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A framework for constructing cognition ontologies using WordNet, FrameNet, and SUMO

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Abstract

Psychoinformatics is an emerging discipline that uses tools from the information sciences to organize psychological data. This article supports that objective by proposing a framework for constructing cognition ontologies by using WordNet, FrameNet, and the Suggested Upper Merged Ontology (SUMO). The first section describes the major characteristics of each of these tools. WordNet is a large lexical data base that was begun in the 1980s by George Miller. FrameNet is a database of event schemas based on a theory of frame semantics developed by the linguist Charles Fillmore. SUMO is a formal ontology of concepts expressed in mathematical logic that supports deductive reasoning. The next section discusses the objectives of science ontologies and includes examples for psychoses and for emotion. The article then describes potential applications of cognition ontologies for (1) studying how people organize knowledge, (2) analyzing major theoretical concepts such as abstraction, and (3) formulating premises that can serve as a link between informal taxonomies and formal ontologies. The final section discusses extending cognition ontologies to related domains such as artificial intelligence and cognitive neuroscience.

Keywords: Attention; Cognition; Language; Ontology; Taxonomy

1. Introduction

The rapid accumulation of human knowledge is creating an increasing urgency to impose some organization on that wealth of information in order for people to fully comprehend its significance. One example of the scope of information about even a single topic is found in a chapter on attention in the *Annual Review of Psychology*. Chun, Golomb, and Turk-Browne (2011) stated that typing the word "attention" into a search engine such as PubMed, Web of Science, or Scopus will return hits numbering in the hundreds of thousands. They therefore created a taxonomy to interpret this research by focusing on the types of information that require attention.

Computers can help organize information when the volume and complexity of that information exceeds human capacity for understanding. But computers have been handicapped by the fact that until recently they have lacked the context of information about the world needed to understand much of the data that is collected. A new combination of resources that can aid in computer understanding and processing of complex and high volume information is emerging.

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Yarkoni (2012) used the term *psychoinformatics* to refer to the emerging discipline that uses tools and techniques from the computer and information sciences to improve the acquisition, organization, and synthesis of psychological data. His search on Google Scholar when writing the article revealed only 18 hits for this term compared to over 3000 hits for *ecoinformatics*, 18,000 hits for *neuroinformatics*, and 1 million hits for *bioinformatics*. Yarkoni suggested that psychologists are already making important contributions to *psychoinformatics* but need to formally recognize the topic to encourage its further development. He also argued that psychologists need to develop comprehensive ontologies of psychological constructs to benefit maximally from publicly accessible data sets.

Our goal in this article is to illustrate how tools from the information sciences – WordNet, FrameNet, and the Suggested Upper Merged Ontology (SUMO) – can be used to construct cognition ontologies. We distinguish between a taxonomy and an ontology based on their degree of formalism. We will use the term *ontology* to refer to organization based on logical relations.

In his book on ontologies Hoekstra (2009) described their purpose. Philosophers construct ontologies to formulate the fundamental building blocks of reality by specifying a vocabulary and definitions for describing things in the world (Abdoullaev, 2008). Their contributions are intended to reflect a commitment to some philosophical theory. Developers in the information sciences seek to construct ontologies based on pragmatic and computational considerations that can be used primarily to retrieve and reason about knowledge (Sowa, 1995). A third purpose, not discussed in Hoekstra (2009), is to provide a framework for organizing and sharing scientific discoveries (Smith & Ceusters, 2010). It is this third purpose that has motivated our project.

We begin by describing the characteristics of each of three resources for organizing knowledge. After describing WordNet, FrameNet, and SUMO we discuss the characteristics of scientific ontologies and provide an example for representing psychoses and two examples for representing emotion. We next propose applications of cognition ontologies to (1) studying the organization of knowledge, (2) analyzing major theoretical constructs, and (3) formalizing taxonomies. We illustrate the last objective by expanding on the attention taxonomy developed by Chun et al. (2011). We conclude by linking cognition ontologies to related domains such as artificial intelligence and cognitive neuroscience.

2. Information science tools

2.1. WordNet

WordNet (http://wordnet.princeton.edu) is a large lexical database for English that was initiated in the 1980s by George Miller at Princeton to understand how children learn new words. Although this particular goal was abandoned, the project did result in productive discoveries about relations among words (Miller & Fellbaum, 2007). One approach to word meaning is based on the hypothesis that meanings can be constructed from a small number of semantic components. An alternative approach, adopted by WordNet, is that words can be related in semantic networks consisting of relations such as *is-a-kind-of*, *is-a-part-of*, *is-an-antonym-of* and *entails*. These semantic relations organize WordNet into a large network of linguistically labeled nodes.

Fellbaum (2010) described an overview of WordNet that serves as a basis for our summary. The Collins and Quillian (1969) hierarchical network model provided the initial inspiration for incorporating hierarchical relations into WordNet by linking specific concepts to more general ones. There are also important nonhierarchical relations. WordNet classifies synonyms (*small*, *little*) into groups called *synsets* in which one member may be substituted for another member because they have equivalent or near equivalent meaning. Whereas synonymy is a many-to-one mapping of words to a concept, *polysemy* is a one-to-many mapping of a word to its meanings. For instance, the word *trunk* may refer to a car, a tree, or an elephant. We plan to use WordNet definitions as much as possible because of their widespread application in the information sciences. However, we will occasionally substitute other definitions when they appear more useful for constructing cognition ontologies. Some of these substitutions are from the *APA Dictionary of Psychology* (VandenBoss, 2006) because of its greater domain specificity.

Using WordNet definitions requires selecting the relevant definition (senses) of each word when there is more than one definition. For instance, the word *attention* has 6 senses in WordNet. One sense is *a courteous act indicating affection;* "*she tried to win his heart with her many attentions*". Another is *a motionless erect stance with arms at the sides and feet together;* "*the troops stood at attention*". These two senses are atypical in the cognitive literature. Two other definitions distinguish between two psychological distinctions that were mentioned by William James' in his book *Principles of Psychology* (James, 1890). The first refers to the faculty or power of mental concentration. The second sense refers to the process whereby a person concentrates on some features of the environment to the (relative) exclusion of others. We will later emphasize these two senses when constructing premises for an attention ontology.

2.2. FrameNet

Frames have a different structure than dictionaries and ontologies because they capture co-occurrence and structural relations among linguistic concepts. An example of their application in cognition is Elman's (2009) proposal that lexical knowledge depends on event schemas. For instance, Elman shows how understanding the verb *cut* depends on the identity of the agent (lumberjack, pastry chef, butcher), the instrument (saw, knife), and location of the underlying event.

The Berkeley FrameNet project (https://framenet.icsi.berkeley.edu) provides a useful data set for representing event and other schemas. FrameNet is based on a theory of Frame Semantics developed by the linguist Charles Fillmore and later Colin Baker (Fillmore & Baker, 2010). They define cognitive frames as the many organized packages of knowledge that enable people to perceive, remember, and reason about their experiences. Examples include event schemas such as going to a hospital, stages of a life cycle, and the organization of the human face. Cognitive frames often consist of interconnected roles together with constraints on possible or likely fillers of those roles. The concept of a script formulated by Schank and Abelson (1977) would be an example of a cognitive frame.

Frame Semantics is concerned with the expression of meaning in cognitive structures (frames) that influence understanding of linguistic expressions. Frame evocation in this sense guides the interpretation of language-specific associations that connect linguistic signs with particular frames. The basic assumption of Frame Semantics is that all content words require a link to background frames in order to understand their meaning. Fillmore and Baker state that Frame Semantics research is necessarily empirical, cognitive, and ethnographic because it depends on the experiences and values in the surrounding culture.

Many frames in FrameNet, such as for the word *Remembering*, are relevant to cognition. The FrameNet distinction between *Remembering_experience* and *Remembering_information* captures the cognitive distinction between remembering experiences in episodic memory and facts in semantic memory (Tulving, 1972). When remembering an *experience*, a Cognizer calls up an episodic memory of past Experience or an Impression of a Salient_entity formed on the basis of past experience. The capitalized words (Cognizer, Experience, Impression, Salient_entity) are core frame elements. Non-core frame elements for this frame are context, duration, manner, time, and vividness. When remembering *information*, a Cognizer retains facts in memory and is able to retrieve them. Non-core frame elements for this frame are accuracy, context, time, and topic. FrameNet provides an intermediate level of organization between word definitions and ontological relations. We will provide examples of connections among words, frames, and ontologies after discussing the organization of ontologies.

2.3. Suggested Upper Merged Ontology (SUMO)

The Suggested Upper Merged Ontology (Niles & Pease, 2001; Pease & Niles, 2002) is an open source formal ontology consisting of an upper ontology and many domain ontologies that are freely available at http://www.ontologyportal.org. The upper level of SUMO consists of approximately 1000 terms and 4000 axioms (logical statements). When combined with its domain ontologies it totals some 20,000 terms and 80,000 axioms (Pease, 2011). This wealth of definitions makes it several orders of magnitude larger than ontologies such as DOLCE or the Basic Formal Ontology. The expressiveness of the logical language used in SUMO also supports a greater richness, variety and completeness of definitions with respect to these other ontologies. SUMO has undergone thirteen years of development, review by a

```
Entity
    Abstract
    Physical
        Object
        Process
            IntentionalProcess
                ContentDevelopment
                Guiding
                IntentionalPsychologicalProcess
                    Calculating
                    Classifying
                    Comparing
                    Learning
                    Planning
                    Predicting
                    Reasoning
                    Selecting
                    Investigating
                Keeping
                Looking
                Listening
                Maintaining
                Making
                Pursuing
                SocialInteraction
            Internal Change
                BiologicalProcess
                PsychologicalProcess
                    Imagining
                    Perception
                        Hearing
                        Seeing
                    Remembering
```

Note: Indentations depict subclasses.

Fig. 1. Part of the SUMO hierarchy showing psychological processes. http://www.ontologyportal.org/. *Note:* Indentations depict subclasses

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community of hundreds of people, and application in expert reasoning and linguistics. It covers areas of knowledge such as temporal and spatial representation, units and measures, processes, events, actions, and obligations.

SUMO has also been mapped by hand (Niles & Pease, 2003) to the entire WordNet lexicon of approximately 100,000 noun, verb, adjective and adverb word senses, which not only acts as a check on coverage and completeness, but also provides a basis for application to natural language understanding. The Global WordNet (Pease, Fellbaum, & Vossen, 2008) effort links many other languages, including Arabic, Chinese, and Hindi to the English WordNet synsets, resulting in a multilingual linked lexicon. SUMO supports the Global WordNet by providing a conceptual ontology that is independent of a specific language.

