such a fragile and complex phenomenon (Götz et al., 2024), therefore remained unconsidered.

This assumption of a simple system also produces the strategies of decomposition and localization in GC. Implicit in much theorizing on grounded cognition is the practice of postulating separate modules having dedicated responsibilities that are selectively recruited. These then combine according to specific rules. These are evident in the classic theories of grounded cognition: In conceptual metaphor theory, mental representations have been decomposed into separate, categorical components (e.g., in the extended conceptual metaphor theory: three distinct levels of representation being the domain, the frame, and the mental space; Kövecses, 2017, 2020). Similarly, in the another commonly-used theory, perceptual symbol systems, simulators constitute an example of localization (Barsalou, 1999). Simulators are single modules which house fragments of perception, which are recruited when a concept is activated.[20]

More reductionism in the form of decomposition can be found in the modalities, described above, which are depicted as modular. GC posits relevant differences between possible grounding substrates, like sensorimotor, interoceptive, or invariant representations. These are considered distinct, natural kinds. Evidencing this is that they were only piece for piece included into GC literature. The

[20] This explication of assumptions in GC theories will be deepened in **Article III**.

'original' grounding substrates was the sensorimotor system, and interoception was often neglected. For example, the seminal Barsalou (1999) paper mentioned "sensory-motor" 47 times, and never mentioned interoception, or any terms related to other modalities (the identical pattern can be detected in conceptual metaphor theory's central texts, e.g., Johnson, 1987; Lakoff, 1987, 2012). It was only later that GC theorizing was extended to include interoception, then later to emotion and social representations (Connell et al., 2018). Indeed, the grounding substrates were, until **Article I** and **Article II** in this dissertation, limited to the body. The mere modularity of dividing bodily information into these separate features aligns with the tradition of reductionism.

Second, localization is also evident in GC research. It can be detected in the frequent use of the term "human conceptual system" (Barsalou, 2003b, p. 513; M. Kiefer & Barsalou, 2013, p. 381), which places the construct of concept representation into a distinct modular system. Similarly, localization often underlies theoretical argumentations. For example, Vigliocco et al. (2014) argue that emotion is important for abstract concepts because there is an association between the abstractness of a concept and "greater engagement of the rostral anterior cingulate cortex, an area associated with emotion processing" (p. 1767). This quote originates from a paper that was written in response to another GC study localizing semantic knowledge to three, ostensibly non-emotion related, cortical regions. This, original target study was decidedly more explicit about its research strategies, being titled "Where Is the Semantic System?" (Binder et al., 2009). These and similar studies evidently do not assume that likely many interacting cortices and networks are responsible for the semantic content of concepts.

Furthermore, conceptual metaphor theory is an example of boxes-and-arrows theories. It posits that image schemas (e.g., FOLLOWING-A-TRAJECTORY or CONTAINER) are recombined using algorithms (called *transformations*) to generate primary metaphors, conceptual metaphors, and so on (Gibbs, 2005a; Gibbs & Colston, 1995; Lakoff, 1987). A depiction in the form of boxes and arrows would be true to the postulated reasoning; The complex phenomenon of abstract concepts is reduced to a process involving few components that sequentially and linearly align. These image schemas are also posited to be natural kinds. Furthermore, their transformations are hypothesized to be of a limited number. This suggests something innate which governs their existence, as opposed to that they emerge naturally.

## 9. Holistic Theories

Having first described the hallmarks of cartesianism, and consequently identified these cartesian features in GC's reasoning, it is possible now to progress to the proposed solution. What type of theories do align with holism? In other words, what are explanations that resist reductionist explanations and capture nature? These insights will serve as the foundation for constructing the consequent reformulation of GC[21].

