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Effects of morphological family on word recognition in normal aging, mild cognitive impairment, and Alzheimer's disease

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ABSTRACT

Reading a word activates morphologically related words in the mental lexicon. People with Alzheimer's disease (AD) or Mild Cognitive Impairment (MCI) often have difficulty retrieving words, though the source of this problem is not well understood. To better understand the word recognition process in aging and in neurodegenerative disorders such as MCI and AD, we investigated the nature of the activation of morphologically related family members in 22 Finnish speakers with AD, 24 with MCI, and 17 cognitively healthy elderly. We presented Finnish monomorphemic (base form) nouns in a single-word lexical decision experiment to measure the speed of word recognition and its relation to morphological and lexical variables. Morphological variables included morphological family size (separate for compounds and derived words) and pseudo-morphological family size (including the set of words that have a partially overlapping form but that do not share an actual morpheme, e.g., *pet and carpet*, or *corn* and *corner*). Pseudo-morphological family size was included to examine the influence of words with orthographic (or phonological) overlap that are not semantically related to the target words. Our analyses revealed that younger and elderly controls and individuals with MCI or AD were influenced by true morphological overlap (overlapping forms that also share meaning), as well as by the word's pseudo-morphological family. However, elderly controls and individuals with MCI or AD seemed

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to rely more on form overlap than young adults. This demonstrates that an increased reliance on form-based aspects of language processing in Alzheimer's disease is not necessarily due to a partial loss of access to semantics, but might be explained in part by a common age-related change of processes in written word recognition.

1. Introduction

New words are often formed by combining morphemes (e.g., *child* + *care*). Derivation and compounding are frequently used in word formation in Indo-European languages (e.g., English) and in Uralic languages (e.g., Finnish). Compounds (e.g., *childcare*, *production designer*) combine free morphemes, which are morphemes that can typically stand alone as words. Thus, the meaning of a compound is relatively transparent by combining the meanings of its constituent morphemes. Derived words (e.g., *childish*, *designer*) involve adding bound morphemes (derivational suffixes such as −*ish* and −*er*) to a stem. Many compounds and derived words are lexicalized − they can be found in dictionaries as different lexical entries. Words that share morphological components form so-called *morphological families*, which are sets of words that are related morphologically (sharing a morpheme) and semantically (sharing a meaning).

1.1. Distinguishing between semantic and orthographic aspects of morphological family effects

A word's morphological family can be composed of both derived and compound words that share a morpheme with the noun. Morphologically related words have been shown to influence the speed of lexical processing. For example, words with larger morphological families are recognized more quickly than words with smaller morphological families (Schreuder & Baayen, 1997), demonstrating that morphological family members aid in lexical processing. Words with larger morphological families also show smaller (i.e., less negative) N400 amplitudes for event-related potentials (Mulder, Schreuder, & Dijkstra, 2013), suggesting that the beneficial effect of morphological family members is mainly driven by overlapping semantics. This is consistent with other work showing that converging semantics from multiple sources speeds up word processing and reduces the size of the N400 component. For example, a word like *doctor* primes a semantically related word like *nurse*, thus, facilitating its recognition. The same mechanism may be driving morphological family effects. Bertram, Baayen, and Schreuder (2000) found semantic facilitation when no explicit semantically related word was presented: the removal of loosely-related members of the morphological family improved the statistical power of the morphological family variable they used. Mulder et al. (2013) argued that if the target word activates its morphological family members, the activation of the semantics of the family members might boost the activation level of the target.

However, the morphological family effect may not operate only at the semantic level. Recent studies have shown that family size effects might also stem from word-form overlap with the target, independent of semantic overlap (Milin, Feldman, Ramscar, Hendrix, & Baayen, 2017; Mulder, Dijkstra, & Baayen, 2015). Bowers, Davis, and Hanley (2005) found automatic semantic activation of words that are embedded within a target word, e.g., *hat* in *that*, without any morphological or semantic relation. Since morphological family members overlap in both their semantic content and their form, this may result in even greater facilitation due to activation boosts from both shared semantics and shared orthographic form.