The concept-word mappings of any given language are somewhat accidental because existing words do not fully represent all available concepts (Pease & Fellbaum, 2010). A semantic network or a frame-based ontology primarily uses natural-language definitions to express the meaning of words. In contrast, a formal ontology uses logical statements (axioms) to represent meaning. SUMO is written in first-order and higher-order logics. The logical statements include over 1000 relations rather than the approximately one dozen relations in WordNet. However, SUMO is not concerned with words in any particular language and therefore does not classify words into synsets. The linking of words in WordNet to either equivalent or more generic concepts in SUMO is mutually beneficial.

Fig. 1 shows a partial depiction of SUMO's hierarchical organization. The root node is **Entity**, which is partitioned into **Physical** and **Abstract**. **Physical** is partitioned into **Object** and **Process**. Of particular relevance to cognition ontologies is the variety of processes that can represent cognitive processes. SUMO lists **Calculating, Classifying, Comparing, Learning, Planning, Predicting, Reasoning,** and **Selecting** as intentional psychological processes. The lower part of Fig. 1 shows that **IntentionalPsychologicalProcess** is a subclass of **PsychologicalProcess,** as are **Imagining, Perception,** and **Remembering**. Imagining (as in dreaming), perception (as in involuntary attention) and remembering (as in spontaneous retrieval) can occur without intention.

2.4. Linking FrameNet to SUMO

In addition to linking WordNet to SUMO, the linking of FrameNet to SUMO (Scheffczyk, Baker, & Narayanam,

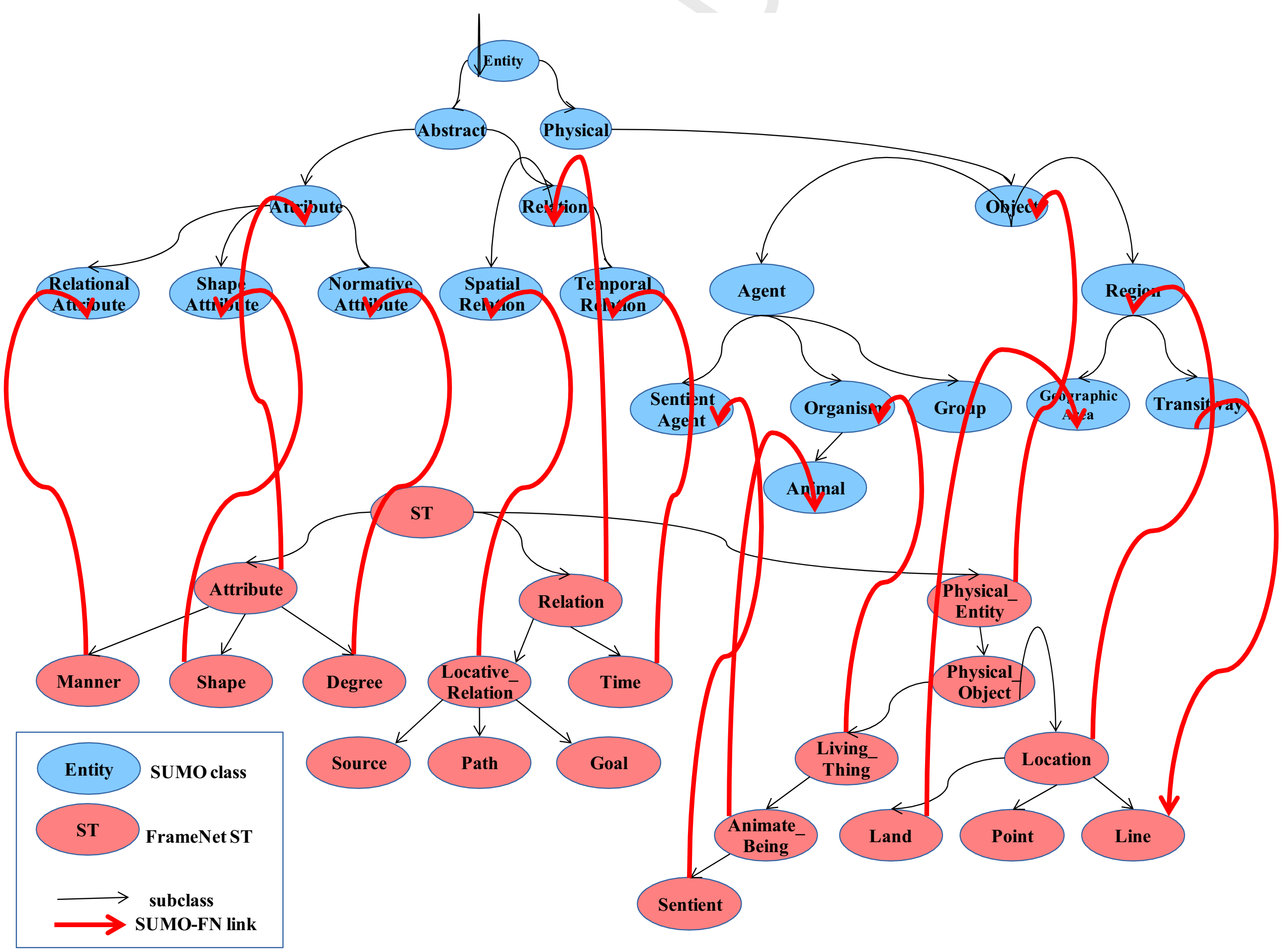

Fig. 2. Example of linking FrameNet to SUMO. From Scheffczk, Pease, and Ellsworth (2006).

2006) is helpful for integrating linguistic and formal conceptual knowledge. Fig. 2 illustrates an example of how frame elements in FrameNet can be linked to classes in SUMO for portions of the Attack frame. The Attack frame inherits from the more general Intentionally_affect frame and uses the Hostile_encounter frame. The FrameNet semantic types (ST), shown in the lower part of the figure, place constraints on the fillers of frame elements. The upper part of the figure shows parts of the SUMO class hierarchy, which differs slightly from the ST hierarchy because it is derived from knowledge engineering principles rather than from linguistic principles. Some STs (*Shape*, *Time*, *Location*, *Animate_being*) have one corresponding SUMO class enabling the STs to become a subclass of its corresponding SUMO concept. However, occasionally a ST (such as *Line*) has a broader meaning than a corresponding SUMO class. The downward arrow from *Transitway* to *Line* in Fig. 2 indicates that *Transitway* is the subclass. The connections among WordNet, FrameNet, and SUMO provide multiple integrated tools for organizing knowledge about cognition.

The distinction between unintentional and intentional cognitive processes can serve as an example of establishing a productive link between SUMO and FrameNet. FrameNet makes this distinction for perception by including both a Perception_experience frame and a Perception_active frame (Fillmore, Baker, & Sato, 2004). The Perception_experience frame refers to unintentional perceptual experiences. The perceiver role is therefore passive, in contrast to the Perception_active frame in which perceivers intentionally direct their attention to some entity or phenomenon. There are different lexical items in each frame. For instance, whereas Perception_experience has *see*, Perception_active has *look*. Whereas the Perception_experience frame has *hear* the Perception_active frame has *listen*. This distinction is consistent with WordNet and with SUMO (Fig. 1) in which only **Look** and **Listen** are classified as intentional processes.

3. Science ontologies

3.1. Guidelines

The purpose of cognition ontologies is to organize scientific knowledge about cognition. Smith and Ceusters (2010) proposed a methodology for organizing scientific knowledge based on the premise that "the most effective way to ensure mutual consistency of ontologies over time and to ensure that ontologies are maintained in such a way as to keep pace with advances in empirical research is to view ontologies as *representations of the reality that is described by science*" (p. 139).

They emphasize that scientific ontologies evolve over time but at any given stage should be consistent with the best available settled science. One might think that his principle would be problematic for a domain such as cognitive psychology in which there will likely be disagreements on which discoveries by cognitive psychologists deserve classification as *settled science*, however, as we will argue later, many such differences can be attributed to how concepts are assigned to labels, rather than the presence or absence of particular concepts. According to Smith and Ceusters (2010):

> *Matters ontological will be more complicated in areas of non-settled science, where they may be multiple camps of experts, and where the appropriate ontological analysis of the very experiments used to test given hypotheses may be subject to dispute. Ontologies may then provide a supporting role in the testing of the relevant hypotheses; however, it is not up to the authors of reference ontologies to pick sides in such disputes; rather this is a decision that should wait for science (p. 178).*

Our goal for building cognition ontologies is to formulate logical axioms that encode the definitions, empirical findings and theoretical statements that have widespread support from cognitive scientists. Such ontologies are, of course, subjective and will evolve over time as they are shaped by new discoveries and critical feedback. Critical feedback is particularly important in unsettled domains such as cognitive psychology. As argued by Smith and Ceusters, even ontologies in settled domains of science can benefit from outside criticism and competing proposals.

Smith and Ceusters advocate that a term should be included in an ontology only if there is experimental evidences that the term exists in reality. They believe that this view is generally endorsed by empirical scientists but not by computer scientists, in part because "computer scientists – unlike most biologists – receive training in cognitive psychology, which encourages them to have strong feelings about what they see as the constructed nature of the human mind" (p. 162). We view the realist methodology advocated by Smith and Ceusters as an attempt to construct a normative ontology for describing science. However, many cognitive psychologists investigate how people's descriptive models of reality differ from normative models. Cognition ontologies should therefore provide a framework for discussing the development and evolution of these constructed models.

We partially concur with Smith and Ceusters that technical terms that have multiple conflicting technical uses should be avoided. For example, one of the reasons Lenat (2008) believes that artificial intelligence has not advanced further as a theoretical discipline is its inconsistent use of terminology. Lenat offers the field of medicine as a contrasting case in which deliberations over the meaning of the term *myocardial infarction* were announced by a joint meeting of the American College of Cardiology and the European Heart Society. The failure to agree on definitions can limit both theoretical and practical advances.

However, elimination of terms that have been used differently by cognitive psychologists could result in very few surviving terms. It is therefore necessary to distinguish among different uses of a word as in indicator that they are different concepts in the ontology. For instance, Schmidt (1991) distinguished among four uses of the word *distinctiveness* when reviewing its effect on memory. Primary distinctiveness refers to items in the immediate context such as a black word included in a list of yellow words. Secondary distinctiveness refers to items in memory based on previous occurrences. A yellow word is more distinct than a black word according to this frame of reference because yellow words occur less frequently. Emotional distinctiveness refers to stimuli that have an emotional impact such as the word *terrorist*. Processing distinctiveness refers to distinctive encodings of stimuli to make them more distinctive, as when people are more likely to recognize a caricature than the actual drawing in a facial recognition memory test (Mauro & Kubovy, 1992).

