Mental Functioning is Neural Functioning: Towards a Unified Ontology of Mind, Brain, and Behavior

Gwen A. Frishkoff\textsuperscript{1,2}

\textsuperscript{1} Department of Psychology & Neuroscience Institute, Georgia State University, Atlanta, Georgia, U.S.A.
\textsuperscript{2} NeuroInformatics Center, University of Oregon, Eugene, Oregon, U.S.A.

\section*{ABSTRACT}

In order to develop a formal ontology for representing mental processes, it will be important to consider two questions: (1) What is mental functioning, and (2) How does it relate to bodily and brain function? In the present paper I offer a straightforward answer to both questions: Mental functioning is neural functioning. While this idea has met with a variety of criticisms through the years, it may be the only solution that can support a unified theory of mind, brain, and behavior. Moreover, it has the advantage of providing a transparent explanation for a variety of psychiatric conditions, as well as their biological basis. I propose an implementation of this view within the BFO/OBO framework and discuss some alternative views.

\section{INTRODUCTION}

In recent years, the health sciences have seen rapid growth in the development and application of bio-ontologies. These informatic resources span a number of domains, such as cellular and molecular biology (GO [8], [21]), experimental and measurement protocols (OBI [1], RadLex [15], cogPO [19], BirnLex [2]), behavior (cogPO [19], BirnLex [2]), phenotypes (PATO [6]) and neuronal structure (GO [8], [21], FMA [14], and NIF [2]) and function (NIF [2], NEMO [5]). As these resources mature, and as the community works to enable interoperability among them, it is increasingly possible to envision a formal, multi-level account of biological structures and functions, as well as their relevance for human health.

Scientific knowledge of how the mind works has an important role to play in this undertaking. Issues surrounding mental health, in particular, call for a systematic treatment of mental processes. A formal ontology could accelerate this work by providing an explicit, machine-readable framework for classifying and integrating relevant data, leading to greater confidence in diagnosis and treatment of mental illness [9].

Curiously, to date there is no reference ontology for cognitive or mental\textsuperscript{1} functioning (although some work in this area has recently emerged ([9], [12]).

From a theoretical standpoint, this gap may reflect the uncertain status of the Mind within the biological sciences, recalling age-old questions about the relationship between mind and brain. These are thorny questions that have traditionally been consigned to philosophy. However, in order to develop a formal ontology for this domain, two questions seem unavoidable: (1) What is mental functioning, and (2) How does it relate to bodily and brain function?

In this paper I propose a straightforward answer to both questions: mental functions are neural functions. I show how this view could be implemented within the Basic Formal Ontology (BFO [7]), and I contrast alternative views. Finally, I suggest that this proposal is not as radical as it appears. On the contrary, it may be the only approach that can lead to a coherent and cross-disciplinary view of mind, brain, and behavior.

\section{DECADE OF THE MIND}

The 2010s may come to be viewed as the "Decade of the Mind." Previously, we have seen the official designation of the 1990s as "The Decade of the Brain," recognizing the extraordinary progress in neuroimaging over the past half century (http://www.loc.gov/loc/brain/). The following decade (2000-2009) was deemed the "Decade of Behavior," stressing the importance of social-behavioral issues such as education, healthcare, poverty, and barriers to economic and political justice (http://www.decadeofbehavior.org/).

A decade of the mind would seem a natural successor: The study of mind is inherently linked to the biological (brain) and the social-behavioral sciences. Indeed, recent discover-

\textsuperscript{1}I use the term "cognitive" and "mental" interchangeably throughout this paper. Likewise, "mind" and "cognition" are used interchangeably. In reference to functions such as executive attention, decision-making, and language, I use the term "higher cognition" to emphasize the role of prefrontal cortex and other recently evolved cortical structures.
ies in social science and neuroscience have prompted reconsideration of the very foundations for defining mental function and dysfunction, leading to the first major revision of the Diagnostic and Statistical Manual of Mental Disorders, or DSM, in over three decades (http://www.dsm5.org). A quick search of "headlines in health" within the past year will show that discussions of proposed changes to the DSM have been remarkably heated, raising debates over the role of biological markers in mental health diagnosis, as well as educational, economic, and social consequences of proposed changes to DSM categories such as autism, dyslexia, and depression.

At the core of the DSM debate is the question of how to define mental functioning. There are many sources that can inform this question, including studies of the brain, cognitive processing, development of behavioral and brain systems, and latent dimensions of mood and temperament (i.e., personality). However, the core question comes down to this: What kind of thing is a mental function. That is, what is its superclass?

3 WHAT IS A MENTAL FUNCTION?

Attempts to define "mind" and "mental function" within a scientific context have stirred up controversy since the early 20th century. In certain areas of British and American psychology, it was famously taboo to use words such as "feeling," "belief," or even "memory" or "consciousness." While behaviorism is now viewed by many as a radical misstep, some of its core principles have survived and continue to inform scientific psychology.

