CoTOn: A Cognitive Theory Ontology for Representing Diverging Conceptualizations of Cognitive Concepts

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Abstract

Cognitive neuroscience is a data-intensive and theory-driven discipline that seeks to explain how human experience and behavior is related to physiological, behavioral, and neural measurements. The investigated cognitive concepts (e.g., memory or attention) are, however, latent, unobservable constructs that are assessed via observable and objectifiable measurements obtained in carefully designed experimental settings. Because their definitions and assumed interrelations may vary depending on the underlying cognitive theories, cognitive concepts must be defined and interpreted in the context of those theories. For communication, however, the cognitive neuroscience community is accustomed to use the same linguistic terms for denoting cognitive concepts that have varying definitions in different theories, effectively introducing terminological ambiguity. An ontology for the domain of cognitive neuroscience thus needs to be capable of representing these varying definitions of cognitive concepts that depend on different theories while preserving the relation to their linguistic terms to meet the communication needs of the community. To address this problem, we propose a Cognitive Theory Ontology (CoTOn) that provides the means to represent and relate 1. the objectifiable knowledge about observable entities of the experimental setting, 2. the theory-dependent conceptualizations of latent cognitive concepts, and 3. the community-specific use of the same linguistic terms for differently defined cognitive concepts. In this paper, we ontologically analyse the relevant entities in the cognitive neuroscience domain and derive a reference model and an operational version of CoTOn on the level of general types. We implement this initial version of CoTOn in Protégé and show its applicability for retrieving objectifiable as well as theory-dependent knowledge.

Keywords

cognitive neuroscience, domain analysis, reference model, operational ontology, SABiO, UFO

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1. Introduction

Cognitive neuroscience is a data-intensive and theory-driven discipline that seeks to explain how human experience and behavior is related to physiological, behavioral and neural measurements. Importantly, the objects of interest being investigated, i.e. cognitive concepts like memory or attention, are *latent, only indirectly observable constructs* [1]. To assess these latent cognitive concepts, they are operationalized via observable measurements that are obtained in carefully designed experimental settings.

Since cognitive concepts are constructs that are not directly observable, cognitive neuroscientists work with assumptions about them. These assumptions are provided by various theories that propagate potentially different definitions for these constructs. In practice, the latent nature of cognitive concepts and their subsequent definitions by different theories often result in ambiguous terminology. Accordingly, the same linguistic terms may be assigned to divergent cognitive concepts, or different linguistic terms are used for putatively identical concepts [1].

Because the definitions and assumed interrelations of concepts may vary depending on the underlying theoretical framework, cognitive concepts must be defined and interpreted in the context of those theories [2]. This is also highly relevant when it comes to providing adequate metadata for annotating neurocognitive datasets (obtained with e.g. functional magnetic resonance imaging, electroencephalography or magnetoencephalography), since a cognitive neuroscientist's research question is defined by the theoretical perspective taken. The research question, in turn, determines the details of the experimental setting in which a dataset is collected [3]. Consequently, the theoretical framework is essential for understanding the scientist's intent, for interpreting neurocognitive data, and thus for the interoperability of the data.

Making the domain knowledege in cognitive neuroscience explicit and negotiating its meaning necessitates an ontological domain analysis that is grounded in a top-level ontology. Deriving a domain ontology from this analysis offers powerful means for structuring this knowledge, resulting in a human-understable as well as machine-readable representation.

Problem statement. From an ontological perspective, the co-existence of competing theories implies diverging conceptualizations of reality, thus propagating different ontological commitments. In terms of representational adequacy, an ontology for the domain of cognitive neuroscience thus needs to be capable of representing these varying definitions while preserving their relation to commonly used linguistic terms in order to meet the communication needs of the community. These fundamental requirements have not been captured before in existing knowledge representation projects in the field. Hence, this paper aims to develop an ontology solving the problem of representing diverging conceptualizations of cognitive concepts put forward by co-existing theories while preserving their relation to commonly applied terminology.