Formally defined concepts derived from these proposed definitions of words such as *distinctiveness* should be included in cognition ontologies. Making distinctions among different definitions of a word will be facilitated by SUMO's link to WordNet (Niles & Pease, 2003), which typically provides more than a single definition. Using SUMO should help resolve many issues regarding multiple interpretations of a word. Concepts such as "primary distinctiveness" and "secondary distinctiveness" can be formally expressed in SUMO and linked to words.

3.2. Psychology ontologies

3.2.1. Psychosis

Lexical resources such as WordNet and FrameNet are beneficial because they enable the syntactic and semantic analysis of language, but they are not intended for deductive logical reasoning. In contrast, formal ontologies can be used for automated logical reasoning (Scheffczyk et al., 2006). Most of the initial efforts to organize cognitive concepts have been based on taxonomies rather than on formal ontologies. However, several groups have recently proposed ontologies for psychological topics such as psychosis (Kola et al., 2010). As stated by the authors:

> *An ontology that would facilitate data sharing would increase the statistical power and validity of findings thereby enhancing our understanding of psychosis and psychotic disorders. If this were achieved, knowledge of prediction, prognosis, and recovery in mental illness should be greatly enhanced (p. 43).*

Kola and his collaborators analyzed how three different professional groups (psychiatrists, neuroscientists, researchers) use symptom labels such as *delusions*, *hostility*, *anxiety*, *emotionally withdrawn*, *disorganized thinking*, and *active social avoidance*. The authors also examined how the two major classification systems, ICD-10 and DSM-IV, describe subtypes of schizophrenia. Their goal is to achieve information interoperability in which data can be moved around without losing its context and meaning. Obstacles to achieving this goal include different levels of granularity, different measures/scales, and different labels/names to represent the same entity.

The developers selected a variant of the Ontology Web Language or OWL (Lacy, 2005) for constructing a psychosis ontology. The variant, OWL-DL (Baader, Calvanese, McGuinness, Nardi, & Patel-Schneider, 2003), uses a description logic to make inferences from defined relations among concepts. An ontology language such as OWL-DL allows definitions of *primitive concepts* that are often hierarchically organized, *properties* that define relationships between concepts, *defined concepts* that are complex descriptions formed from primitive concepts and properties, *restrictions* that use logical attributes such as "some" and "only", *axioms* that are assertions about concepts, and a *reasoner* that checks axioms and descriptions for logical consistency. However, the limited expressive power of a description logic compared to first- and higher-order logic limits the sort of automated checking that is possible (Pease, 2011).

3.2.2. Emotion

Other examples of psychology ontologies include two different ontologies for emotion that are connected to different upper ontologies. Lopez, Gil, Garcia, Ceareta, and [Q3] Garay (2008) used the Ontology Web Language, the more specialized Descriptive Ontology for Linguistics and Cognitive Engineering (DOLCE), and FrameNet to represent emotions. They used the Ontology Web Language to establish an interface between the physical world consisting of sets of stimuli and the mental world consisting of perceptual descriptions that can trigger emotions. The authors used DOLCE (Gangemi, Guarino, Masolo, Oltramari, & Schneider, 2002) to provide generic terms including *Situation*, *Description*, *Event*, *Process*, and *Action*. DOLCE consists of just over 100 terms formalized in first order logic with many extensions defined in OWL. The Emotions Ontology then adds more specific terms such as *SocialContext*, *EnvironmentalContext* and *PersonalContext*. FrameNet enabled the authors to model specific situations such as "Torres scored a winning goal in the last minute".

The inclusion of DOLCE as an ontology is likely related to the authors' interest in human–computer interaction because of DOLCE's applications to engineering functions (Borgo, Carrara, Garbacz, & Vermaas, 2010). In contrast, Hastings, Ceusters, Smith, and Mulligan (2011) connect an emotions ontology to the upper Basic Formal Ontology based on terminology defined in the Ontology of Mental Disease in a collaborative effort with the Swiss Centre of Affective Sciences and the University of Buffalo. The Basic Formal Ontology partitions entities into independent continuants, dependent continuants, and occurrents. Terms such as *Bodily Process*, *Mental Process*, and *Cognitive Representation* come from the Ontology of Mental Disease and connect upward to the Basic Formal Ontology and downward to the Emotion Ontology. The Emotion Ontology includes more specific terms such as *Appraisal*, *Emotion*

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Occurrent, and *Emotion Action Tendencies*. More recently, a SUMO version of the Emotion Ontology has been released (http://sigmakee.cvs.sourceforge.net/viewvc/sigmakee/KBs/emotion.kif) that builds on the Emotion Ontology created by Hastings et al. (2011).

4. Application of cognition ontologies

The previous section provided examples of initial efforts within psychology to construct ontologies for organizing knowledge. This section illustrates how cognitive ontologies could be used to (1) study knowledge organization, (2) analyze a major theoretical concept, and (3) formalize a taxonomy.

4.1. Study knowledge organization

An ongoing research program by Chi illustrates how ontologies can contribute to studying knowledge organization. Chi (2008) uses an ontological framework to analyze how knowledge organization can determine resistance to conceptual change. She refers to categories that occupy parallel branches within an ontological tree as laterally different and argues that misconceptions assigned to an inappropriate lateral category are particularly difficult to modify. One example is the distinction between *entities* (objects or substances that have volume) and *processes* (that occur over time). Chi discovered that students mistakenly think of force, heat, electricity, and light as substances, such as closing a door to keep the heat from escaping. Instead, she argued that heat should be thought of as the speed of molecules, which is a process.

Chi represents the difference between entities and process as distinct ontological trees, as shown in Fig. 3 (Chi, in press). The difference is also represented in SUMO, which partitions ***PhysicalEntity*** into ***Object*** (that subsumes ***Substance)*** and ***Process***. However, SUMO, like most other upper ontologies, consists of a single ontological tree in which ***Entity*** is the top node. We propose to relate Chi's multiple ontological trees to SUMO's single ontological tree. A single ontological tree will not change the nature of her arguments regarding lateral categories because lateral categories will still be distinguishable as occupying different branches within a single tree. Providing an upper ontology, such as SUMO, for discussing conceptual change should facilitate comparing competing arguments.

Gupta, Hammer, and Redish's (2010) perspective is quite different from Chi's (2008) static-ontology perspective. They argue for a dynamic perspective in which entities in the world may have multiple ontological classifications that are sensitive to context and can vary from moment to moment. Both novices and experts may therefore use either matter-based or process-based explanations to reason about the physical phenomena such as heat, light, and electronic current. Gupta et al. (2010) conclude that

> *This evidence points toward a dynamic picture of ontological knowledge as being flexible and ideas in the world and ontological categories as being multiply connected. Theoretically speaking, this suggests that conceptual knowledge organization is likely to be network-like rather than hierarchical (p. 317).*

This distinction between hierarchies and networks has a long history (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). A prominent example of a hierarchy is Aristotle's classification of animals into vertebrates and invertebrates, which had a major influence until eventually replaced by Linnaeus's taxonomy consisting of multiple hierarchical categories such as kingdom (animal), class (mammal), order (primate), family (hominid), genus (homo), and species (homo sapiens). Wright explained that in contrast to a hierarchy's system of nested groups, there is no top in a network. Each node is equal and self-directed. The distinction between hierarchies and networks has also played a prominent role in cognitive science. The evolution of the Hierarchical Network Model (Collins & Quillian, 1969) into a Spreading Activation Theory (Collins & Loftus, 1975) occurring within a semantic network is one example.

The selection of a particular organization of knowledge – such as a hierarchy, network, or matrix – depends on how well the characteristics of each representation match the requirements of the task (Novick & Hurley, 2001). A difference between a hierarchy and a network is that there is only a single path (link) that connects one node to another when ascending a hierarchy. Thus a *chair* is an example of *furniture*, which is an example of an *artifact*, which is an example of an *object* (Fig. 3). Although SUMO typically follows this principle by linking a subclass to only one class, it occasionally uses more than a single link to provide greater flexibility. As illustrated in Fig. 1, **IntentionalPsychologicalProcess** is a subclass of both **IntentionalProcess** and **PsychologicalProcess**.

Another common structure for organizing knowledge is the matrix. Reed (2012) used a matrix to classify learning as mappings across situations. The rows of the matrix correspond to three types of mappings across knowledge states; one-to-one, one-to-many, and partial. The columns of the matrix correspond to four types of situations; problems, solutions, representations, and socio-cultural contexts. Selecting an appropriate structure is important for both providing a good fit for representing data (Kemp & Tenenbaum, 2008; Tenenbaum, Kemp, Griffiths, & Goodman, 2011) and using the structure to make inferences (Novick & Hurley, 2001).

Although each of these knowledge structures is important for organizing knowledge in cognition, they lack the organizational capabilities of a formal ontology. SUMO is not just a hierarchy or even a network. It is a mathematical theory expressed axiomatically, which is far richer in

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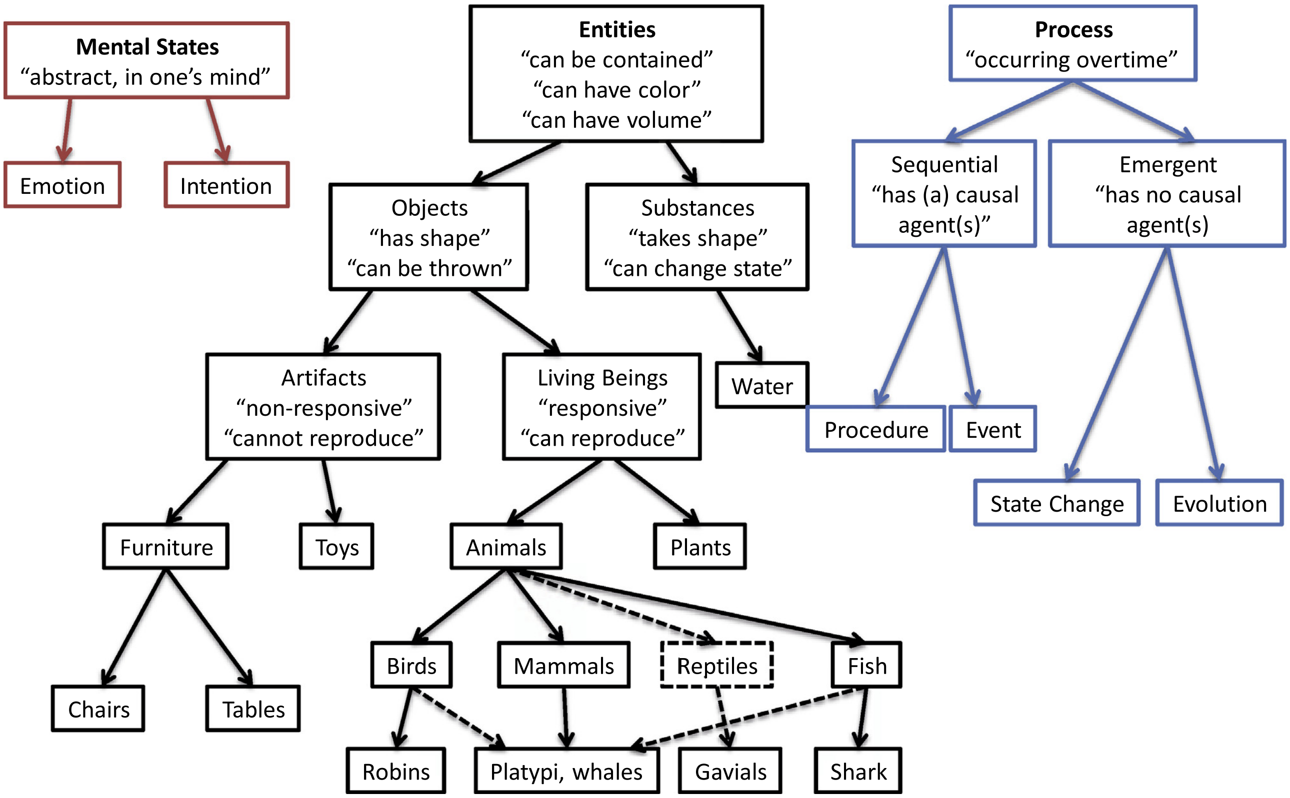

Fig. 3. Chi's (in press) ontological trees that distinguish between objects and processes.

representational power than any network of binary relations.