Recent work suggests that the effect of semantic and orthographic overlap may change over the lifespan. Milin et al. (2017) analyzed lexical decision latencies from the English Lexicon Project (Balota et al., 2007). They found that semantic units ("lexomes") with more connections to other semantic units slowed reaction times (RT) more for younger adults than for older adults. The authors explained this as an increase in the amount of information which the younger participant group was less proficient in dealing with.

Older adults' larger vocabularies (Ramscar, Hendrix, Shaoul, Milin, & Baayen, 2014) and less reliance on semantic connections might have implications for morphological family effects. Thus, increasing age might result in continued facilitation due to orthographic overlap but less facilitation due to semantic overlap. This effect may be magnified by neurodegenerative diseases like Mild Cognitive Impairment (MCI) and Alzheimer's dementia (AD). Hence, we hypothesized that our measure of orthographic overlap (pseudo-morphological family) might be a more important predictor of response latencies than true morphological family size for a) older compared to younger adults, or b) only the pathological groups (MCI and AD) of older adults, or c) only those in the prodromal stage of the disease (AD).

1.2. Morphological family effects in individuals with Mild Cognitive Impairment and Alzheimer's disease

One of the most common memory complaints among older adults is difficulty retrieving words for production (e.g., Ossher, Flegal, & Lustig, 2013). Most of these failures appear to be due to problems accessing the phonological form of the word rather than a degradation of the word's semantic representation (e.g., Barresi, Nicholas, Connor, Obler, & Albert, 2000), at least before age 70. However, semantic decline has been the major focus in the study of language breakdown in Alzheimer's disease (AD) (e.g., Chertkow, Whatmough, Saumier, & Duong, 2008; Cuetos, Arce, & Martínez, 2015;

Obler, 1983; Obler & Albert, 1981; Obler & Gjerlow, 1999; Stilwell, Dow, Lamers, & Woods, 2016).

Little is known about how morphological family members affect lexical processing in healthy aging and in neurodegenerative diseases. The word-finding difficulties observed in older adults may be due also to changes in how the morphological components of words are processed. Some researchers have reported differences in morphological processing for people with AD compared to elderly controls (for French, Irigaray, 1973; for English, Ullman et al., 1997; Altmann, Kempler, & Andersen, 2001; Ahmed, Haigh, de Jager, & Garrard, 2013; Sajjadi, Patterson, Tomek, & Nestor, 2012; Grossman, Mickanin, Onishi, & Hughes, 1995; for Italian, Walenski, Sosta, Cappa, & Ullman, 2009; Colombo, Fonti, & Stracciari, 2009; Fyndanis et al., 2018; for Greek, Fyndanis, Manouilidou, Koufou, Karampekios, & Tsapakis, 2013; Fyndanis et al., 2018), whereas others have found no differences (for Hebrew, Kavé & Levy, 2003; for Greek, Kaprinis & Stavrakaki, 2007; for German, Blanken, Dittman, Haas, & Wallesch, 1987; for English, Ahmed, de Jager, Haigh, & Garrard, 2012). For a review of morphological processing in AD, see Auclair-Ouellet (2015).

Evidence provided in Section 1.1 suggests that the way different people process lexical items differs, with some people using a more semantic-driven process of lexical search/recognition and others using a more form-based approach. Since the language deficits seen in people with AD appear to be fundamentally semantic, rather than orthographic or lexical (Adlam, Bozeat, Arnold, Watson, & Hodges, 2006; Chertkow & Bub, 1990; Duong, Whitehead, Hanratty, & Chertkow, 2006; Hodges, Salmon, & Butters, 1992; Martin, 1992), this suggests that individuals with AD would be less likely to gain benefits from the semantic overlap of morphological family members compared to elderly healthy controls or younger adults, but that they may continue to be sensitive to form-based overlap of morphological family members.