Perhaps the defining principle is that "we cannot observe the mind." According to this view, we can observe and measure physical entities (e.g., button presses, vocalizations) and neural activity (e.g., changes in hemodynamics, electroencephalograms). By contrast, the Mind is an impenetrable black box, whose contents are private and therefore beyond the reach of scientific study. For this reason, cognitive psychologists are often careful to say that, technically speaking, they do not study cognition, but rather the behavioral and brain processes that are "associated with" (or "map to" or "subserve") cognitive functions. In one sense, this is a very sensible position: methodological behaviorism tends to promote a rigorous approach to experimental design, and it avoids sticky philosophical issues.

If we cannot observe mental functions, however, this presents a challenge in developing formal ontologies of cognition. What are mental processes if they are not observable, material entities? How can we develop a cognitive ontology that is compatible with realist principles [7] and is also grounded in scientific knowledge? What is it, exactly, that behavioral and brain processes are supposed to map to?

These questions inevitably raise the Mind-Body (or Mind-Brain) problem, that is, the problem of how the mind is related to the brain and to overt (observable) behavior, the two aspects of human functioning that we can describe in concrete, scientific terms. This problem has been the subject of many books, and it is impossible to do justice to arguments for and against different positions. However, for practical purposes, it can be boiled down to some relatively straightforward choices.

The Basic Formal Ontology (BFO [7]) and the Ontology for Biological Investigations (OBI [1]) are rigorous upper ontologies that are widely adopted in the bioinformatics community. They provide a set of basic distinctions that can help us frame our questions more analytically. To begin, "mind" is an ambiguous term: it can refer to a mental process (or function), a mental state, or a mental representation. These three concepts can be characterized as follows:

- **Process.** A process is an occurrent, that is, an entity that exists in four dimensions and that "unfolds itself in time," i.e., has temporal parts ([7]: p. 140).
- **State** — A state is a type of dependent continuant. It is a continuant because it endures through time ([7]: p. 151), and it is dependent, because it requires the existence of another, substantive or "independent" entity to exist (ibid.). More specifically, a state is a kind of realizable entity that "inheres in" a substantive entity.
- **Representation** — Representation is not defined within BFO. It can be defined as an information content entity, since the defining feature of a representation is that it is "about" something else.

While these distinctions may seem burdensome, Smith and colleagues have shown that ontologies are at risk of committing errors — sometimes serious (e.g., false reasoning over medical data) — unless the terms of natural language rigidly defined [3]. Further, the use of an upper ontology can facilitate ontology integration for closely related domains, such as scientific paradigms, neuroimaging results, and health-related applications.

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3 Technically, "function" is distinct from "process," within BFO. However, for the sake of simplicity, I do not discuss the more complex concepts of "function" and "dysfunction." See Smith & Ceusters (2010) for a discussion of this topic.

4 http://www.ifomis.org/bfo/1.1/realizableEntity

5 http://purl.obolibrary.org/obo/IAO_0000030
4 HOW ARE MIND AND BRAIN RELATED?

Below are three views of how to represent mental processes, vis-a-vis neural processes. BFO. Once we address this issue, it is fairly simple to work out the relations between mental and brain processes, states and representations within the BFO/OBI framework.

**View #1**: A mental process is a process (but it is not necessarily a bodily process).

**Figure 1.** Mental processes are (nonphysical) processes.

View #1 is consistent with folk psychology: It explicitly defines mind as something other than brain or body. In philosophical terms, it assumes a dualist worldview: there is physical stuff, and there is nonphysical stuff. Mind is part of the nonphysical stuff, according to this view.

The problems with this position are well-known. Most important: it is difficult, if not impossible, to explain how the mind and brain interact. This is unacceptable for a biologically based theory of mental function.

Views #2 and #3 both suggest the opposite, that mind is part of the physical world (a materialist position). Materialism has met with several objections. One objection is that the mind cannot be reduced to the brain, because it "makes no sense" to say "My brain felt like having a nap." Thinkers sometimes use the term "category error" to describe this supposed misstep. However, as Churchland notes, "one person's category error is another person's deep theory about the nature of the universe" ([4]: p. 273). Theories about nature — and the idioms that are used to express them — do change over time. Therefore, this argument appears weak.

Two other arguments concern the "aboutness" of mental representations, and subjective experience, which are both claimed to be incompatible with physical entities. This may not be the case. For instance, Figure 4 suggests a way to represent the "aboutness" of mental representations, and the claim that purely physical entities cannot have subjective experience appears circular, much like the argument based on natural language and folk psychology of mind and brain.

The following two views both represent mental processes as physiological processes. However, there is an important difference: View #3 explicitly states that Mind=Brain. View #2 is agnostic on this point.

**View #2**: A mental process is a bodily process (but not necessarily a brain process).

In other words, View #2 leaves open the possibility that some mental processes are not brain processes. There could be a rationale for this position if "mental" were defined to include functions outside the central nervous system (e.g., processes within the heart, the respiratory system, the digestive tract, and so forth). However, this would be an unusual (and perhaps over-extended) use of the term "mental."