One option to identify plausible features that do not violate what is known about emergence is to avoid specific components and examine systems as a whole. Such an approach allows to retain insights gained from understanding the underlying mechanisms of a phenomenon but with acknowledgement of the reciprocal interactions between components. Such approaches therefore describe the emergent phenomena as a whole, without decomposition. Take, for example, network approaches in research on psychopathology. Instead of defining mental disorders and their research by decomposing them into specific biological components or symptoms, network-based explanations map the complex web of symptom interactions that sustain and define mental disorders (Briganti et al., 2024). Such a view can take into account the reciprocal influences of interacting symptoms which are in feedback loops with biological features that are themselves interacting within themselves (Borsboom et al., 2019). Therefore mental disorders are viewed as being produced by complex interactions between symptoms, instead of being reduced to single discretized components (Borsboom & Cramer, 2013; Eysenck, 1986). By conceptualizing disorders in networks, one avoids the assumptions connected with decomposition, and gives way to emergence (Bringmann et al., 2023). In the same vein, other work has recently argued that future measures of clinical psychology should focus on experience sampling, because this allows to, via patterns in the dynamics of the whole system, generate insights into the emergent behavior of the system (Bar-Kalifa et al., 2024; Grunfeld et al., 2025). Beyond psychopathology and the strategy of decomposition, a fruitful avenue to counter localization, has been to examine whole-system dynamics of the brain, such as neural oscillations or hyperdimensional state-space activations (Buzsaki, 2006; Kriegeskorte, 2015; Wang et al., 2024). These neural oscillations also provide a plausible mechanism connecting brain and body signals via rhythms (Engelen et al., 2023; Rebollo & Tallon-Baudry, 2022).

Another option for theorizing that avoids reductionism is *first principles*. When taking as point of departure the assumption of a complex system, it is evident that a boxes-and-arrows theories could not capture the causes of phenomena, which are emergent. Therefore, it may be helpful to identify the basic features which, when scaled up, produce the phenomenon. First principles, much more common in physics than any life sciences, are facts which do not rely on any other fact to be true (Herfeld &

[21] The recommendations in this section are those that pertain or capture an important aspect in the context of GC. For more comprehensive collections of recommendations on how theories can better reflect the complexity of phenomena see: for cognitive science, Favela (2020); for philosophy Hylighen et al. (2007); and for psychology Sanbonmatsu & Johnston (2019)

Ivanova, 2021). For example, the principle of least action, which states that systems follow the paths which require the least energy. An important feature which distinguishes these 'first principles' from the boxes in reductionist research, is that the explanatory load is not localized to a specific component but on interactions and processes. Another construct, closer to cognition, which positions itself as a first principle is the aforementioned free-energy principle (Colombo & Wright, 2021; Friston et al., 2023). It does not argue that any one behavior begins with prediction-error minimization, but rather that a system which has this imperative will demonstrate such a behavior at scale.

The first principles approach relates to another, perhaps counterintuitive, holistic strategy: to go 'back to basics' and proceed with less theory (Bringmann et al., 2022; Sanbonmatsu & Johnston, 2019). Here, it is argued, to capture the complexity of a system one must be necessarily vague in detail. In practice, this corresponds to descriptive research, exploratory research, or bottom-up research, which all involve getting to know the phenomenon without top-down theories which are being confirmed or falsified. This pertains to the notion of intellectual humility, that grand theories may promise more explanatory certainty than is warranted. A good construct should only be as precise as is justifiable based on the supporting data (James, 1890; Sanbonmatsu & Johnston, 2019). Under the assumption that experimental phenomena are the product of many components that interact in reciprocal feedback loops (as described above in relation to the replication crisis), it is most useful to first begin with describing those phenomena that are robust across situations and replications (Eronen & Romeijn, 2020; Rozin, 2001). Such robust phenomena can consequently serve as constraints on theorizing (Eronen & Bringmann, 2021). If there is an undeniable phenomenon, one has a base from which to depart by limiting the space of possible theories. This acknowledges the inability for current research to describe the causes of phenomena in the current, reductionist, terms available.