1.3. *Morphological family measures*

A word's morphological family is typically measured according to its size (the number of morphologically and semantically related compounds and derived words) and frequency (the summed base frequency of all family members). Most previous studies investigating the effect of these morphological family measures on word processing have assumed that compounds and derived words facilitate lexical access of the target word in the same way, perhaps because in languages like English and Dutch, the majority of family members are compounds (e.g., Baayen, Piepenbrock, & Gulikers, 1995). Nikolaev, Lehtonen, Higby, Hyun, and Ashaie (2018) tested this assumption in Finnish, where compounds are an extremely productive class, allowing speakers to form new compounds at a high rate (Niemi, 2009) due to their semantic transparency. However, unlike compounds that are compact phrases, and thus are transparent, some Finnish compounds represent more opaque formations, like the compound *kottikärry* 'wheelbarrow', where the first component *kotti* does not exist in the language as a free morpheme. Finnish compounds are almost always written without spaces, unlike in English, where onomasiological units like compounds or idioms are typically split into distinct orthographic words.

Derived words in Finnish are typically more opaque than compounds, and thus, they are usually more strongly lexicalized. For example, according to the Language Bank (of Finland) corpus (http://www.csc.f; 131.4 million word tokens), the word *kivi* 'stone' is used in 2137 different compounds but in only 15 derived words. Nikolaev et al. (2018) administered a simple lexical decision experiment to young adults using only monomorphemic words (words consisting of a single morpheme, such as *child*). Both measures of morphological family (size and frequency) that were measured for derived words significantly predicted word recognition speed. By contrast, for compounds, only morphological family frequency, not size, was a significant predictor. This suggests that to understand word recognition processes, morphological family should be measured according to both size and frequency, and that it should be measured separately for compounds and derived words, at least in languages with rich morphology.

1.4. *Pseudo-morphological family measures*

While morphological family size has often been suggested to be semantic in nature (e.g., Baayen, Lieber, & Schreuder, 1997; Bertram et al., 2000; Jong, Feldman, Schreuder, Pastizzo, & Baayen, 2001; Moscoso del Prado Martin, Bertram, Schreuder, & Baayen, 2004), studies by Bowers et al. (2005), Mulder et al. (2015), and Milin et al. (2017) suggest that the morphological family effect might stem also from orthographic (i.e., form-based) overlap between the target and its family members. In order to test our hypothesis about whether morphological family effects in older adults are more semantic or orthographic in nature, we added a variable that we call pseudo-morphological family. For each target word, we calculated all words (in their base forms) that happened to include the target word. To provide an example in English, if our target word was *corn*, we would include the words *corner*, *cornea*, and *cornel* as members of the target word's pseudo-morphological family, and we would also add their base frequencies to the word's pseudo-morphological family frequency. These associates do not represent true morphologically related words nor do they necessarily need to be parsed into at least two morphemes including the target word (e.g., *corn* + *er*). Pseudo-complex forms like *cornea* and *cornel* are not processed as complex, multimorphemic forms unless they contain both a potential stem (e.g., *corn*) and a potential suffix (e.g., *-er*) (Rastle & Davis, 2008; Whiting, Shtyrov, & Marslen-Wilson, 2014, but see Milin et al., 2017, for counterevidence, and Feldman, O'Connor, & Moscoso del Prado Martín, 2009, for arguments against the form-then-meaning assumption). Instead, from a discriminative perspective (Milin et al., 2017), *corn* will be activated to some extent by *corner*, *cornel*, and *cornea*, just as *hat* is activated by *that* (Bowers et al., 2005).