4.2. Analyze a major theoretical concept

A second application of cognition ontologies is to analyze a single concept. *Abstraction* is a good example because it occurs throughout cognition as different degrees of conceptual generality (Burgoon, Henderson, & Markman, 2013). The hierarchical nature of ontologies requires that they have generic terms (such as *entity*) at the top and more specific terms at lower levels. This structure is ideal for supporting an analysis of cognitive representations and processes at different levels within a hierarchy.

Levels of abstraction play a predominate role in the representation of knowledge including comprehending text, representing concepts, learning principles, understanding diagrams, performing actions, and forming values (Reed, submitted for publication). The hierarchical organization of ontologies makes them a helpful tool for comparing multiple levels of abstraction within a common framework.

For instance, Trope and Liberman (2010) have proposed a construal-level theory of psychological distance in which construals become more abstract as psychological distances increase. Psychological distance refers to the perception of *when* an event occurs, *where* it occurs, to *whom* it occurs, and *whether* it occurs. The theorists define abstraction within a hierarchical representation in which both categories (poodle, dog, mammal) and actions are parts of hierarchies. For actions, the superordinate, abstract level focuses on *why* an action occurs and the subordinate concrete, level focuses on *how* the action is performed. The representation of actions at multiple levels of abstraction is consistent with action–identification theory (Vallacher & Wegner, 1987).

Abstraction can have both beneficial and detrimental effects on cognitive processing. Abstract ideas can form an obstacle in understanding text when words are so generic that their referents are unclear (Bransford & Johnson, 1973). But in other cases, abstraction can be helpful. Abstract formulations of problems can improve transfer across a variety of isomorphic problems when the problems are seen as examples of a generic solution. However, noticing these generalities is often challenging.

Gick and Holyoak (1980) found that students seldom noticed the similarity between two isomorphic problems that required using either radiation to destroy a tumor or an army to capture a fortress. These problems can be analyzed within the Cause_motion frame in FrameNet in which some entity (Theme) starts out in one place (Source) and ends up in some other place (Goal), having covered some space between the two (Path). Transfer is difficult because each of these frame elements have different instantiations in the two problems: radiation vs. army for Theme, outside body vs. outside fortress for Source, tumor vs. fortress for

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Goal, and body tissue vs. roads for Path. Noticing the analogy requires focusing on the Change_direction frame that is common to both solutions. Converging on the Goal from multiple directions is the key to solving both problems.

These are a few of many studies in which cognitive scientists have found both positive and negative consequences of abstract ideas. Mapping the concepts from a wide variety of these studies to SUMO and FrameNet would provide common a framework for comparing and contrasting the findings.

4.3. Formalize a taxonomy

Another application of a cognition ontology is to formalize a taxonomy such as the one included in a chapter on attention in the *Annual Review of Psychology* (Chun et al., 2011). Three advantages of using the Chun et al. taxonomy as an example for developing cognition ontologies are that it was developed by experts, contains important terms that should be included in an ontology, and focuses on a manageable topic within cognition.

Fig. 4 shows the major components of the taxonomy, including its division into internal and external attention. External attention is directed toward objects and features in the physical environment. Internal attention is directed toward mental representations stored in working and long-term memory. The taxonomy provides an organizational structure that can serve as a starting point for building an attention ontology by selecting major empirical and theoretical findings that can serve as axioms in the ontology.

Defining terms is also central for building an ontology. Taxonomies define some terms but many are left undefined, in part, because they are uncontroversial and too many definitions could disrupt a literature review. Variable or vague definitions, nonetheless, pose a barrier to organizing knowledge. Our methodology for defining terms was to initially check a general source (WordNet), then a domain-specific source (*APA Dictionary*), and finally a particular source (Chun et al., 2011). WordNet definitions include general terms such as *attention*, *object*, *feature*, *select*, *task*, and *response* in addition to some theoretical terms such as *long-term memory* and *working memory*. The *APA Dictionary* definitions include other theoretical terms such as *chunking*, *early selection*, and *bottom-up processing*. References to particular authors are needed for specific theoretical terms (*internal attention*, *external attention*) and for empirical findings.

There are two advantages to beginning with WordNet definitions. The first is that WordNet is widely used in the information sciences and therefore aids in integration of knowledge across domains. The second is that, as shown in the right column of Appendix A, WordNet definitions are linked to terms in SUMO. The links are labeled *equivalent* when there is a corresponding term in SUMO or *subsuming* when the term is associated with a larger class in SUMO. For example, attention as mental concentration is subsumed by **capability** in SUMO. Attention as selection has the equivalent term **Selecting** in SUMO. The number in parentheses following each word in the left column of Appendix A shows the number of senses of the word

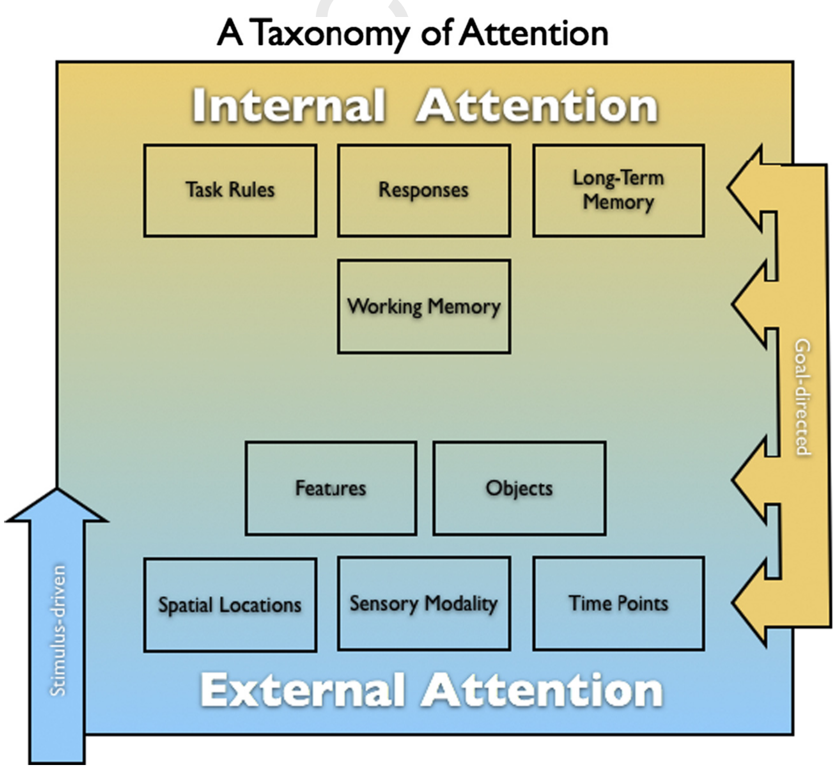

Fig. 4. A taxonomy of attention proposed by Chun et al. (2011).

defined in WordNet. The definition(s) in the middle column are the ones most relevant for an attention ontology.

The next section contains premises that can provide a foundation for constructing an attention ontology.

5. Premises for constructing an attention ontology

A challenge for organizing knowledge in a particular domain is to formulate statements that describe that domain. We will refer to such statements as "premises", defined as natural-language statements that are assumed to be true and from which a conclusion can be drawn. In contrast, statements in SUMO are stated as logical axioms rather than in natural language. Terms in SUMO mean only what their formal axioms constrain them to mean and linguistic terms are just a helpful guide to help humans understand the mathematics.

Our long-germ goal is to translate premises into the language used by SUMO and use them within a formal ontology. However, there are several advantages of initially formulating statements as premises rather than as axioms:

1. Premises are more reader-friendly than axioms. For instance, the rule expressing the precondition: "International flights require a passport." is expressed in SUMO as
```
(=
  (and
    (instance ?F InternationalFlight)
    (experiencer ?F ?A))
  (exists (?P)
    (and
      (instance ?P Passport)
      (possesses ?P ?A))))
```
2. Premises can therefore be more easily evaluated by peers to provide feedback on their suitability before they are formally expressed as axioms within an ontology.
3. Large ontology projects have typically required either commercial or government investment for producing computer programs. Funds may be more accessible if part of an ontology project has been completed by formulating premises to describe the domain.

The premises represent a mix of definitional, empirical, and theoretical statements. The definitions are usually based on the WordNet definitions in Appendix A although some are based on the *APA Dictionary of Psychology* (VandenBoss, 2006) or on a particular research article when a more domain-specific source is required. Empirical and theoretical premises have at least one reference to identify the source. The references are based on classical formulations, recent overviews of empirical or theoretical developments, and occasional important findings from single studies.

5.1. Examples of premises

We mark premises with the symbol • to identify their status within the text and list them in Appendix B. For instance, the initial two premises define two senses of attention:

- Attention is the faculty or power of mental concentration (WordNet), and
- Attention is the process whereby a person concentrates on some features of the environment to the (relative) exclusion of others (WordNet)

Other relevant definitions distinguish between the previously discussed distinctions between active and passive perception of auditory information,

- Hearing perceives sound via the auditory sense (WordNet, FrameNet, SUMO), and
- Listening hears with intention (WordNet, FrameNet, SUMO)

and visual information

- Seeing perceives by sight or has the power to perceive by sight (WordNet, FrameNet, SUMO), and
- Looking perceives with attention (WordNet, FrameNet, SUMO)

These distinctions are broadly consistent across WordNet, FrameNet, and SUMO so all are listed as sources. They are all specific examples of the Perception_experience frame in FrameNet that refers to unintentional perceptual experiences and the Perception_active frame that refers to the direction of attention.