A similarly pragmatic proposal relates to the need to encourage revising existing constructs. When, via empirical work, novel indices are uncovered which improve the bounds of a natural kind (i.e., suggest better bounds for a construct's natural category), these should inform the theory, generating an iterative cycle (Dubova & Goldstone, 2023; Eronen & Bringmann, 2021). Many constructs, posited as natural kinds, originate from folk psychology, such as attention (e.g., "Everybody knows what attention is" James, 1890). After increasing research, it is at times identified that a construct, as found in folk psychology may not be a natural kind, and has problems (e.g., "No one knows what attention is"; Hommel et al., 2019, p. 1). This can then lead to discarding the construct ("There is no such thing as attention"; B. Anderson, 2011, p. 1) or re-evaluating ("A taxonomy of external and internal attention" Chun et al., 2011, p. 1) and refining ("Attention as an effect not a cause"; Krauzlis et al., 2014, p. 1) it.

This iterative cycle should be encouraged and accepted, as it allows to, with time, approach describing natural kinds. It thereby continually improves theorizing by refining the accuracy of theoretical constructs.

## 10. Generating a Holistic GC

With the shortcomings of reductionism, and possible antidotes to these offered by holistic research practices fully explained, these insights can now be applied. First, in **Article III,** to produce a reading which discards GC's cartesian stowaways, and aligns it with holism, called *the minimalist account of* GC. Our holistic version of GC will pick up from the lessons described above, and especially address the problem of theories (boxes) with simple causal relations (arrows). To do this, the theories of GC will be analysed, with special focus on going 'back to basics'. Specifically, we argue that GC theories have been prematurely elaborate, postulating very specific theories without such specificity being justified. We also discuss the implications of this for research. Firstly, that it generates a lack of conceptual clarity, and second it generates unsystematic empirical work. Such unsystematic empirical work involves authors of experiments failing to explicitly state theoretical allegiance, which hinders falsification of these grand theories, for example. We propose to reduce these grand the theories to their basic mechanisms, *simulation* and *metaphoric mapping*, which we argue are natural kinds.

It must be mentioned that some developments in GC research have made in-roads in counteracting the detriments of reductionist practices. A classic dichotomy underlying many discussions in GC has been that of concrete and of abstract concepts. These are often treated as natural kinds that require different mechanisms. For example, Barsalou (2020) refutes the common misconception that GC theories "can explain concrete concepts but not abstract concepts" (p. 10; see also e.g., Borghi & Pecher, 2011; Mahon & Caramazza, 2008). The categorical distinction between abstract and concrete is not warranted though. For example, in Brysbaert et al.'s (2014) 'concreteness norms' participants judged 40,000 terms' concreteness, with higher scores indicating more concreteness and vice versa. In this study, a prototypical example of an abstract concept, FREEDOM, scores 2.34. This is less abstract than concrete concepts like e.g., FUN (1.78) or TROUBLE (2.25; Lupyan & Winter, 2018) though. Indeed, the fact that there even is such vast variability, i.e., a continuous not categorical distinction, already suggests that these may not be natural kinds. This is further supported by earlier theoretical work emphasizing the variability within the domain of 'abstract concepts'. Dove (2016) identified three separate issues underlying the same construct of abstract concepts and Barsalou (2003a) identifies six distinct challenges within abstraction. More recently though, there have been calls to nuance the notion of abstract concepts further, by distinguishing different types of abstract concepts (Villani et al., 2019) or getting rid of the distinction of abstract vs concrete concepts entirely (Barsalou et al., 2018).

After producing this minimalist account of GC in **Article IV**, consisting only of GC's central, natural kind, mechanisms, we turn beyond this limited scope and integrate it with other literatures and their postulates about cognition. Specifically, in **Article I** and **Article II** it was demonstrated that only two theories could account for invariant representations, predictive processing and conceptual spaces. In this final article, we integrate these three positions (GC, predictive processing, and conceptual spaces) under the banner of LMC, which demonstrates the strength of our novel account. By being simple and made of natural kinds, this minimalist account can integrate with other frameworks. It also displays the benefits of focusing on natural kinds. Because the minimalist account aligns with the assumption of a complex system, it makes the same assumptions of self-organization outlined above in 8.2. LMC's Research Practices, and is therefore positioned to integrate with it.