**View #3**: A mental process is a brain (i.e., neurophysiological) process.

Finally, View #3 defines mental processes as brain processes. There are two major advantages in adopting this view:
(1) Defining mental processes with respect to basic subdivisions of the brain will make it easier to describe mappings of core functions, such as sensation, action, and memory, across species [11].

(2) Our knowledge of the brain and its structural and functional subdivisions can provide a framework for understanding different kinds of mental processing, and how they are related (see Fig. 4).

The first point is important, because a key goal within the bio-ontology community is to develop resources that can be used together, to integrate data and knowledge across domains. Comparative neurobiology has a critical role to play in bridging the domains of biology, neuroscience, and experimental psychology. Therefore, it may be useful to consider the semantic foundations for a cognitive ontology and whether they can support cross-species mappings of behavioral and brain systems.

The second point gets at the explanatory power of the view that mind is brain. The brain is undeniably complex. However, it is not infinitely complex. In fact, there are relatively straight-forward mappings between types of behavior and parts of the central nervous system, brain, and cortex (Table 1; see also [10], [17]).

In conclusion, View #3 (mental processing is neural processing) is most compatible with our larger aim: to develop a mental functioning ontology that is scientifically plausible and consistent with a realist framework.6

5 LEVELS OF BRAIN, LEVELS OF MIND

Table 1 summarizes four categories of mental processing, their primary functions, and the corresponding parts of the nervous system, brain, and cortex. From a neuropsychological view, all of human behavior (including covert as well as overt processes) can be explained with respect to one or more of these basic processes [17]. One advantage of this organizing framework is that mental processing can be viewed at different levels of analysis: with a focus on observable behavior (motor output), or on patterns of neural activity within different regions of cortex, brain, and nervous system.

Another virtue of considering the functional architecture of the brain is that it affords clear predictions about different kinds of mental and behavioral disorder [10]. For example, damage to parts of the motor control system (e.g., within cortico-striatal circuits) result in predictable symptoms, such as the slowed and uneven gestures that are characteristic of Parkinson's Disease (PD). Even more interesting, some PD patients exhibit linguistic disorders that resemble those of Broca's aphasics: i.e., difficulties with processing of natural language syntax [20]. While it may be possible to explain this comorbidity without reference to the brain, it is much easier to predict when we consider the connections between the basal ganglia and regions of left inferior prefrontal cortex. In general, understanding the distributed networks that relate different regions of the brain and body could help to explain clusters of psychological and behavioral symptoms, and when and why they occur.

Table 1. Mental processes (left-most column), major functions associated with these processes, and key regions of the body and brain that give rise these processes (right-most columns).

<table>
<thead>
<tr>
<th>Process</th>
<th>Function</th>
<th>Region of Body (NS)</th>
<th>Region of Cortex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory</td>
<td>Afferent connections to outer world (input)</td>
<td>Peripheral NS</td>
<td>Unimodal (V1, A1, etc.)</td>
</tr>
<tr>
<td>Motor (somatic)</td>
<td>Efferent connections to outer world (output)</td>
<td>Peripheral NS</td>
<td>Unimodal (M1)</td>
</tr>
<tr>
<td>Affective (visceral)</td>
<td>Sensory-motor processing of internal milieux (self)</td>
<td>Autonomic NS</td>
<td>Polymodal (Limbic/Paralimbic Regions)</td>
</tr>
<tr>
<td>Cognitive (central)</td>
<td>Association &amp; integration of sensory-motor, affective processes</td>
<td>Central NS (brain)</td>
<td>Polymodal (AssociationAreas)</td>
</tr>
</tbody>
</table>

6 I do not discuss "idealistic" views (brain and body are reducible to mind or consciousness), because most biological workers assume that the physical world is real. By contrast, there is no consensus on how to define mental phenomena within a biological context (other than use of "operational," that is, experiment-specific, definitions). The Mind-Body question is usually avoided in standard textbooks on behavioral and biological psychology.
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Figure 4 represents some of the key points discussed above. The subtypes of mental processing are linked to specific parts of the brain and central nervous system. This can help to explain the nature of higher cognitive processes, which are subserved by regions of association cortex, as well as sensory-motor and emotional processes, which are linked, respectively, to sensory-motor and autonomic systems through other parts of the cortex. Most interesting, some puzzling properties of Mind, such as "aboutness" and subjectivity, can be understood here in a concrete context, by considering how the mind-brain responds to (maps or "represents") the internal (visceral) and external environment.

SUMMARY AND CONCLUSION

In conclusion, there are advantages in defining mental processes as neural processes. First, it avoids the problems associated with view that mind is something non-physical. Second, it helps to explain a variety of psychological conditions and comorbidities. Third, it can support an integrated understanding of mind, brain, and behavior. In this sense, we have already experienced the "Decade of the Mind" (the 1990s): Mind just is the neural activity that makes us who we are.

Finally, it may useful to define a mental process more precisely as a distributed (BFO "aggregate") neural process. Although there is functional specialization within parts of the brain, it is equally clear that each mental process involves actions that are distributed over time and across the brain's neuraxis [17].
REFERENCES


