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Automated semantic indices related to cognitive function and rate of cognitive decline

Serguei V.S. Pakhomov [a,b,*], Laura S. Hemmy [c,d], Kelvin O. Lim [c,d]

[a] Center for Clinical and Cognitive Neuropharmacology, University of Minnesota, MN 55455, USA
[b] Department of Pharmaceutical Care and Health Systems, University of Minnesota, MN 55455, USA
[c] Department of Psychiatry, University of Minnesota, MN 55455, USA
[d] Geriatric Research Education and Clinical Center (GRECC), Minneapolis VA Health Care System, MN 55455, USA

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ABSTRACT

The objective of our study is to introduce a fully automated, computational linguistic technique to quantify semantic relations between words generated on a standard semantic verbal fluency test and to determine its cognitive and clinical correlates. Cognitive differences between patients with Alzheimer's disease and mild cognitive impairment are evident in their performance on the semantic verbal fluency test. In addition to the semantic verbal fluency test score, several other performance characteristics sensitive to disease status and predictive of future cognitive decline have been defined in terms of words generated from semantically related categories (clustering) and shifting between categories (switching). However, the traditional assessment of clustering and switching has been performed manually in a qualitative fashion resulting in subjective scoring with limited reproducibility and scalability. Our approach uses word definitions and hierarchical relations between the words in WordNet®, a large electronic lexical database, to quantify the degree of semantic similarity and relatedness between words. We investigated the novel semantic fluency indices of mean cumulative similarity and relatedness between all pairs of words regardless of their order, and mean sequential similarity and relatedness between pairs of adjacent words in a sample of patients with clinically diagnosed probable ($n=55$) or possible ($n=27$) Alzheimer's disease or mild cognitive impairment ($n=31$). The semantic fluency indices differed significantly between the diagnostic groups, and were strongly associated with neuropsychological tests of executive function, as well as the rate of global cognitive decline. Our results suggest that word meanings and relations between words shared across individuals and computationally modeled via WordNet and large text corpora provide the necessary context to account for the variability in language-based behavior and relate it to cognitive dysfunction observed in mild cognitive impairment and Alzheimer's disease.

1. Introduction

The question of how concepts are represented and associated with each other in the human brain has been the subject of many studies in multiple disciplines including neuroscience (Caramazza & Mahon, 2006; Chan, Butters, Salmon, & McGuire, 1993; Mahon & Caramazza, 2009; Patterson, Nestor, & Rogers, 2007; Pylkkanen, Llinas, & Murphy, 2006), neuropsychology (Salmon, Butters, & Chan, 1999; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998a,b; Weber, Thompson-Schill, Osherson, Haxby, & Parsons, 2009), psycholinguistics (Levelt, 1989; Tverski & Hemenway, 1984), and computer science (Miller & Fellbaum, 1991; Rada, Mili, Bicknell, & Blettner, 1989; Resnik, 1999). The pathway to a comprehensive answer to the question of conceptual representation is likely to be found at the intersection of multiple fields of study and approaches. For example, computational modeling of naturally occurring language (e.g., news, books, speeches, conversations) coupled with fMRI has strongly suggested that the patterns of hemodynamic activity in the brain in response to words presented as stimuli are predictable from the distributional co-occurrence statistics of these words in a very large corpus of text (Mitchell et al., 2008). This study has convincingly demonstrated the value of using computational linguistic approaches in the investigation of semantic representations. Our present study further contributes to this investigation by introducing a novel, fully automated, computational linguistic technique based on the standard semantic verbal fluency test (SVF) to characterize the differences in semantic representations of the "animals" category in patients with mild cognitive impairment (MCI) and

* Corresponding author at: Center for Clinical and Cognitive Neuropharmacology, University of Minnesota, 7-125F Weaver Densford Hall, 308 Harvard St. SE, Minneapolis, MN 55455, USA. Tel.: +1 612 624 1198; fax: +1 612 625 9931.
E-mail address: pakh0002@umn.edu (S.V.S. Pakhomov).

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Alzheimer's disease (AD). We show that our technique has clear neuropsychological correlates and is related to global cognitive function, as evidenced by diagnostic group differences, correlation with traditional neuropsychological measures, and relation to the rate of cognitive decline in this population.

2. Background

2.1. Test of semantic fluency, and clustering and switching

The test of Semantic Verbal Fluency (SVF; (Benton, Hamsher, & Sivan, 1983) requires naming as many items from a particular category (e.g., animals) as possible within a 60-second time period. The phonemic counterpart of the semantic fluency test requires generating words that start with a certain letter of the alphabet (e.g., F, A, S). These simple tests of verbal fluency have been used extensively as part of standard neuropsychological test batteries to study cognitive effects of dementia (Gorno-Tempini et al., 2004; Hodges et al., 2004; Knopman et al., 2008; Libon et al., 2007). In particular, semantic fluency deficits have been widely reported in patients with various stages of AD and MCI (Chan, Salmon, & De la Pena, 2001; Ober, Dronkers, Koss, Delis, & Friedland, 1986; Rosen, 1980; Troyer et al., 1998a,b) and often show early and disproportionate decline relative to other language, attention, and executive abilities (see Lezak, 2004 and Henry, Crawford, & Phillips, 2004 for review).