Thus, the pseudo-morphological family measures include not only "true" morphological family members but also words that mimic morphological family members by including the target word, whether or not it is an actual morpheme, and thus represent orthographic overlap but not necessarily semantic overlap. However, in some cases, morphological family members are not included in the pseudo-morphological family measures because there is not complete orthographic overlap between them. For instance, the word *lapsi* 'child' requires stem changes before adding some derivational or inflectional suffixes. Thus, the derived word *lapsellinen* 'childish' is not part of *lapsi*'s pseudo-morphological family because the stem *lapse* does not completely overlap with the target word *lapsi*. As a result, a word's pseudo-morphological family is not entirely a superset of its regular morphological family. However, pseudo-families are typically larger than regular families, since a pseudo-family included many regular morphological family members with orthographic overlap with the target as well as other words with orthographic overlap with the target.

1.5. Aims of the present study

Most previous studies have focused on only the semantic component of the effect of morphological family, ignoring the potential activation of words with form overlap. One reason for the focus on the semantic aspect of morphological family effects may be because most studies tested healthy young adults. Word recognition processes may be different for older adults, however. A recent study by Milin et al. (2017) showed that older adults may rely more on orthographic aspects of words than younger adults do. Furthermore, the semantic decline seen in people with Alzheimer's disease suggests that semantics may play a lesser role in word recognition for these individuals, which may lead them to rely more on orthographic information.

The aim of the current study was to investigate a) whether healthy younger and older adults differ in terms of their word recognition processes, and b) whether word recognition changes for individuals with AD or MCI compared to healthy older adults. If the nature of the effect of morphological family is at the level of both semantic and orthographic overlap, then pseudo-morphological family should contribute to word recognition speed more than morphological family. If the effect of morphological family is more semantically driven, morphological family should contribute to word recognition speed more than pseudo-morphological family.

In order to test these hypotheses, we re-analyzed the young adult data reported in Nikolaev et al. (2018) by incorporating pseudo-morphological family size and frequency in the analysis in addition to the measures originally included. We then administered the same lexical decision experiment to individuals with MCI or AD, and to cognitively healthy elderly.

2. Materials and methods

2.1. Participants

The young adult group included 31 college students (mean age 25.4 years, SD 5.3, 24 females). The older adult sample included 17 healthy elderly adults (aged 55–79, mean 65.8, SD 6.6, 8 females), 22 individuals with AD (age 56–83, mean 72.7, SD 7.6, 12 females), and 24 individuals with MCI (age 58–81, mean 72.4, SD 6.5, 11 females). All were native Finnish speakers, and none of them had learned another language before starting school. Before the session, each participant gave written informed consent. The research was approved by the local ethical research committee.

Patients with AD and MCI were recruited during their visit to the Neurological Clinic at Kuopio University Hospital. AD patients met the research criteria of the NINCDS-ADRDA Alzheimer's criteria (McKhann et al., 2011) and Dubois et al. (2007) for probable AD or prodromal AD. MCI patients met the criteria set by the International Working Group on Mild Cognitive Impairment (Albert at al., 2011; Winblad et al., 2004) for amnestic or multiple domain MCI. Healthy elderly who did not show obvious neurological, psychiatric, cognitive, or functional changes in daily life were recruited through a research project at the Brain Research Unit of the University of Eastern Finland.

The inclusionary and exclusionary diagnostic measures included an MRI assessment, cerebrospinal fluid analysis, electrocardiography, screening for hypertension and depression, blood test, neuropsychological assessment, and interviews. Participants were excluded from enrollment in the study if they had any obvious brain, systemic, or psychiatric disorders that could potentially affect cognitive functions. Such disorders included: stroke, severe depression, or endocrine disorders. Experienced neurologists diagnosed individual patients and determined the person's disease status.

One of the global assessment measures used in this study was the Clinical Dementia Rating Scale (CDR, Hughes, Berg, Danziger, Coben, & Martin, 1982) and the Sum of Boxes score from the CDR (CDR-SOB), which reflects the sum of six domains of the CDR (memory, orientation, judgment and problem solving, community affairs, home and hobbies, and personal care), and it is considered to provide a good measure of disease severity (Balsis, Benge, Lowe, Geraci, & Doody, 2015; Ito & Hutmacher, 2014; O'Bryant et al., 2010). In the older adult group, there were statistically significant differences between the AD and control groups (multiple comparison test after Kruskal–Wallis: observed difference = 39.8, critical difference = 13.9), and between the AD and MCI group (obs. dif. = 17.7, crit. dif. = 12.8), as well as between the MCI and control group (obs. dif. = 22.1, crit. dif. = 13.6) on this measure.