Contribution. To address this problem, we propose a Cognitive Theory Ontology (CoTOn) that provides the means to represent and relate 1. the objectifiable knowledge about observable entities of the experimental setting, 2. the theory-dependent conceptualizations of latent cognitive concepts, and 3. the community-specific use of the same linguistic terms for differently defined cognitive concepts.

The remainder of this paper is organized as follows. Section 2 introduces related work on knowledge representation in cognitive neuroscience that we aim to reuse as a basis for CoTOn. In Section 3 we provide an ontological analysis for the domain of cognitive neuroscience, identifying the relevant entities and how they relate to each other. In Section 4, we present an initial operational version of CoTOn covering a selection of general types that are populated with domain-specific instances. Further, we execute exemplary queries for knowledge retrieval on the operational version of CoTOn. Lastly, in Section 5, we summarize our contributions and provide an outlook on planned future developments.

2. Related Work

The need for structured knowledge representation in cognitive neuroscience is reflected in the growing number of knowledge representation projects covering different aspects of the domain [4]. One of the few projects that focuses on the most challenging aspect, i.e. the representation of cognitive concepts, is the Cognitive Atlas [5, 6]. It is a collaborative knowledge-building project that was initiated to capture the current state of knowledge in cognitive neuroscience with the goal of agreeing on unique definitions for cognitive concepts. To bridge the gap between cognitive concepts and the experiments performed to assess them, the Cognitive Atlas uses the concept of *tasks* which in turn is reused from the Cognitive Paradigm Ontology [7, 8]. The conceptualization of the Cognitive Atlas asserts that cognitive concepts can be subkinds or parts of other cognitive concepts. Tasks, on the other hand, consist of one or more conditions that define the relevant experimental manipulations. These conditions have indicators, such as behavioral or neural measures, that are recorded for analysis. Related cognitive concepts are in turn either assessed via the indicator value for a specific condition or, following a subtraction logic commonly used in neuroimaging, isolated by contrasting the indicator values of multiple conditions.

With currently 886 entries for cognitive concepts and 788 entries for tasks, the Cognitive Atlas is the most comprehensive compilation of these entities available. Subsequent iterations have added concepts of phenotypes (i.e., mental disorders, personality traits, and behaviors), theories, and task batteries. With the exception of mental disorders with 221 entries, the remaining additions have not yet been fully embraced by the broader community as the number of entries for these concepts on the Cognitive Atlas website are comparatively small.

Of conceptual relevance to the present manuscript is that in the Cognitive Atlas, each cognitive concept can only be assigned with one unique definition. Accordingly, it does not provide the means to represent divergening definitions of cognitive concepts and how they relate to each other as proposed by competing theories. For CoTOn, we build on the Cognitive Atlas by reusing the definitions for the entities *Theory, Cognitive Concept, Task, Condition*, and *Indicator* as well as by adopting the linguistic terms used by the community for cognitive concepts. However, we address the limitations of the Cognitive Atlas with respect to the theory-driven representation of cognitive concepts by enabling diverging definitions of cognitive concepts although they are assigned the same linguistic term.

3. Ontological Domain Analysis

As stated above, a particular challenge for the domain of cognitive neuroscience lies in balancing the need for a shared vocabulary (to ensure interoperability and machine readability) while reflecting scholarly disagreement as a driver and necessity for scientific progress. The Cognitive Theory Ontology CoTOn, which we present as a possible solution, represents and relates theory-specific definitions of cognitive concepts to their commonly used linguistic terms and objectifiable measurements. CoTOn is grounded in the Unified Foundation Ontology (UFO [9]), so the notions of Endurant, Event, Aspect, Quality, Disposition, Quality Space and Quality Value as well as the relations involving them (e.g., inherence, instantiation, historical and existential dependence) should be interpreted as they are defined in that ontology. We recognize that many of these notions could be found in other top-level ontologies such as DOLCE [10] and BFO [11].

Subsequently, we follow a convention where the concepts from a top-level ontology are underlined and **those of the Cognitive Theory Ontology (CoTOn)** are represented in bold. For the running example in Section 3.3 we use italic letters to represent the *instances* of selected CoTon concepts.