Maintaining active perception requires vigilance, which "refers to the ability to sustain attention over extended periods of time" (Chun et al., 2011, p. 76). This definition closely matches one of the two senses in WordNet:

- Vigilance is the process of paying close and continuous attention (WordNet)

Perception is its subsuming category in SUMO.

5.2. External attention

The dichotomy between external and internal attention is a focal point in the Chun taxonomy, as emphasized in the chapter's title – a taxonomy of external and internal attention. External attention "refers to the selection and modulation of sensory information" (p. 73):

- External attention selects and modulates sensory information (Chun et al., 2011)

As indicated in Fig. 4, external attention is directed to various objects and features in the environment that differ

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in sensory modality, spatial locations, and points in time. Features are points in modality-specific dimensions such as color, pitch, saltiness, and temperature. When *objects* are selected, all of the features of an object are selected together. The use of these terms by Chun et al. (2011) is consistent with the WordNet definitions, resulting in the following premises:

- An Object is a tangible and visible entity; an entity that can cast a shadow (WordNet)
- A Feature is a prominent attribute or aspect of something (WordNet)
- Modality is a particular sensory system (WordNet)
- Space is the unlimited expanse in which everything is located (WordNet)
- Time is the continuum of experience in which events pass from the future through the present to the past (WordNet)

Because external attention selects and modulates sensory information, the words *select* and *modulate* also require definitions. The word *select* has only a single sense in WordNet

- Select is to choose from a number of alternatives (WordNet)

that is appropriate for a wide range of situations. However, the word *modulation* has a restricted use in the Chun et al. taxonomy: "Modulation refers to what happens to the selected item, such that attention influences the processing of items in the absence of overt competition" (pp. 75–76). This definition restricts modulation to processing that follows selection. In contrast, we use the more generic definition from WordNet in which modulation refers to a modification or adjustment that can apply to any stage in processing information.

- Modulation is the act of modifying or adjusting according to due measure and proportion (WordNet)

This more generic definition of modulation is illustrated in a model in which both perception and action planning influence the weighting of perceptual features. The model was influenced by research that demonstrates searching for shape-defined targets is more efficient after preparing a grasping action and searching for location-defined targets is more efficient after preparing a pointing action. Hommel (2012) proposed that "the perception–action system modulates the output gain ω from the feature maps, so that information from goal-relevant feature maps has more impact in sensorimotor processing" (p. 227).

5.3. Internal attention

Internal attention refers to the "selection, modulation, and maintenance of internally generated information, such as task rules, responses, long-term memory, or working memory" (p. 73), which is summarized as a premise:

- Internal attention selects, modulates, and maintains internally generated information (Chun et al., 2011)

Each of the four examples (task, responses, long-term memory, working memory) in Fig. 4 is defined in WordNet. The definition of task,

- A Task is any piece of work that is undertaken or attempted (WordNet)

states a general definition that should be sufficient.

WordNet lists seven senses for *response* but the one most consistent with its use in psychology is

- A Response is a bodily process occurring due to the effect of some antecedent stimulus or agent (WordNet)

The equivalent term for response in SUMO is **causes**, which requires explanation. **causes** in SUMO refers to a causal relation between instances of a process. The formal specification **(causes ?PROCESS1 ?PROCESS2)** means that the instance of **?PROCESS1** brings about the instance of ?**PROCESS2. ?PROCESS2** would therefore be a response caused by the antecedent stimulus or agent **?PROCESS1**.

The other two terms – long-term memory and working memory – refer to memory, defined in WordNet as the cognitive process whereby past experience is remembered. The equivalent term in SUMO, **Remembering**, is more elaborate and therefore added as a premise:

- Remembering is the class of psychological process which involve the recollection of prior experiences and/or of knowledge which was previously acquired (SUMO)

Long-term memory is defined in WordNet as

- Long-term memory is your general store of remembered information (WordNet)

Working memory is a conceptual elaboration of *short-term memory* (STM) so we briefly discuss this concept as a prelude to discussing working memory. The WordNet definition of STM is "what you can repeat immediately after perceiving it". This definition is interesting because of George Miller's (1956) classic article on the limited capacity of STM that was based on the findings of two research paradigms, memory span and absolute judgment. The WordNet definition of STM fits the memory span paradigm, but absolutely judgment requires identifying the magnitude of sensory sensations rather than recalling a list of items. The WordNet definition is therefore too limiting, even for describing Miller's own theoretical contributions to understanding STM. An alternative source for con-

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structing a domain ontology comes from definitions within the domain. According to the *APA Dictionary of Psychology*:

- Short-term memory is the reproduction, recognition, or recall of a limited amount of material after a period of about 10–30 s (APA Dictionary)

This definition is more elaborate than the WordNet definition because it includes reproduction and recognition as measures and because it states a duration for STM.

The theoretical concept, *working memory*, extended research on STM to include its application to a variety of tasks (Baddeley & Hitch, 1974). In this case the WordNet definition is suitable:

- Working memory is memory for intermediate results that must be held during thinking (WordNet)

In contrast, the *APA Dictionary* definition of working memory is too theoretical. It defines working memory as "a multicomponent model of short-term memory or active memory that has a phonological loop to retain verbal information, a visuospatial scratchpad to manipulate visual information, and a central executive to deploy attention between them". This definition describes the working memory model developed by Baddeley and Hitch (1974). One problem with using theoretical formulations as definitions is that theories change. This 2006 definition was already dated because Baddeley (2000) had added another component to the working memory model (the episodic buffer) six years earlier.

Theoretical formulations should be included as additional premises that follow a more neutral and generic definition. For instance,

- The Baddeley working memory model includes as components a phonological loop, a visuospatial scratchpad, an episodic buffer, and a central executive (Baddeley, 2000), and
- The central executive in Baddeley's working memory model controls attention (Baddeley, 2000),

The other three components of Baddeley's model are not relevant for our current objective and therefore not defined.

5.4. Capacity

Chun et al. (2011) list limited capacity, selection, modulation, and vigilance as the basic characteristics of attention. Limited capacity applies to all aspects of Fig. 4 because "at any given moment the environment presents far more perceptual information than can be effectively processed, one's memory contains more competing traces than can be recalled, and the available choices, tasks, or motor responses are far greater than one can handle" (Chun et al., 2011, p. 75).

Capacity has nine senses in WordNet including (1) the amount that can be contained and (2) the amount of information (in bytes) that can be stored on a disk drive. The first measure is not appropriate for cognition ontologies because it is subsumed by senses in WordNet pertaining to physical volume. The second (disk drive) sense is inappropriately specific for our purposes but is subsumed by WordNet senses pertaining to quantities of encoded computer information. Unfortunately, WordNet does not provide a suitable definition of capacity for cognition ontologies, at least with respect to the lexicalized token "capacity".

We therefore again consulted the *APA Dictionary of Psychology* to formulate a premise based on a more domain-specific definition:

- Capacity is the maximum ability of an individual to receive or retain information and knowledge or to function in mental or physical tasks (APA Dictionary).

We link Capacity to **InformationMeasure** in SUMO because cognition ontologies focus on mental, rather than physical, tasks.

An advantage of this definition is that it refers both to receiving and retaining information. Capacity limitations on the ability to receive information were the focus of Kahneman's (1973) book *Attention and Effort*. Kahneman argued that people have limited amounts of mental effort to distribute across simultaneously performed tasks. This limit on multitasking differs from the storage limits on STM in which people store a list of sequential items. According to the capacity model of attention

- An allocation policy distributes mental effort across simultaneously performed tasks (Kahneman, 1973), and
- Performance on simultaneous tasks deteriorates when the total demand on mental capacity exceeds available capacity (Kahneman, 1973)

Capacity limitations on the ability to retain information was the topic of Miller's (1956) classic article on STM in which he used *chunks* as a measure of this capacity. According to the *APA Dictionary*:

- Chunking is the process by which the mind sorts information into small, easily digestible units (chunks) that can be retained in short-term memory (APA Dictionary).

According to Miller

- The capacity of short-term memory varies from 5 to 9 chunks of information (Miller, 1956)

The conceptual evolution from STM to working memory has emphasized that the limited capacity of working

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memory has to be partitioned between processing and storing information

- Both processing and storage place demands on the limited capacity of working memory (Cowan, 2005; Engle, 2002)

An impressive demonstration of the tradeoff between processing and storage in working memory is shown in Fig. 5 (Barrouillett, Portart, & Camos, 2011). Storage requires maintaining memory traces and processing requires updating the content of working memory. The time-based resource-sharing model proposes that working memory creates a central bottleneck in which its use for processing information reduces the amount of capacity available for refreshing memory traces. The resulting premise is

- Increasing the demand on processing in working memory decreases the amount of information that can be actively maintained (Barrouillett et al., 2011)

Fig. 5 illustrates the robustness of this principle across several kinds of processing that include updating the content of working memory, inhibiting responses, selecting responses, and retrieving information from LTM.

A major distinction between the classic division of STM and LTM is that LTM is not limited by capacity:

- There is no known limit on the capacity of long-term memory (Craik & Lockhart, 1972).

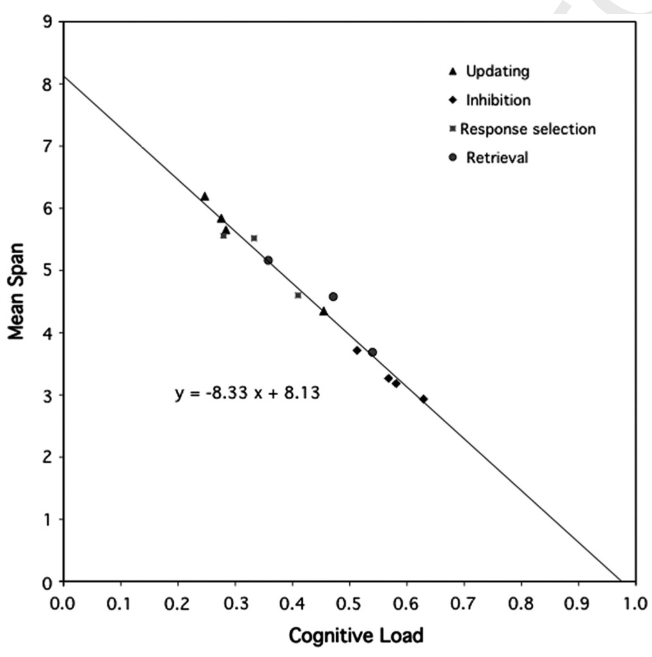

Fig. 5. Tradeoff between maintenance and processing in working memory. From Barrouillet et al. (2011).