# 11. Article III: Issues in Grounded Cognition and how to solve them – The Minimalist Account

Friedrich, J.; Fischer, M.H.; Raab, M.

In: *Journal of Cognition*, 8(1), 31.

**Abstract**

The field of grounded cognition is concerned with how concepts are represented by re-activation of the bodily modalities. Considerable empirical work supports this core tenet, but the field is rife with meta-theoretical issues which prevent meaningfully progressing beyond this. We describe these issues and provide a solution: an overarching theoretical framework. The two most commonly cited grounded cognition theories are *perceptual symbol systems* and *conceptual metaphor theory*. Under perceptual symbol systems, concepts are represented by integrating fragments of multi-modal percepts in a simulator. Conceptual metaphor theory involves a limited number of image schemas, primitive structural regularities extracted from interaction with the environment, undergoing a limited number of transformations into a concept. Both theories constitute important developments to understanding mental representations, yet we argue that they currently impede progress because they are prematurely elaborate. This forces them to rely on overly specific assumptions, which generates a lack of conceptual clarity and unsystematic testing of empirical work. Our *minimalist account* takes grounded cognition 'back to basics' with a common-denominator framework supported by converging evidence from other fields. It postulates that concepts are represented by simulation, re-activating mental states that were active when experiencing this concept, and by metaphoric mapping, when concrete representations are sourced to represent abstract concepts. This enables incremental theory development without uncertain assumptions because it allows for descriptive research while nonetheless enabling falsification of theories. Our proposal provides the tools to resolve meta-theoretical issues and encourages a research program that integrates grounded cognition into the cognitive sciences.

Keywords: Embodied Cognition, Semantics, Action and Perception, Emotion and Cognition

# 12. Article IV: Higher-Level Cognition under Predictive Processing: Structural Representations, Grounded Cognition, and Conceptual Spaces

Friedrich, J.; Fischer, M.H.

In: *Minds and Machines* (under review)

**Abstract**

Predictive processing posits that prediction-error minimization underlies all perception, action, and cognition. Yet, despite its considerable popularity and explanatory scope, it is unclear how this enables higher-level cognitive abilities, such as representing and reasoning over abstract concepts. We combine insights from predictive processing, structural representations and grounded cognition to address this issue. Predictive processing argues from the free energy principle that an anticipatory model of the person-relevant environment is simulated. Structural representations state that these representations are isomorphic to, i.e., retain the relational pattern of, the world. Building on this assembly, grounded cognition research provides four insights into how abstract concepts are represented. First, a hierarchical organization allows abstracting from specific sensory qualities. Second, language glues together sensory qualities into representations that share no intrinsic properties, and acts as a social tool. Third, metaphoric mapping allows fragments of concrete percepts to represent abstract concepts. Lastly, conceptual spaces can represent concepts by generating multi-dimensional spaces consisting of abstract quality dimensions. By transplanting these four insights to predictive processing's (structural) hierarchical generative model, we explain higher-level cognition through detached models of perception and action simulations, isomorphic to actual behavior, in abstract conceptual spaces. This constitutes a significant expansion to life-mind continuity approaches by providing specific mechanisms for how the principles driving the emergence of life can account for the sophisticated higher-level cognition in humans. By synthesizing insights from these three literatures, we generate a coherent description of higher-level cognition under predictive processing.