3.1. Top-Level Ontological Distinctions

We employ the top-level ontological distinctions put forward by UFO [9], i.e. we assume the following: Firstly, there are Endurants and Perdurants (Events). Endurants can be Objects or Aspects, the latter inhering (and, thus, being existentially dependent) in the former. Aspects can be either Intrinsic Aspects - which inhere in a single individual, or Relators - which are existentially dependent on multiple individuals, thus, binding them. Intrinsic Aspects can be either Qualities or Dispositions. Qualities are aspects of individuals that are associated with (and can be measured on) Quality Values in specific Quality Spaces. Dispositions, in contrast, are Aspects that are manifested in certain situations as Events. Complementarily, Events are always manifestations of Dispositions. Lastly, Agents are Objects with intentionality.

3.2. CoTOn: A Cognitive Theory Ontology

As mentioned before, the domain of cognitive neuroscience comprises theory-dependent knowledge on cognitive concepts, community-specific usage of linguistic terms denoting these, and objectifiable knowledge on experimental settings. With respect to these three areas, we subsequently identify their relevant entities and how they relate to each other.

Theory-dependent knowledge. A **Cognitive Theory** is an **Artifact** created by an **Author**, who is a **Creator**. Thus, the theory is historically dependent on that author, meaning that it could not have existed without this author having existed before. **Artifact** creators are **Agents**, which can be **Individual Agents** or **Collective Agents**. A **Cognitive Theory** can define a number of **Cognitive Concepts** and can re-use concepts defined by other theories. Importantly, if a concept A is defined in theory T then A is existentially dependent on that theory, i.e., it cannot exist without that theory. Further, a **Cognitive Concept** can be notionally dependent on other concepts. If a concept A is notionally dependent on a concept B then A cannot be defined without reference to B. As an **Agent**, a **Cognitive Subject** bears a number of **Cognitive Aspects** (**Cognitive Qualities** and **Cognitive Dispositions**), including **Cognitive Capacities** (which are **Cognitive Dispositions**). The theory being tested hypothesizes the existence of **Cognitive Aspects** in that subject that are instances of **Cognitive Concepts** of that theory.

Community-specific terminology use. A **Scientific Community** is a collective agent whose members are **Scientists**. The **Scientific Community** uses **Linguistic Terms**, i.e. sequences of letters, as a symbol to denote **Cognitive Concepts**. **Terminological Usage** is a relator that connects a **Scientific Community**, **Linguistic Terms**, and **Cognitive Concepts**. As such, **Terminological Usage** represents the collective consensus of a **Scientific Community** to refer to different conceptualizations of **Cognitive Concepts** defined in different **Cognitive Theories** by a common **Linguistic Term**.

Objectifiable knowledge. **Cognitive Tasks** are types of experiments designed to test hypotheses formulated about **Cognitive Concepts** constituting a **Cognitive Theory**. A **Cognitive Task** can yield multiple **Cognitive Task Executions**. A **Cognitive Task Execution** is a complex event in which at least a **Cognitive Subject** (who is also an **Individual Agent**) participates. Further, a **Cognitive Task** is characterized by a number of **Task Conditions**, designed to test the presence of the hypothesized **Cognitive Aspects** inhering in a **Cognitive Subject**. A **Task Condition** has **Indicators** whose instances can be used to measure properties associated to these **Cognitive Concepts**. A **Cognitive Task Execution** (a run of the designed experiment) has as parts events termed **Task Condition Executions** that are instantiations of each of the **Task Conditions** prescribed by that **Cognitive Task**. **Task Condition Executions** are interpreted as manifestations of the hypothesized **Cognitive Dispositions** tested by the experiment (the **Cognitive Task**).