There is still no known limit on the capacity of LTM so we include it as a premise.

5.5. Cognitive load

The limited capacity of some information-processing components constrains the effective performance of tasks that are demanding of cognitive resources. According to the *APA Dictionary*:

- Cognitive load is the relative demand imposed by a particular task, in terms of mental resources required (APA Dictionary)

Difference in the relative demand of mental resources is illustrated by the distinction between selecting stimuli at an early, vs. a late, stage of processing. According to the *APA Dictionary*

- An early selection theory is any theory of attention proposing that an attentional filter blocks unattended messages early in the processing stream, prior to stimulus identification (APA Dictionary), and
- A late selection theory is any theory of attention proposing that selection occurs after stimulus identification (APA Dictionary)

Johnston and Heinz (1978) hypothesized that selecting stimuli at an early stage based on sensory information would require less mental effort than selecting stimuli at a late stage based on meaning. The results confirmed their hypothesis. Selecting one of two simultaneously spoken words required less effort when the selection was based on pitch (a woman's voice) than when it was based on meaning (the name of a city). Their multi-mode theory states that

- Selecting stimuli at an early stage based on sensory information requires less mental effort than selecting stimuli at a late stage based on meaning (Johnston & Heinz, 1978)

Cognitive load is of particular concern when multi-tasking or when performing a complex task with many components. One method of avoiding a performance decline in these situations is to perform some of the tasks automatically.

- An automatic action is an act that is performed without requiring attention or conscious awareness (APA Dictionary)

Because automatic processing does not require attention, it makes no demands on the available capacity in Kahneman's (1973) capacity model. The result is that:

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- Automatic processing does not cause interference with other tasks (Posner & Snyder, 1975)

The rationale for this claim is that interference in Kahneman's capacity model occurs when the demand for capacity exceeds the supply. If automatic processing places no demands on capacity, then it does not impact the available capacity that can be used for other tasks.

One implication of this argument is that

- Some component skills required to perform complex tasks such as reading require automatic processing in order to prevent cognitive overload (LaBerge & Samuels, 1974)

Component skills for reading include recognizing letters, recognizing words, pronouncing works, retrieving meanings of a word, selecting the appropriate meaning based on context, and combining the meaning of individual words to understand the sentence. LaBerge and Samuels (1974) proposed that the demands on capacity would be overwhelming unless some of these skills could be performed automatically.

5.6. Selection

Automatic processing can be helpful in overcoming a limited capacity of mental effort, and chunking can be helpful in overcoming the limited capacity of STM. However, automatic processing typically requires extensive practice and chunking depends on having appropriate chunks in LTM. Selection of information therefore plays a predominate role in the Chun et al. (2011) taxonomy:

> Limited processing capacity dictates a need for selection and a primary goal of attention research is to understand which information is selected, how it is selected, and what happens to both selected and unselected information (p. 75).

One influence on external attention is bottom-up attentional control that is driven by factors external to the observer such as the salience of a stimulus. WordNet does not define bottom-up processing but the *APA Dictionary* does:

- Bottom-up processing proceeds from the data in the stimulus input to higher level processes, such as recognition, interpretation, and categorization (*APA Dictionary*)

This definition is contrasted with top-down processing:

- Top-down processing proceeds from a hypothesis about what a stimulus might be to a decision about whether the hypothesis is supported by an incoming stimulus (*APA Dictionary*)

Awh, Belopolsky, and Theeuwes (2012) argue that the distinction between bottom-up and top-down processing is insufficient for explaining selection biases because there are multiple sources of top-down processing such as current goals and selection history. They therefore propose that

- Physical salience, current goals, and selection history influence stimulus selection (Awh et al., 2012)

According to WordNet

- Salient is having a quality that thrusts itself into attention (WordNet)

Awh et al. (2012) use the term *physical salience* or *stimulus salience* to refer to "the degree to which a stimulus is likely to attract attention based on its low-level properties and independently of the internal mental state of the observer" (p. 437). Stimulus salience is the driving force behind bottom-up processing.

Top-down processing is more problematic for them because of its failure to distinguish between current goals and selection history. Although top-down processing has often been equated with goal-driven selection, it can also be influenced by selection history, defined on p. 437 as

- Selection history is the bias to prioritize items that have been previously attended in a given context (Awh et al., 2012)

Selection history requires retention and Hutchinson and Turk-Brown (2012) review how multiple memory systems can influence attention.

Selective attention is not necessarily a deliberative action. The allocation policy in Kahneman's capacity model is influenced by both enduring dispositions (involuntary attention) and momentary intentions (voluntary attention). The APA Dictionary defines involuntary attention as:

- Involuntary attention is attention that is captured by a prominent stimulus, for example in the peripheral visual field, rather than by deliberately applied or focused by the individual (APA Dictionary)

Involuntary attention might occur through automatic processing because occurring without intention is another characteristic of automatic processing in the Posner and Snyder (1975) formulation:

- Automatic processing occurs without intention (Posner & Snyder, 1975)

Although involuntary attention may be a reflex action to a threatening stimulus, it can also be influenced by the goals of the observer. A preliminary cue that provided no

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information for identifying the location of a perceptual target nonetheless attracted attention when it had a feature value that matched the feature value used to identify the target (Folk, Remington, & Johnston, 1992). For instance, observers would attend to the location of a colored cue when it matched the color of the target even though the cue provided no information about the location of the target:

- An uninformative perceptual cue can attract attention when it contains a feature used to identify the target (Folk et al., 1992)

Observers ignored the cue when it did not contain a feature used to identify the target. Involuntary attention was therefore influenced by voluntary attention.

5.7. Conscious awareness

Chun et al. (2011) briefly discuss the relation between attention and conscious awareness. WordNet has two definitions of awareness: (1) having knowledge of, and (2) a state of elementary or undifferentiated consciousness. The first refers to the content of awareness and the second to the state of awareness. We prefer the *APA Dictionary* definition because of our current focus on content and because it explicitly states that the content can be either internal or external experiences:

- Awareness is consciousness of internal or external events or experiences (APA Dictionary)

This focus on the content of awareness, rather than on states of consciousness, was the basis for a recent literature review of the relation between attention and awareness (Cohen, Cavanaugh, Chun, & Nakayama, 2012). In agreement with Chun et al. (2011) the reviewers found evidence that attention can be directed toward stimuli that are not consciously perceived. However, they failed to find convincing evidence that awareness could occur without attention and therefore proposed a model in which attention enables selected information to reach conscious awareness. We use this review as a basis for the premise:

- Attention is necessary, but not sufficient, for conscious awareness (Cohen et al., 2012)

The description of automatic processing by Posner and Snyder (1975) provides another premise on conscious awareness:

- Automatic processing occurs without conscious awareness (Posner & Snyder, 1975)

As stated across three premises in Appendix B, automatic processing occurs without intention, without conscious awareness, and without interference with other tasks. One must be careful, however, when identifying the information-processing stage at which automatic processing occurs. Consider the Stroop effect (Stroop, 1935) in which people have difficulty naming the color of a word (such as red) when the word has a competing color name (blue). Attempts to eliminate the effect by attending only to the color without reading the word are difficult because people typically automatically read a word. Reading the word in this case occurs without intention, without conscious awareness of the cognitive processes involved in word recognition, and without interference with simultaneous cognitive actions. It is this automatic *reading* of the word that makes it difficult to avoid the Stroop effect and subsequently creates the conscious interference effect in naming the color of the word.

Perceptual recognition can be considered a low-level cognitive function and it is not surprising that we can quickly recognize a perceptual pattern without being aware of how we did it. It is less clear that high-level cognitive functions can occur without conscious awareness. Nonetheless, based on a recent literature review, Hassin (2013) proposed that

- Many high-level functions, including goal management and reasoning, can occur without conscious awareness (Hassin, 2013)

The same constraints influence the unconscious performance of low-level and high-level functions according to Hassin (2013). For example, both low-level and high-level functions are more likely to recede from consciousness as they become automatic.

To summarize, the premises listed in Appendix B build on an attention taxonomy to define terms and identify major empirical and theoretical discoveries by cognitive scientists. They are intended to elicit feedback before beginning the more costly and less transparent programming of axioms based on the premises.

6. Extension to related domains

A benefit of constructing cognition ontologies is their potential contribution to other domains of knowledge. Two closely related domains are artificial intelligence and cognitive neuroscience.

6.1. Artificial intelligence

We made the distinction at the beginning of this proposal between the development of ontologies to support either computer-based retrieval and reasoning (Hoekstra, 2009) or the organization of knowledge for scientific advancement (Smith & Ceusters, 2010). These two objectives, of course, are not incompatible. Although cognition ontologies should help advance our understanding of cognition, their subsequent formalization would make them available for computer-based retrieval and reasoning.

Building cognition ontologies that are compliant with SUMO requires using terms that are defined by SUMO or linking terms in cognition ontologies to more generic terms in SUMO. Terms in SUMO are defined in first- and higher-order logic and used by a logical theory development environment called Sigma (Pease & Benzmueller, 2013). A challenge in deriving logical inferences is to find a small set of relevant axioms among a much larger set of axioms (Pease, Sutcliffe, Siegel, & Trac, 2010). Sigma includes a set of optimizations that improve the performance of reasoning in SUMO, typically by trading space for time – pre-computing certain inferences and storing them in the knowledge base. In many cases this can result in speedups of several orders of magnitude.

A SUMO-compliant ontology requires that its axioms are consistent; that a contradiction cannot be derived from the logical statements in the ontology. Table 1 illustrates a set of inconsistent premises. A logical deduction based on premises 1 and 2 results in the inference that incidental learning (I) requires mental effort (M). A logical deduction based on premises 3 and 4 results in the inference that incidental learning (I) does not require mental effort (–M). Removal of premise 2 would eliminate the contradiction.

Cognition ontologies attempt to facilitate logical reasoning – and the understanding of the resulting inferences – by partitioning compound statements into simpler statements. An example is the Posner and Snyder (1975) theoretical claim that automatic processing occurs without intention, without conscious awareness, and without interference with other tasks. These three criteria are listed separately as individual premises that are then displayed in the different clusters of premises about cognitive load, selection, and interference (Appendix B). The premise about automatic processing in Table 1 refers to mental effort so it is clear which characteristic of automatic processing is used in the inference. Simpler axioms would also make logical inferences more transparent.

Another connection of cognition ontologies to AI is AI's effort to build human-level artificial general intelligence that exhibits the broad range of general intelligence found in humans (Adams et al., 2012). According to the authors "aside from the many technological and theoretical challenges involved in this effort, we feel that the greatest impediment to progress is the absence of a common framework for collaboration and comparison of results" (p. 26). Many of the important competency areas for artificial intelligence selected by the authors – perception, attention, memory, reasoning, planning, creation, and learning – align with the cognitive skills proposed for cognition ontologies. Cognition ontologies could therefore provide a common framework for comparing work in cognitive psychology and artificial intelligence.