Keywords: generative models, embodied cognition, symbol grounding, active inference, life-mind continuity thesis, free-energy principle

# 13. An Integrated GC

In **Article III,** we formulate an overarching framework of GC, one that avoids the cartesian stowaways of prior theories, which we call a *minimalist account*. This article began by demonstrating the more socio-scientific consequences of reductionist research practices and especially of illusory essences. They cause a lack of conceptual clarity, as overly specific theories are continually amended, eliciting jingle jangle and conceptual clutter. It also causes unsystematic empirical work as it becomes unreasonable to align with overly specific theories which are further along theoretically than empirically. In the minimalist account, we postulate only two constructs, simulation and metaphoric mapping. With this, we are able to discard the boxes-and-arrows decomposition, while maintaining the central insights, that mental representations involve the simulation of their referents, or in the case of metaphoric mapping, simulating more concrete stand-ins for abstract referents. In line with holism, both simulation and metaphoric mapping are natural kinds. Simulation is when a mental state is activated in absence of the referent which typically activates it, and metaphoric mapping describes such an activation in service of a concept more abstract than the referent. The strict definition of simulation already demonstrates that there is little distance between the theoretical construct and the phenomenon it describes. It is not dependent on any other theoretical construct, or even theory, to be true in order for its existence to hold. There is significant evidence for the existence of simulation generally, as well as for simulation in service of mental representations. The same holds for metaphoric mapping. These constructs also do not postulate a process or indeed even a causal relation. The limited nature of the minimalist account, has the drawback that it has much less explanatory power than the more elaborate theories which it subsumes, making no sweeping explanations. Yet this means that it carries fewer risks of being false. Therefore, while this reformulation produces much less theoretical detail, we argue the sophistication of past theories was not justified. Therefore, our portrayal, because our constructs do not position themselves as providing a detailed story of concepts and mental representations, is arguably more in line with the current state of knowledge.

Next, in **Article IV**, we applied this holistic, minimalist account of GC to synthesize with other frameworks a description of mental representations. We first drew on work from the field of philosophy of mind on *structural representations*. These describe representations in which the internal relational structure of the referent is retained in the mental representation. Structural representations form a theoretical link between predictive processing and GC. On the one hand, structural representations meet the demands of a LMC reading of predictive processing, in which the nervous system is tasked with being a model of the world. Structural representations state that, the hierarchical generative model is not only in its meaning a model of the world, but because the way this representation retains the world's structure, it literally is a model of the world. On the other hand, we argue that GC's simulation will also necessarily retain the relational structure of its referent, meaning that GC also posits structural representations. Furthermore, GC argues beyond a more conservative reading of structural representations. It proposes the stronger notion that covert simulations of actual perception or action constitute the mental representation, meaning that not only internal relations are retained but these are filled out with experiential (i.e., sensorimotor, interoceptive, etc.) detail. Another point of alignment is that GC's notion of simulation aligns with predictive processing's detached models, which are identical postulates. Furthermore, as GC has well-described how such simulations can serve higher-level cognition via simulations, these also apply to predictive processing's detached models. Specifically, that higher-level cognition involves simulations of perception and action, including the metaphoric simulation of perception and action. They also, in line with the words as social tools approach, include words acting as embodied representations of tools. Additionally, the theory of conceptual spaces posits the simulation of space as critical for the representation of concepts. Therefore, these detached simulations not only involve simulations of perceptions and actions, but also of spaces.

## 14. Conclusion

With these final articles we can return to the question posed at the outset: what is the format of mental representations? By first adding to GC invariant representations, removing the vast majority of its theoretical postulates, and consequently transplanting it to the existing predictive processing literature, I argue for the mental representational format of *Analog representations* (Beck, 2018; Maley, 2024). Analog representations, involve what may be grossly simplified as a richer version of structural representations (because it goes beyond just retaining internal relational structure; Shea, 2018). As described above, they retain the structure (like structural representations) but also other components of their referents (formally, that the the representational format covaries with its representational medium; Maley, 2011; Shepard, 1978), similar to e.g., mental imagery. Analog representation contrasts with digital computation, the category to which also symbolic representations belong (to which amodal symbolic representations belong; Maley, 2024). Our proposal aligns with this format, because the notion of simulation is closer to a mirroring conception than the comparatively simple structural representation.