A **Task Condition Execution** also has as parts **Indicator Measurements**, which are events that produce **Data Items** that represent qualities associated with those **Task Condition Executions**. A collective of **Data Items** composes a **Dataset**. Those **Data Items** can be either **Indication Data Items** or **Indication Contrast Data Items**. **Indication Data Items** result from **Indications** that are created by **Indicator Measurements** and are instances of the **Indicators** associated with the **Cognitive Theory** being tested and which can have their measurements (termed **Cognitive Quality Measured Value**) measured in a Quality Space associated with a Quality of a **Task Condition Execution**. An **Indication Contrast Data Item** is a **Data Item** that represents a **Cognitive Indication Contrast** which is a relator connecting two different **Indications**.

3.3. Running Example

To better illustrate the problem statement and our proposed solution, we introduce the following examples. **Cognitive concepts** to which **Scientists** commonly refer to as *working memory* have been extensively studied in psychology and cognitive neuroscience. This resulted in several co-existing **Cognitive Theories**. Here, we introduce three influential theories that, while refering to the same **Linguistic Term** *working memory*, propagate different conceptualizations of different **Cognitive Concepts**.

The *Modal model* [12], a **Cognitive Theory** created by the **Authors** *R. Atkinson* and *R. Shiffrin*, defines the **Cognitive Concept** of *short-term store* as the capacity to maintain information for a brief period of time and explicitly equates it with the **Linguistic Term** of *working memory*. Based on that, *working memory* can be assessed via the *forward condition* (a **Task Condition**) of the *digit span task* (a **Cognitive Task**), in which **Cognitive Subjects** are presented with a sequence of numbers and are asked to recall them in the same order immediately after presentation. The *number of correctly remembered digits* is interpreted as an **Indicator** of *short-term store*.

The *Multicomponent model* [13, 14] (created by *A. Baddeley* and *G. Hitch*), on the other hand, defines the **Cognitive Concept** of *working memory* as the capacity to maintain and manipulate information. In this conceptualization, *working memory* has as parts other **Cognitive Concepts**, i.e. the *phonological loop*, *visuospatial sketchpad*, *episodic buffer*, and *central executive*. According to its defintion, *working memory* cannot be measured with the *forward condition* of the *digit span task* because no manipulation of information is required. Instead, *working memory* as defined by this model must be assessed with more complex **Task Conditions**, such as the *sequencing condition* of the *digit span task*, in which **Cognitive Subjects** must mentally arrange the numbers presented to them in ascending order before reporting them.

In the **Cognitive Theory** *Embedded-process model* [15], the **Author** *N. Cowan* explicitly refers to *working memory* as a **Linguistic Term** for communication. This term, in turn, points to the **Cognitive Concept** of *activated memory*. As such, *activated memory* is defined as maintaining old and novel information in an accessible state that is suitable for manipulation during the performance of interfering tasks. Here, the **Cognitive Concept** of *short-term memory* is explicitly defined as a subcomponent of *activated memory*. A **Cognitive Task** that assesses *working memory* as defined in this **Cognitive Theory** is the *reading-span task*, in which **Cognitive Subjects** are instructed to remember the last word of a sentence while simultaneously making judgements about the content of the sentences.

4. CoTOn: Reference Model and Initial Implementation

The traditional two-level schema in conceptual modeling (i.e. the level of types or classes and the level of instances [16]) does not fully suffice the representational complexity needed for the domain of cognitive neuroscience. As explicated in the previous section, the type-level of CoTOn (e.g. containing the classes Cognitive Concept and Cognitive Task) is instantiated again by types (e.g. working memory and digit span task). According to [16], this means that the former are second-order types, i.e. types whose instances are first-order types, and the latter are in turn first-order types, i.e. types whose instances are individuals that cannot play the role of types in the instantiation relation. Ultimately, those individuals are the neurocognitive datasets, e.g. the particular Cognitive Task Execution of a digit span task that measures the Cognitive Aspect working memory in a particular Cognitive Subject as an instantiation of a respective Cognitive Concept.