While traditional SVF scores are useful in identifying and quantifying semantic memory deficits, the actual words produced on this test can give us much more detailed and in-depth information about how the patients organize their semantic space. Successful performance on the SVF test depends to a large extent on how well semantic information is organized into conceptually related clusters and whether the patient is able to use an efficient strategy that accesses these clusters during the test (Estes, 1974; Hodges & Patterson, 1995; Laine, 1988). The size of semantic clusters and the efficiency of switching from one cluster (after it has been exhausted) to another have been found to have different neuroanatomical correlates (Rich, Troyer, Bylsman, & Brandt, 1999; Troyer, 2000; Troyer et al., 1997). Semantic cluster size was found to be associated with the left temporal lobe, whereas the processing associated with switching was associated more with the function of the frontal lobe. These studies have found that cluster size and the amount of switching between clusters can measure the strength of associations in the patient's lexical-semantic networks. Studies of clustering and switching in AD also found smaller and fewer clusters produced on this task (Ober et al., 1986; Rosen, 1980) and significantly fewer switches (Raoux et al., 2008) than by healthy controls. Troyer (2000) also found positive cluster size effects as a function of age, where older adults tended to produce larger clusters on the "animals" category relative to younger adults. These prior studies have also suggested that clustering may be related to more automated cognitive processes such as memory, whereas switching may rely on more effortful processes involved in executive functioning (Troyer et al., 1997). However, the model that relies on clustering and switching to disassociate temporal-semantic from frontal-executive processes remains controversial. Subsequent work by Mayr and colleagues has criticized Troyer's clustering and switching model by demonstrating that switching in particular is more ambiguous with respect to the underlying cognitive processes (semantic vs. executive) than was previously believed and may not provide clear evidence for disassociating these processes (Mayr, 2002; Mayr & Kliegl, 2000).

Furthermore, prior studies of clustering and switching have relied on subjective assessments of semantic similarity between at least two (Rich et al., 1999; Troyer, Moscovitch, & Winocur, 1997; Troyer et al., 1998a,b) or three (Laine, 1988) adjacent words to define clusters. For example, the qualitative assessment proposed by Troyer et al. (1997) relies on manual determination if adjacent words belong to a top-level subcategory (e.g., zoological categories, human use, and living environment) with further more fine-grained subcategorizations (e.g., living environment category composed of African, Australian, Arctic/Far North, Farm, North American and Water Animals). In addition to their subjectivity, these manual approaches are time consuming and are difficult to implement and standardize, which may be responsible for some of the conflicting results obtained with these methods (Raoux et al., 2008). Therefore, clustering and switching analysis on verbal fluency tasks has been reserved largely for relatively few and small research studies (or random subsamples) and is not widely used for clinical assessment or larger scale investigations involving hundreds or thousands of patients. To make clustering and switching assessment more objective, reliable, and scalable it is necessary to use computational approaches to the determination of semantic relations between words, which we introduce in the current study.

2.2. Semantic similarity vs. relatedness

An established body of work in psycholinguistics focuses on lexical semantics and semantic relatedness (Collins & Loftus, 1975; Ferrand, Ric, & Augustinova, 2006; Thompson-Schill, Kurtz, & Gabrieli, 1998; Tverski & Hemenway, 1984). In addition to the work in psycholinguistics, a variety of computational approaches have been developed to automatically measure the degree of semantic similarity or relatedness between concepts (Lin, 1998; Patwardhan & Pedersen, 2006; Pedersen, Patwardhan, & Michelizzi, 2004; Rada et al., 1989; Resnik, 1999). While the notions of semantic similarity and relatedness are sometimes treated as indistinguishable, for computational purposes it is important to make a clear distinction between them. Clarifying this distinction is also important because of a potentially confusing overlap in terminology between the fields of psycholinguistics and computational linguistics.

In psycholinguistics, a distinction is made between *semantic relatedness* and *associative relatedness*. Associative relatedness refers to the probability that one word calls to mind another word (e.g., needle-thread), while semantic relatedness reflects the degree of semantic feature overlap between words (e.g., whale-dolphin). This distinction is based on the results of priming experiments in which, for example, a prime word that is either semantically related or unrelated to the target is shown to the subject first and the reading time or another type of response to the presentation of the target word (e.g., eye movements) is measured. These experiments indicate that subjects respond faster to targets primed with words that have common semantic features (i.e., are semantically similar) rather than those that have an associative relationship to the target (i.e., are semantically related; (Ferrand et al., 2006; Thompson-Schill et al., 1998)). In addition to the priming experiments, neuroimaging studies also demonstrated that semantically related words elicit clearly detectable differences in neural response from unrelated words (Mitchell et al., 2008; Weber et al., 2009). In computational linguistics, a distinction is made between the terms *semantic similarity* and *semantic relatedness* that roughly correspond to the psycholinguistic terms *semantic relatedness* and *associative relatedness,* respectively. To avoid any potential confusion, we will use the computational linguistic terminology throughout the present paper.

Treating semantic similarity as a special case of a more general notion of semantic relatedness is well-established in the field of