When applying this representational format to computation, one compares analog with digital computation (MacLennan, 2017). Although in society, digital computers are currently much more favored over analog computers, this is not necessarily always so. In order to predict a system with high degrees of freedom and complexity, the importance of capturing the self-reinforcing feedback loops seems vital, and constitutes a problem for digital computation. As an example of the power of analog computation, take the tricky undertaking of tidal predictions. In the 1800's, by failure of linear (digital) mathematical prediction, analog computers in the form of mechanical tide predictors were built. These, thanks to their self-referential ability, vastly improved on other methods (Rossiter, 1972). This was termed *brass-for-brains* for the ability of the ostensibly primitive mechanical movement to supersede the accuracy of sophisticated mathematical models (Thomson, 1868). This is surely one reason why science engages in experimentation and modelling (Craik, 1943; Godfrey-Smith, 2006), but also why cognition evolved mental models (Hesslow, 2002; Johnson-Laird, 1983), and what favors the here-proposed analog representation in the brain, over the amodal symbol systems theories of cognition. The notion of analog computation, but especially the reading presented here, in which exapted abilities in detached models can furnish such a rich abstract conceptual repertoire, is a similar instance of brass-for-brains.

The insight of this **Article IV** tells a much more detailed story of mental representations than just a format, though, because it produces phenomenological detail. The simulations are argued to be a part of detached models and these take place in conceptual spaces. One could speculate that if these simulations are indeed, integrated into one single coherent model, as opposed to individually, modularly, representing separate aspects of a representation, it suggests that higher-level cognition involves simulations of small-scale 'strange worlds'. These models are 'strange' because they can involve metaphorically mapped simulations of perceptions and actions, and these take place in spaces bounded by abstract quality dimensions. For example, representing joy may involve a metaphorical mapping of happiness by moving up in a conceptual space with a vertical happiness gradient. These small-scale 'strange worlds' would nonetheless be isomorphic to the external three-dimensional world, but made up of abstracted quality dimensions, in which concrete representations have abstract meanings, words act as tools, and so on.

### 14.1. Strengths and Limitations

This dissertation had some strengths which allow for robust conclusions. One central aspect of this dissertation is that in order to draw the conclusion that GC is indeed harboring cartesian stowaways, a rigorous experimental test was done in **Article II**. Although later conclusions are based on theoretical arguments, the central thesis of GC harboring stowaways is predicated on an empirical finding. This dissertation therefore connects and leverages empirical and theoretical insights together. Furthermore, a critical facet of **Article IV** is the proposal that GC puts forth structural representations. We are the first, to our knowledge, to frame grounded cognition as positing structural representations, performing important transdisciplinary integrative work. Lastly, the critical importance of performing theoretical work within disciplines, such as that presented in **Article III**, to complement the typically empirically-minded research programs is well-established (e.g., Forscher, 1963; Gigerenzer, 2010; Hommel, 2024). Indeed, even the empirical aspect of this dissertation is not for the experiment's sake but exclusively necessitated by theoretical reasoning.

On the other hand, there are also limitations to the findings reported here. For one, although the central assumption is based in an empirical test, and much research supports the independent postulates in the article, there is no test of the final synthesis in **Article IV**. Although it may be argued that the **Article I** and **Article II** already constitute evidence of an empirical test, it is important to note that this only assesses one small aspect of mental representations. It therefore could not serve as evidence in favour of the final synthesis we have provided here. In fact, it is possible that some parts of the story will remain impossible to test directly indefinitely. For example, whether a simulation takes place in a simulator, image schema, or detached model. Future directions should nonetheless aim to develop empirical tests for the theoretical proposals posited here, and others in predictive processing (Litwin & Miłkowski, 2020; Miłkowski & Litwin, 2022). Some possible options can be gleaned from the structuralist program of neural correlates of consciousness research (Fink et al., 2021; Fink & Lee, 2023), as well as significant potential of mathematical modelling (Kleiner, 2024).