We acknowledge that this additional layer of complexity requires a multi-level modeling approach which will be adressed in future work with respect to neurocognitive data annotation (see Section 5). As a first step, however, it is necessary to derive an ontological representation that is capable to disambiguate the conflation of linguistic terminology use and theory-dependent conceptualizations of cognitive concepts. As the purpose of the current paper is to address this first step, in the following we will model selected second-order types as classes and the first-order types as individuals instantiating those classes.

The development process described in the subsequent sections was guided by the Systematic Approach for Building Ontologies (SABiO, [17]). In accordance with the SABiO guidelines, we employ the term reference model for denoting the domain reference ontology, i.e. a solution-independent conceptual model describing and organizing a selection of relevant domain entities. The term operational ontology in turn refers to an implemented, machine-readable version of the reference model.

4.1. Purpose Identification and Requirement Elicitation

The intended use of CoTOn targets two main aspects, i.e. knowledge representation and data annotation. Regarding knowledge representation, we aim to capture objectifiable knowledge on the experimental settings (i.e. Cognitive Tasks, Task Conditions, and Indicators) as well as theory-dependent knowledge on Cognitive Concepts, their assumed interrelations, and their connection to common Linguistic Terms. With respect to Cognitive Concepts, an essential aspect is that we do not aim to provide a (subjective) intersection of current (heterogeneous) thinking, but rather to allow the representation of the co-existing heterogeneity of Cognitive Concepts - embedded in their respective defining Cognitive Theories. For the purpose of this paper, we will apply CoTOn for knowledge retrieval. Exploiting its reasoning capabilities for knowledge discovery (e.g., by finding implicit commonalities across Cognitive Theories, Cognitive concepts, or Cognitive Tasks) as well as neurocognitve data annotation will be part of future work.

To describe the functional requirements that the initial version of CoTOn must satisfy, we followed the SABiO guidelines [17] and formulated seven competency questions (CQ) based on the running example. We again highlight **classes** in bold, and the respective *inidividuals* of interest in italics. In terms of evaluation, these competency questions are used as example queries on the operational ontology in Section 4.4.

- **CQ1:** Which **Cognitive Theories** define **Cognitive Concepts** that are denoted with the **Linguistic Term** *Working memory*?
- **CQ2:** Which **Authors** created the **Cognitive Theory** *Modal model*?
- **CQ3:** Which **Cognitive Concepts** are denoted with the **Linguistic Term** *Working memory*?
- **CQ4:** What are parts of the **Cognitive Concept** that is denoted with the **Linguistic Term** *Working memory* as defined by the **Cognitive Theory** *Multicomponent model*?
- **CQ5:** What are parts of the **Cognitive Concept** that is denoted with the **Linguistic Term** *Working memory* as defined by **Cognitive Theory** *Embedded-process model*?
- **CQ6:** Which **Indicators** measure the **Cognitive Concept** that is denoted with the **Linguistic Term** *Working memory* as defined by the **Cognitive Theory** *Modal model*?
- **CQ7:** Which **Indicators** measure the **Cognitive Concept** that is denoted with the **Linguistic Term** *Working memory* as defined by the **Cognitive Theory** *Multicomponent model*?