Integrating work in artificial intelligence with work in cognitive psychology has the advantage of reintroducing AI back into the field of cognitive science. Although AI played a predominate role in the founding of cognitive science, its general impact diminished as it became a more specialized and isolated domain (Forbus, 2010; Gentner, 2010). Gentner's (2010) prediction for the future of cognitive science is that both AI and the study of representations will regain some of their lost prominence because of the increasing importance of web-based retrieval systems.

Table 1
Premises that result in a logical contradiction.

Premises
1. Incidental learning (I) stores information (S)
2. Storing information (S) requires mental effort (M)
3. Incidental learning (I) requires automatic processing (A)
4. Automatic processing (A) does not require mental effort (M)
Inference 1
1. I implies S (Premise 1)
2. S implies M (Premise 2)
3. I implies M (deduction)
Inference 2
1. I implies A (Premise 3)
2. A implies –M (Premise 4)
3. I implies –M (deduction)

6.2. Cognitive neuroscience

Cognitive neuroscience studies how the brain implements the cognitive functions discussed in this article. Each field can support the other (Forstmann, Wagenmakers, Eichle, Brown, & Serences, 2011). Formal models of cognition can decompose tasks into components, allowing brain measurements to more precisely target cognitive processes. In return, cognitive neuroscience can provide additional data for constraining the development of formal models.

Although data from cognition and cognitive neuroscience may converge to mutually support a model, the two domains can also diverge to offer different perspectives. An example is Franconeri, Alvarez, and Cavanagh's (2013) two-dimensional map architecture based directly on the brain:

> *In this two-dimensional 'map' architecture, individual items must compete for actual, bounded space. This architecture defines a flexible resource that is physical rather than metaphorical: it is cortical real estate*" (p. 134).

According to the map model, competitive interactions from items that are cortically close to each create capacity limits. The authors contrast their model with a more cognitive slot model that has a fixed number of slots. The distinction between slots and brain area has ontological implications as revealed in our previous discussion between measuring capacity in information (chunks) rather than in volume. Although two-dimensional maps have area rather than volume, they refer to physical space rather than to amount of information.

A challenge for the field of cognitive neuroscience is to integrate knowledge from a rapidly increasing number of studies that determine how mental processes are imple-

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mented in the brain (Poldrack et al., 2011). The resulting organizational problems are discussed by Yarkoni, Poldrack, Van Essen, and Wager (2010):

A major barrier to progress, however, is the relative absence of an overarching framework for describing neural and mental function. There is currently little consensus about how to classify or group different brain regions, networks, experimental tasks or cognitive functions, let alone how to develop mappings between different levels of description (p. 491).

Two major projects to address this problem are the Cognitive Atlas (Poldrack et al., 2011) and the Cognitive Paradigm Ontology (Turner & Laird, 2012).

Poldrack and his coauthors identify two major problems in integrating research in cognitive neuroscience. One is the use of ambiguous terminology and the other is the confounding of cognitive processes with the tasks used for measurement. As depicted in Fig. 6, a database of mental concepts is impressively displayed in the Cognitive Atlas. However, our approach to defining terms differs by using previously specified definitions rather than formulating new ones. One advantage is that it is easier to share knowledge if others are using the same definitions. Entering "WordNet" into Google Scholar (on June 7, 2013) returned 6590 results for papers published in the year 2012.

Another advantage of using widely-used definitions is that a community of scholars has had an opportunity to provide feedback. The definition of *working memory* in Fig. 6 is:

active maintenance and flexible updating of goal/task relevant information (items, goals, strategies, etc.) in a form that resists interferences but has limited capacity. These representations may involve flexible binding of representations, may be characterized by the absences of external support for the internally maintained representation, and are frequently temporary due to ongoing interference.

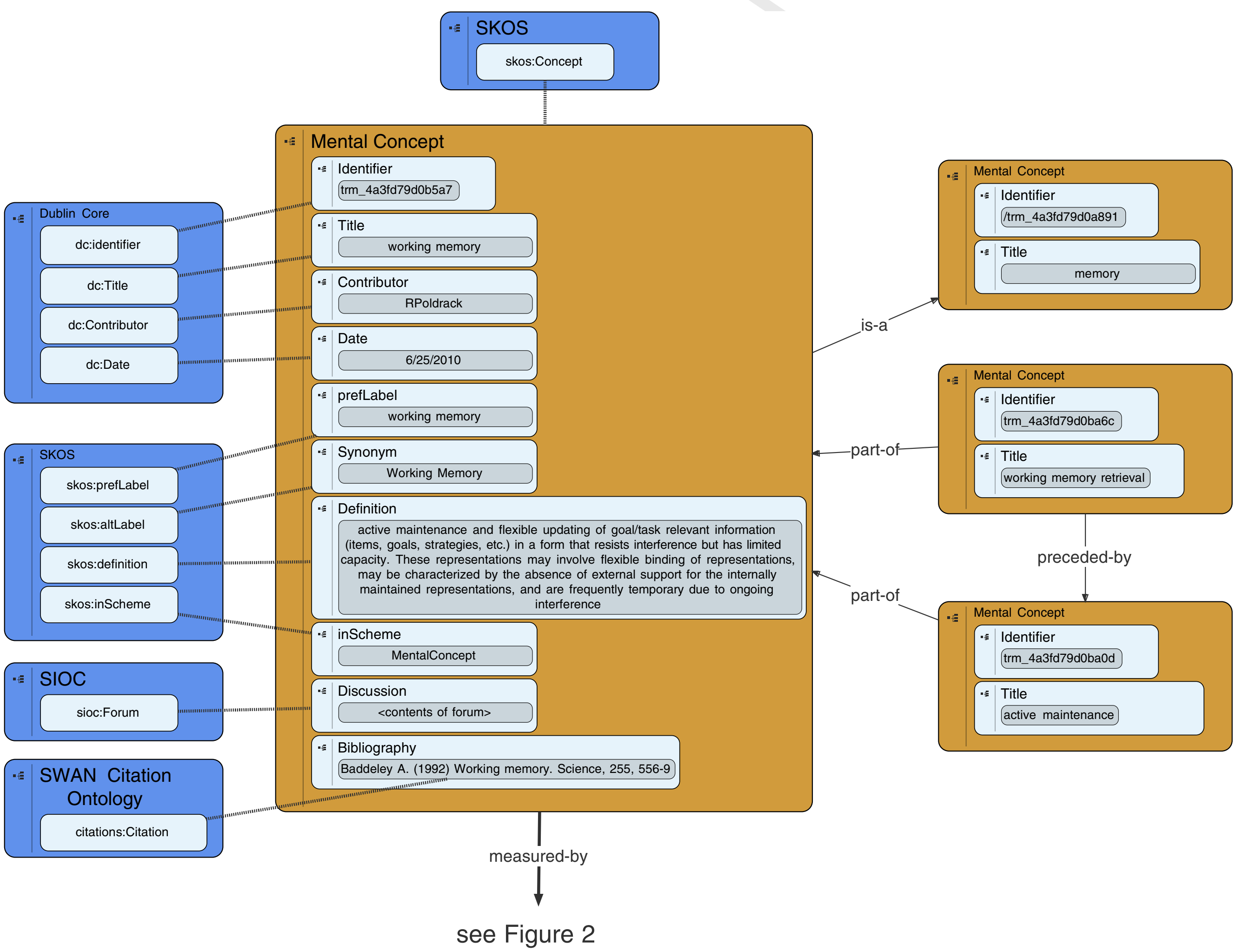

Fig. 6. A data-base schema for representation of mental concepts in the Cognitive Atlas. From Poldrack et al. (2011).

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Although this definition provides many details about working memory, its reference to multiple concepts (maintenance, updating, goal, task, strategies, interference, capacity, binding) needs to be "unpacked" to facilitate logical inferences.

Cognition ontologies provide simple definitions of concepts and then elaborates on these concepts in additional premises. For instance, we use the WordNet definition of working memory as a memory for intermediate results that must be held during thinking. We then state in another premise that the Baddeley (2000) working memory model includes as components a phonological loop, a visuospatial scratchpad, an episodic buffer, and a central executive. In general, our goal in formulating premises is to separate definitions, theoretical models, and empirical results.

An additional challenge for organizing research on cognitive neuroscience is to link mental constructs to the tasks used to measure them (Poldrack et al., 2011; Yarkoni et al., 2010). This challenge is being addressed in the Cognitive Paradigm Ontology (http://www.wiki.cogpo.org) by specifying characteristics of cognitive paradigms that have been used during fMRI and PET brain scans (Turner & Laird, 2012). The Cognitive Paradigm Ontology uses the Basic Formal Ontology (http://www.ifomis.org/bfo/) as a foundational ontology. The Basic Formal Ontology is coordinated through the Open Biomedical Ontologies (OBO) Foundry to support the development of biomedical ontologies.

In contrast, the Data-Brain initiative uses OWL to construct a global framework based on four dimensions that integrate data, information, and knowledge on brain informatics (Zhong & Chen, 2012). The *function* dimension describes cognitive functions and their hierarchical relations. For example, it partitions cognitive functions into thinking-centric and perception-centric, thinking-centric into problem solving and reasoning, and reasoning into deduction and induction. The *experiment* dimension describes the task (auditory, visual), the measuring instrument (EEG, MRI), and the participants (patient, normal). The *data* dimension describes the data by using partitions such as structured or unstructured and original or derived. The *analysis* dimension describes the analysis in terms of analytics (such as feature extraction) and software programs.

Although we support efforts to use ontologies to describe cognitive functions we believe that ontologies such as OWL and the Basic Formal Ontology are limited for the formal construction of ontologies. They provide a taxonomy but lack the expressive logical definitions that are possible only in first order and higher order logic used by SUMO. SUMO has been automatically mapped to the Open Biomedical Ontologies (Pease, 2011, pp. 98–100), which should be helpful in making comparisons across cognition ontologies, the Cognitive Atlas, the Cognitive Paradigm Ontology and the Data-Brain initiative to relate work in cognitive psychology to work in cognitive neuroscience.

7. Conclusion

Because of the growing interest in organizing knowledge within the cognitive sciences we proposed a framework for constructing cognition ontologies by using WordNet, FrameNet, and SUMO. The advantage of defining terms by using WordNet is that WordNet is widely used across domains in the information sciences. However, its definitions are occasionally too general to satisfy word usage in a particular domain so we also relied on the *APA Dictionary* for more domain-specific definitions.