### 14.2. Implications

With what could be characterized as a plain architecture, consisting of few components and only a single basic imperative, the diversity of human cognition (the capability to daydream, reason about mathematical formulas or hypothesize about others' emotions) seems distant. Yet, as we demonstrate, there are, empirically supported, ways in which such simple embodied processes can come to account for many features of higher-level cognition. These function by *exaptation*: the process when a feature originally evolved for one purpose is reused for another (Gould, 1991). For example, humans developed sophisticated abilities for navigation which not only represent a given space, but also a person's location within it, and their heading (e.g., Burgess, 2006; Hafting et al., 2005; T. Hartley et al., 2014; O'Keefe & Dostrovsky, 1971). This in-built ability is exapted to perform the sophisticated ability of reasoning in semantic meaning by generating semantic maps, as posited by conceptual spaces. Not only conceptual spaces, but also metaphoric mapping, or the words as social tools approach, demonstrate how the unique demands of higher-level cognition are served by ostensibly primitive embodied abilities. This insight also contributes significantly to the evolutionary aspect of LMC literature. Specifically, bridging the gap between the self-organization of cells to sophisticated human cognition. Conventional readings of LMC argue, collections of cells first became a model of their environment as, over the course of evolution by natural selection, relevant features of the environment were captured in the phenotype. Next, the environment was able to be modeled moment-to-moment, by a nervous system, which maintained a model of the environment. Then, forward models developed to enable anticipatory behavior, and these became progressively more detached to become full-fledged simulations. Here ends the conventional LMC story. We add a critical final point. Human cognition then exapted these models; First, organisms *become* models, then *maintain* models, then *detach* models, and finally *exapt* models.

A few insights from these articles have impact beyond the boundaries of GC. For one, predictive processing and free-energy principle have touted themselves as grand unifying theories (Friston, 2010; Hohwy, 2013, 2020; Poth, 2022), and we have added significant expansions in the format of its mental representations. Further, although the articles included here have mostly addressed cognition, a research program around *neurophenomenal structuralism* (Fink et al., 2021; Lyre, 2022), and the similar, *Quality Space* theory (Fleming & Shea, 2024; Rosenthal, 2010) which build on structural representations to explain neural correlates of consciousness, also profits. Neurophenomenal structuralism builds on structural representations and integrates much of conceptual spaces' reasoning. It argues that the content of consciousness involves isomorphisms between the world, neurons and the phenomenological experience. In fact, they argue further, that the content of consciousness is exhausted by its relational structure (D. M. Weger, 2024). For example, the experience of a color involves the color's location in an abstract 'color space', made up of the dimensions hue, saturation, and lightness (see also Fleming & Shea, 2024; Kuehni, 2003). The proposal put forth in **Article IV** connects such notions with explanations of cognition. The formulated description therefore expands this research to an ambitious position.

## 15. Closing Thoughts

Much work cited here is part of an exciting change in tone embracing complexity, which is in stark contrast to the near-ubiquitous reductionism of the past (Krakauer, 2024). This includes the theoretically-driven solutions to the replication crisis, which emphasize the complexity underlying empirical testing on human subjects, and parallel evolutions across the life sciences. Far more than just a swing of the paradigmatic pendulum, the complexity approach constitutes a humanistic, and perhaps even romantic, view of science. It aims not for a rational, idealized, 'enlightened' theory, but rather wants to catch the whole muddy truth of nature as it is. The *Naturphilosophie*, led by the German Romantics Goethe, Schiller, Schlegel, and others, had a similar view. Yet, they turned their back on the, reductionist, 'enlightenment' science, for its inability to capture what they believed to be truly beautiful: the organic features of nature (Wulf, 2022). Goethe described a distaste for reductionist science, saying "gray are all theories, And green alone life's golden tree." (Goethe, 1912, p. 68; Mainzer, 2007), as if science takes away the beauty inherent in nature. Indeed, science is often portrayed by laymen as an antithesis to art, because science is not beautiful but art is. They could not be more wrong. Yet, this constitutes, not a failure of the romantics or laymen to appreciate science, but a failure of science to appreciate what everyone else already appreciates, nature. Reductionism takes inherently beautiful natural phenomena and sterilizes them, reducing them to uninspired boxes to make them palatable for the limited imagination of 'enlightened' thinkers. Only 'gray' theories could be defied by the beauty of a flower or the intricate patterns of a butterfly's wings. Complexity science not only acknowledges natural processes, it embraces and places their complexity centerstage. It subordinates itself to nature. Perhaps, a turn towards complexity may foster a culture of science which is not tasked with sterilizing natural forms, but rather with understanding them where and how they are. It is my sincere hope that this dissertation has contributed something to this culture.