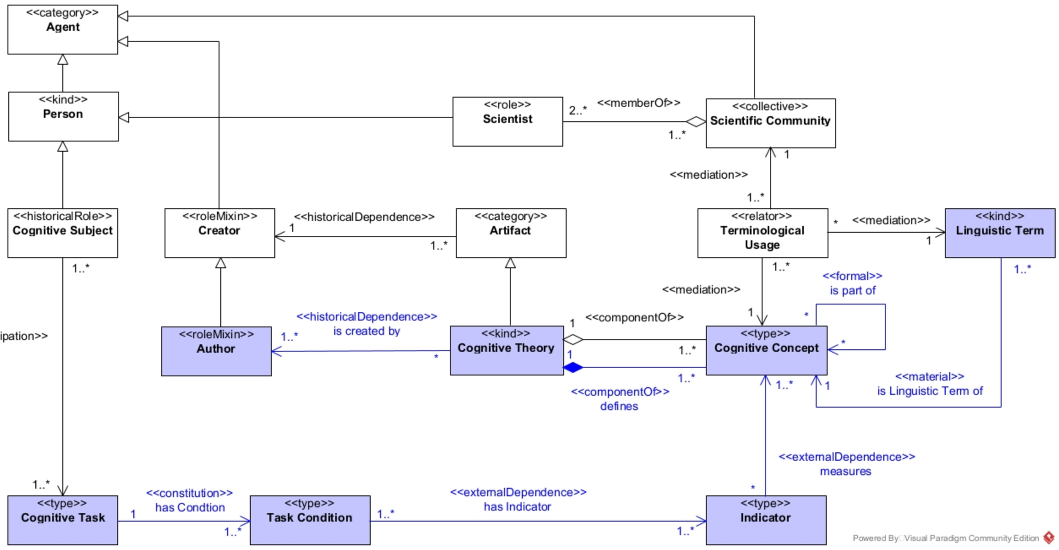

Figure 1: Reference model for CoTOn. Blue color indicates the concepts and relations that are implementend in the operational ontology.

4.2. Reference Model

Based on these competency questions, we derived a reference model (Figure 1) that employs a selection of CoTOn concepts and their interrelations that were identified and described in the ontological domain analysis in Section 3. The reference model was designed in OntoUML [18], a conceptual modeling language that is specifically developed to reflect the ontological distinctions put forward by UFO. In accordance with SABiO [17], we use the reference model as the basis for implementing an operational version of CoTOn.

For the initial operational version (see Section 4.3), we implement the CoTOn concepts Cognitive Theory, Author, Cognitive Concept, Linguistic Term, Cognitive Task, Task Condition, and Indicator as classes (highlighted in blue in Figure 1). Table 1 shows definitions for those classes as well as exemplary instances. Note that for those classes, we reuse definitions provided by the Cognitive Atlas and the American Psychological Association Dictionary, a widely accepted knowledge source in the cognitive neuroscience community, whenever possible.

4.3. Operational Ontology

We use Protégé [20, 21] to implement the initial operational version of CoTOn in OWL [22], the Web Ontology Language [1]. This operational version currently contains the seven second-order types Cognitive Theory, Author, Linguistic Term, Cognitve Concept, Cognitive Task, Task Condition, and Indicator that are instantiated with the respective first-order types. Figure 2 depicts exemplary class instantiations for the Multicomponent model (i.e. an instance of a Cognitive Theory).

[1]An aplha release of the current development status of CoTOn is availabe via https://gitlab.com/ccns/neurocog/neurodataops/anc/classification/cognitive-ontology/-/releases/alpha-release

Table 1
Definition and examples of classes in the reference model that are implemented in the operational ontology.

Entity	Definition	Example
Cognitive Theory	A principle or body of interrelated principles that purports to explain or predict a number of interrelated phenomena [19]	Multi-component model, Modal model
Author	The creator of a Cognitive Theory	A. Baddeley, N. Cowan
Cognitive Concept	A latent unobservable construct postulated by a psychological theory [5]	Activated memory, Phonological buffer
Linguistic Term	A colloquial name used by the cognitive neuroscience community to denote Cognitive Concepts	Working memory
Cognitive Task	A prescribed activity meant to engage or manipulate mental function in an effort to gain insight into the underlying Cognitive Concepts [5]	Digit span task, Reading span task
Task Condition	Subsets of an experiment that define the relevant experimental manipulation [5]	Digit span task: forward condition, Digit span task: sequencing condition
Indicator	A specific quantitative or qualitative variable that is recorded under a particular condition for analysis [5]	Number of items remembered correctly

Since the Cognitive Atlas database provides a list of commonly used linguistic terms for cognitive concepts, we reuse them by selectively importing (`owl:import`) these terms as instances of the class Linguistic Term into our ontology. Note that the decision to model the entity Linguistic Term as a class rather than an annotation property of Cognitive Concepts indicating synonymy (e.g., skos:altLabel) was driven by the necessity to confine the list of selectable terms to a predefined range of options. This guarantees that only the terms imported from the Cognitive Atlas (or future extensions thereof) can be assigned as Linguistic Terms of Cognitive Concepts rather than arbitrary annotation strings. This is especially important for CoTOn's purpose to reflect our community's communication habits (i.e. the Linguistic Terms used by our Scientific Community) that are then further disambiguated via Cognitive Theories that define the respective Congitive Concepts.