FrameNet captures co-occurrence and structural relations among linguistic concepts. The frames provide organized packages of knowledge that represent how people perceive, remember, and reason about their experiences. For instance, the distinction between remembering experiences and remembering information mirrors the common distinction between episodic and semantic memory in cognitive psychology. Core (cognizer, experience, impression) and non-core (duration, vividness) frame elements provide generic slots that are instantiated with specific information.

SUMO is a formal ontology consisting of an upper ontology and numerous domain ontologies. It has many advantages for serving as an upper ontology including its large number of definitions and axioms, the expressiveness of its logical language, and its mapping onto information science tools such as WordNet, FrameNet, and other ontologies. Its inclusion of a large number of psychological processes (Fig. 1) makes it an ideal upper ontology for cognition.

Cognition ontologies can be used to study knowledge organization, analyze major theoretical concepts such as abstraction, and formalize taxonomies. Creating premises for cognition ontologies is a useful preliminary step for the subsequent creation of axioms, as illustrated by our premises for extending a taxonomy of attention. As stated by Chun et al. (2011) for their proposed attention taxonomy:

> *The value of this taxonomy will not lie on whether it is correct in its proposed form, but rather as a starting point to sketch a big-picture framework and to develop common language and concepts. At a minimum, the taxonomy serves as a portal for the attention literature, and at its best, it can stimulate new research and more integrative theories (p. 75).*

This perspective also applies to other efforts to develop taxonomies and ontologies for understanding cognition. Tools from the information sciences can enhance these efforts by providing additional resources for organizing knowledge in the new field of psychoinformatics.

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Appendix A

Relevant senses of words (WordNet 3.1) for attention in cognition ontologies

Word (senses)	WordNet definitions	SUMO link
Action (10)	something done (usually as opposed to something said)	**IntentionalProcess** (subsuming)
Attention (6)	1. the faculty or power of mental concentration; "keeping track of all the details requires your complete attention"	**Capability** (subsuming)
	2. the process whereby a person concentrates on some features of the environment to the (relative) exclusion of others	**IntentionalPsychological Process** (equivalent)
Awareness (2)	1. having knowledge of; "he had no awareness of his mistakes"	**IntentionalRelation** (subsuming)
	2. state of elementary or undifferentiated consciousness; "the crash intruded on his awareness"	**PsychologicalAttribute** (subsuming)
Capacity (9)	1. the amount that can be contained	**VolumeMeasure** (subsuming)
	2. the amount of information (in bytes) that can be stored on a disk drive	**InformationMeasure** (subsuming)
Concentration (7)	1. complete attention; intense mental effort	**Perception** (subsuming)
	2. great and constant diligence and attention	**SubjectiveAssessmentAttribute** (subsuming)
Emotion (1)	1. any strong feeling	**EmotionalState** (subsuming)
External (4)	1. happening or arising or located outside or beyond some limits or especially surface; "the external auditory canal"	**located** (subsuming)
Feature (6)	1. a prominent attribute or aspect of something; "the map showed roads and other features"	**Attribute** (subsuming)
Goal (4)	1. the state of affairs that a plan is intended to achieve and that (when achieved) terminates behavior intended to achieve it	**hasPurpose** (equivalent)
Hear (5)	1. perceive (sound) via the auditory sense	**Hearing** (equivalent)
Interference (5)	1. the act of hindering or obstructing or impeding	**inhibits** (subsuming)
Internal (5)	1. happening or arising or located within some limits or especially surface; "internal organs"	**Contains** (equivalent)
Load (9)	1. a quantity that can be processed or transported at one time; "the system broke down under excessive loads"	**ConstantQuantity** (subsuming)
Long-term memory (1)	1. your general store of remembered information	**Remembering** (subsuming)
Look (10)	1. perceive with attention, direct one's gaze toward; "Look at your child"	**Looking** (equivalent)
Listen (3)	1. hear with intention; "listen to the sound of this cello"	**Listening** (equivalent)
Memory (5)	1. The cognitive process whereby past experience is remembered	**Remembering** (equivalent)
Modality (5)	1. sensory system (a particular sense)	**capability** (subsuming)
Modulation (5)	1. the act of modifying or adjusting according to due measure and proportion	**Process** (subsuming)
Object (5)	1. a tangible and visible entity; an entity that can cast a shadow; "it was full of rackets, balls and other objects"	**CorpuscularObject** (equivalent)
	2. the focus of cognitions or feelings; "objects of thought"	**patient** (subsuming)
Performance (5)	1. the act of performing; of doing something successfully; using knowledge as distinguished from merely possessing it; "experience generally improves performance"	**IntentionalProcess** (subsuming)
Response (7)	1. a bodily process occurring due to the effect of some antecedent stimulus or agent; "a bad reaction to the medicine"; "his responses have slowed with age"	**Cause** (equivalent)
Salient (3)	1. having a quality that thrusts itself into attention; "salient traits"	**SubjectiveAssessmentAttribute** (subsuming)

(*Continued on next page*)

Search (4)	1. inquire into; "He searched for information on his relatives on the web";	**Investigating** (subsuming)
	2. try to locate or discover, or try to establish the existence of; "The police are searching for clues"	**Pursuing** (equivalent)
Select (1)	1. pick out, select, or choose from a number of alternatives; "Take any one of these cards"	**Selecting** (equivalent)
See (24)	1. perceive by sight or have the power to perceive by sight	**Seeing** (equivalent)
Short-term memory (1)	1. what you can repeat immediately after perceiving it	**Remembering** (subsuming)
Space (1)	1. the unlimited expanse in which everything is located; "they tested his ability to locate objects in space"	**SpaceRegion** (equivalent)
Task (2)	1. any piece of work that is undertaken or attempted; "he prepared for great undertakings"	**IntentionalProcess** (subsuming)
Time (10)	1. the continuum of experience in which events pass from the future through the present to the past	**TimeMeasure** (subsuming)
Vigilance (2)	1. the process of paying close and continuous attention; "vigilance is especially susceptible to fatigue"	**Perception** (subsuming)
Working memory (1)	1. memory for intermediate results that must be held during thinking	**Remembering** (subsuming)

Appendix B

Premises regarding attention

Attention
Attention is the faculty or power of mental concentration (WordNet)
Attention is the process whereby a person concentrates on some features of the environment to the (relative) exclusion of others (WordNet)
Hearing perceives sound via the auditory sense (WordNet, FrameNet, SUMO)
Listening hears with intention (WordNet, FrameNet, SUMO)
Seeing perceives by sight or has the power to perceive by sight (WordNet, FrameNet, SUMO)
Looking perceives with attention (WordNet, FrameNet, SUMO)
Vigilance is the process of paying close and continuous attention (WordNet)

External attention
External attention selects and modulates sensory information (Chun et al., 2011)
An Object is a tangible and visible entity; an entity that can cast a shadow (WordNet)
A Feature is a prominent attribute or aspect of something (WordNet)
Modality is a particular sensory system (WordNet)
Space is the unlimited expanse in which everything is located (WordNet)
Time is the continuum of experience in which events pass from the future through the present to the past (WordNet)
Select is to choose from a number of alternatives (WordNet)
Modulation is the act of modifying or adjusting according to due measure and proportion (WordNet)

Internal attention
Internal attention selects, modulates, and maintains internally generated information (Chun et al., 2011)
A Task is any piece of work that is undertaken or attempted (WordNet)
A Respones is a bodily process occurring due to the effect of some antecedent stimulus or agent (WordNet)
Remembering is the class of psychological process which involve the recollection of prior experiences and/or of knowledge which was previously acquired (SUMO)
Long-term memory is your general store of remembered information (WordNet)
Short-term memory is the reproduction, recognition, or recall of a limited amount of material after a period of about 10–30 s (APA Dictionary)
Working memory is memory for intermediate results that must be held during thinking (WordNet)

The Baddeley working memory model includes as components a phonological loop, a visuospatial scratchpad, an episodic buffer, and a central executive (Baddeley, 2000)
The central executive in Baddeley's working memory model controls attention (Baddeley, 2000)

Capacity
Capacity is the maximum ability of an individual to receive or retain information and knowledge or to function in mental or physical tasks (APA Dictionary)
An allocation policy distributes mental effort across simultaneously performed tasks (Kahneman, 1973)
Performance on simultaneous tasks deteriorates when the total demand on mental capacity exceeds available capacity (Kahneman, 1973)
Chunking is the process by which the mind sorts information into small, easily digestible units (chunks) that can be retained in short-term memory (APA Dictionary)
The capacity of short-term memory varies from 5 to 9 chunks of information (Miller, 1956)
Both processing and storage place demands on the limited capacity of working memory (Cowan, 2005; Engle, 2002)
Increasing the demand on processing in working memory decreases the amount of information that can be actively maintained (Barrouillett et al., 2011)
There is no known limit on the capacity of long-term memory (Craik & Lockhart, 1972)

Cognitive load
Cognitive load is the relative demand imposed by a particular task, in terms of mental resources required (APA Dictionary).
An early selection theory is any theory of attention proposing that an attentional filter blocks unattended messages early in the processing stream, prior to stimulus identification (APA Dictionary)
A late selection theory is any theory of attention proposing that selection occurs after stimulus identification (APA Dictionary)
Selecting stimuli at an early stage based on sensory information requires less mental effort than selecting stimuli at a late stage based on meaning (Johnston & Heinz, 1978)
An automatic action is an act that is performed without requiring attention or conscious awareness (APA Dictionary)
Automatic processing does not cause interference with other tasks (Posner & Snyder, 1975)
Some component skills required to perform complex tasks such as reading require automatic processing in order to prevent cognitive overload (LaBerge & Samuels, 1974)

Selection
Bottom-up processing proceeds from the data in the stimulus input to higher level processes, such as recognition, interpretation, and categorization (APA Dictionary)
Top-down processing proceeds from a hypothesis about what a stimulus might be to a decision about whether the hypothesis is supported by an incoming stimulus (APA Dictionary)
Physical salience, current goals, and selection history influence stimulus selection (Awh et al., 2012)
Salient is having a quality that thrusts itself into attention (WordNet)
Selection history is the bias to prioritize items that have been previously attended in a given context (Awh et al., 2012)
Involuntary attention is attention that is captured by a prominent stimulus, for example in the peripheral visual field, rather than by deliberately applied or focused by the individual (APA Dictionary)
Automatic processing occurs without intention (Posner & Snyder, 1975)
An uninformative perceptual cue can attract attention when it contains a feature used to identify the target (Folk et al., 1992)

Conscious awareness
Awareness is consciousness of internal or external events or experiences (APA Dictionary)
Attention is necessary, but not sufficient, for conscious awareness (Cohen et al., 2012)
Automatic processing occurs without conscious awareness (Posner & Snyder, 1975)
Many high-level functions, including goal management and reasoning, can occur without conscious awareness (Hassin, 2013)

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