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# Appendix

**Calculation of Mini Meta and Bayes Factor Transformation**

To combine the results of the individual experiments, we performed a mini meta according to Goh et al. (2016) and consequently applied a Bayes factor transformation. An R script including these calculations is available online (OSF Link).

These analyses were based on the t-values (t = [1.99, 0.44, 1.03, 1.31]), corresponding degrees of freedom (df = [31, 75, 69, 90]), and p-values (p = [0.03, 0.33, 0.15, 0.09]) of the respective experiments.

From this, correlation coefficients (Pearson's r) were calculated using the formula:

$$r = \sqrt{(t^2 / (t^2 + df))} = [0.34, 0.05, 0.12, 0.14]$$

The resulting correlation coefficients were then transformed using Fisher's z transformation:

$$z = (1 / 2) \times \ln((1 + r) / (1 - r)) = [0.35, 0.05, 0.12, 0.14]$$

The weighted Fisher's z mean was calculated with:

$$\bar{z} = \sum((n_i - 3) \times z_i) / \sum(n_i - 3) = 0.13$$

where $n_i$ represents the sample sizes of the respective studies. The weighted Fisher's z mean was then converted to a mean Pearson's r using the inverse Fisher transformation:

$$r = (e^{(2\bar{z})} - 1) / (e^{(2\bar{z})} + 1) = 0.13$$

Which in turn produces a mean Cohen's d across all studies of

$$d = (2r) / \sqrt{(1 - r^2)} = 0.27$$

with a 95% confidence interval (CI) of

$$CI = [d \pm 1.96 \times SE\_d] = [0.02, 0.52]$$

where the standard error for Cohen's d was derived from the Fisher's z standard error. The p-values from the individual studies were combined using Stouffer's method

$$Z\_combined = \sum Z_i / \sqrt{k} = 3.14$$

where $Z_i$ are the individual study Z-scores, and k is the number of studies. This in turn produces a combined p-value

$$p\_combined = 2 \times (1 - \Phi(|Z\_combined|)) = .002$$

where Φ represents the cumulative distribution function of the standard normal distribution. Furthermore, heterogeneity across studies was assessed using the Q and $I^2$ statistics:

$$Q = \sum((z_i - \bar{z})^2 / SE\_z^2) = 1.87$$

$$I^2 = ((Q - (k - 1)) / Q) \times 100\% = 0.00\%$$

**Bayesian Analysis**

In order to arrive at a BF10 for the results of the mini meta, we used the combined Cohen's D. For the prior distribution we chose $\sigma = 1$ as is standard for being very uninformative, because there is no prior information on this effect (Rouder et al., 2009). Because it is argued that this distribution favors larger effects, which would increase the value of the BF10. This prior distribution can therefore be characterized as mildly conservative for our assessment of the very small 'embodied effects'. Therefore, following Rouder et al. (2009) and Ly et al. (2016), we used a prior centered at 0 with a scale parameter $r = 1 / \sqrt{2}$. This prior reflects a modest expectation of effect size variability.

The likelihoods under the respective hypotheses ($H_0$ and $H_1$) were modeled as

$$L(H_0) = Normal(d, SE\_d) = Normal(0.28, 0.09)$$

$$L(H_1) = Normal(d, \sqrt{(SE\_d^2+\sigma^2)}) = Normal(0.28, 1.00)$$

Using these formulas and the observed Cohen's d = 0.276, the Bayes factor was computed as the ratio of the marginal likelihoods:

$$BF_{10} = L(H_1) / L(H_0) = 13.25$$