To distinguish differently defined instances of the class Cognitive Concept that have identical display names (and thus, connect to the same instance of the Linguistic Term class) we assign unique Internationalized Resource Identifiers (IRIs) that contain the theory name. In order to enable more exhaustive representation of the knowledge that theories encapsulate, we plan to elevate the current Cognitive Concept instances to second-level types, i.e. classes in the operational ontology, in future work.

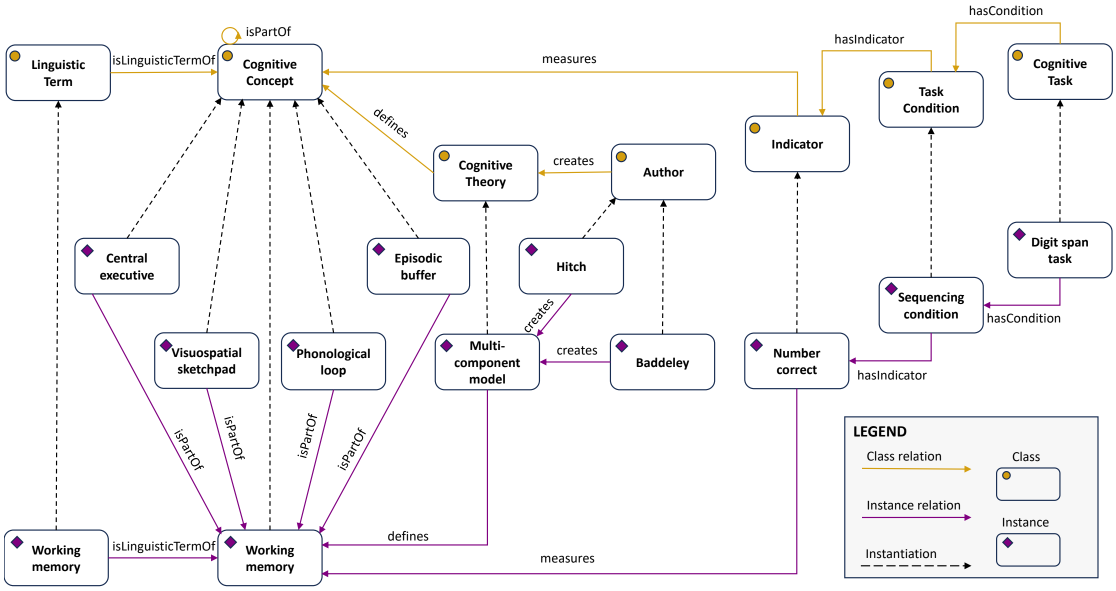

Figure 2: Exemplary instantiation for the Multicomponent model.

4.4. Ontology Application

The operational version of CoTOn can now be applied to answer the competency questions stated in Section 4.1. For answering these questions, we use the built-in function for description logic (DL) queries in Protégé and provide an overview of the results in Table 2.

The first three competency questions ask for objectifiable knowledge (adressing the first requirement for CoTOn, i.e. representing objectifiable knowledge) about theories that define a concept that is commonly termed working memory (**CQ1**), the authors of one of those theories (**CQ2**), and concepts that are denoted with the linguistic term working memory (**CQ3**). In contrast, **CQ4** to **CQ7** require theory-dependent knowledge about the diverging conceptualizations of cognitive concepts that are commonly termed working memory and which indicators are eligible for measuring these concepts as defined by particular theories. Note that, while **CQ4** and **CQ5** as well as **CQ6** and **CQ7** ask for the same kind of knowledge, the queries return different instances depending on the theoretical context - thus satisfying the second and third requirements CoTOn was developed to address (i.e., representing theory-dependent knowledge and its relation to linguistic terms used in the cognitive neuroscience community).

The importance of the three requirements we formulated for CoTOn can be particularly well observed when comparing the query results for **CQ3** and **CQ5**. Consider the similar sounding cognitive concepts of short-term store (result for **CQ3**) and short-term memory (result for **CQ5**). Short-term store is a cognitive concept that is defined in the modal model (see Section 3.3) and is commonly denoted with the linguistic term working memory. Short-term memory, however, is a cognitive concept defined in the embedded-process model. Importantly, here short-term memory itself is not denoted with the linguistic term working memory, but is part

Table 2
DL queries and query results for competency questions. The violet diamond shapes indicate that the results are instances of the queried classes.

	DL Query	Results
CQ1	Cognitive Theory **and** defines **some** (hasLinguisitcTerm **value** Working memory)	◆ Embedded-process model ◆ Modal model ◆ Multicomponent model
CQ2	Author **and** creates **value** Modal model	◆ Atkinson ◆ Shiffrin
CQ3	Cognitive Concept **and** hasLinguisticTerm **value** Working memory	◆ Activated memory ◆ Short-term store ◆ Working memory
CQ4	Cognitive Concept **and** isPartOf **some** (hasLinguisticTerm **value** Working memory **and** isDefinedBy **value** Multicomponent model)	◆ Central executive ◆ Episodic buffer ◆ Phonological loop ◆ Visuospatial sketchpad
CQ5	Cognitive Concept **and** isPartOf **some** (hasLinguisticTerm **value** Working memory **and** isDefinedBy **value** Embedded-process model)	◆ Short-term memory
CQ6	Indicator **and** measures **some** (hasLinguisticTerm **value** Working memory **and** isDefinedBy **value** Modal model)	◆ Digit span task Forward Number correct
CQ7	Indicator **and** measures **some** (hasLinguisticTerm **value** Working memory **and** isDefinedBy **value** Multicomponent model)	◆ Digit span task Sequencing Number correct

of the cognitive concept that is commonly termed working memory in this theory, namely activated memory.

5. Conclusion and Future Work

In this paper, we provided a solution for representing diverging theoretical assumptions of the latent cognitive concepts studied in cognitive neuroscience. With CoTOn, we proposed a Cognitive Theory Ontology to represent and relate 1. the objectifiable knowledge about observable entities of the experimental setting, 2. the theory-dependent conceptualizations of latent cognitive concepts, and 3. the community-specific use of the same linguistic terms for differently defined cognitive concepts. Further, we presented an ontological analysis, grounded in UFO, for the domain of cognitive neuroscience. Based on this analysis, we derived a reference model and implemented an initial operational version of CoTOn on the type-level in Protégé. Lastly, we exemplified and evaluated its application for knowledge retrieval by answering the competency questions we formulated during the development process. In contrast to existing knowledge representation projects in the field such as the Cognitive Atlas, CoTOn is capable of representing different theory-dependent conceptualization of cognitive concepts and disambiguate their conflation with linguisitic terms commonly used by our community.

In future work, we aim to extend the operational version of CoTOn by including additional entities as identified in the ontological domain analysis and use its reasoning capacities for knowledge discovery. Further, we intend to use CoTOn to annotate neurocognitive datasets with domain-specific metadata, allowing researchers to deeply evaluate the characteristics of a dataset. We expect that domain-specific, machine-readable annotations will facilitate data search, integration, and reuse by enabling the discovery and combination of datasets based on desired characteristics for purposes beyond those for which they were originally collected.

To address the need for data annotation, we aim to apply a multi-level modeling approach to represent this additional layer of complexity. We believe that incorporating neurocognitive data instances as an additional level will help to address two longstanding issues in cognitive neuroscience, i.e. 1) estimating how well theories explain existing data, ultimately allowing empirically based judgments between competing theories, and 2) addressing the unsolved problem of reverse inference, i.e. inferring the presence of cognitive processes from neural activation patterns [23, 24].

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