2.2. Material and procedure

The same procedure and stimulus materials used to test young adults in Nikolaev et al. (2018) were used for the older adult groups with the exception that we added pseudo-morphological family size and frequency to our analyses.

Ninety-nine Finnish *i*-final monomorphemic nouns were selected and divided into three sets of 33 nouns from three inflectional types (*lasi* 'glass', *savi* 'clay', and *vesi* 'water'). Nikolaev et al. (2014) and Nikolaev et al. (2018) have found that words with greater stem allomorphy (*vesi*-type) are recognized more quickly than words with lower stem allormophy (*lasi*-type and *savi*-type). *Vesi*-type words have 3–4 different stem allomorphs, whereas *savi* and *lasi* types have two stem allomorphs (see Table 1). We chose these word types to examine whether paradigmatic complexity is modulated by age (younger *vs* older adults) or by disease type (MCI and AD).

Table 1 – A partial number and case matrix of a subset of Finnish *i*-final noun paradigms.

Singular Nominative	Singular Partitive	Singular Genitive	Singular Essive	Plural Partitive	Plural Illative	English gloss
vesi	vet–tä	vede–n	vete–nä	vesi–ä	vesi–in	‘water’
savi	save–a	save–n	save–na	savi–a	savi–in	‘clay’
lasi	lasi–a	lasi–n	lasi–na	lase–ja	lase–ihin	‘glass’

The base and surface frequencies were extracted from the Language Bank (of Finland) corpus (http://www.csc.f), which includes 131.4 million word tokens from written texts. From the same corpus we calculated morphological family size and frequency and pseudo-morphological family size and frequency (see Fig. 1(a–d)). Morphological family was calculated separately for compounds and derived words. We analyzed pseudo-morphological family as a single measure, but also separately included word position to describe the way in which the family member and target word overlapped: in word-initial position (e.g., *corn* and *corn*er), word-internal position (e.g., *pop* and soa*p op*era; in Finnish, all compounds are written without spaces that would indicate boundaries between constituents of a compound), or word-final position (*pet* and car*pet*). The reason for describing pseudo-morphological family members by position of overlap is that the word position contains different aspects of a word's semantics. In Finnish, the initial constituent of a compound is a modifier and the final constituent is a head (similar to English, where *classroom*, *dining room*, and *bedroom* refer to different types of rooms). Thus, an influence of orthographic overlap at different positions of the word might reveal the semantic links between the target and the compound.

In addition to the 99 *i*-final monomorphemic nouns, 99 *i*-final pseudo-words were created, the phonotactics of which did not violate Finnish phonology. In order to prevent participants from guessing the right answer based on pseudo-words' lower bigram frequency (cf. Grainger, Dufau, Montant, Ziegler, & Fagot, 2012), the pseudo-words were matched with the target word groups for grapheme length and bigram frequency. Seventy-eight *a*-final nouns from two different inflectional types and 78 *a*-final pseudo-words acted as fillers.

The relationship between the real and pseudo-morphological family size and frequency measures is shown in Fig. 1a–d, where logarithmically transformed pseudo-morphological family size (1a and 1c) or frequency (1b and 1d) is plotted on the y-axis against logarithmically transformed real morphological family size or frequency measured in compounds (1a and 1b) and derived words (1c and 1d) plotted on the x-axis. A smoother was fitted using function *xylowess* in the “languageR” package in R (Baayen, 2008, 2013).

To be able to better explain variance in reaction times, we also included additional variables that have been widely used in the psycholinguistic literature and that might have an influence on the speed of word recognition. Orthographic neighborhood density, as well as Hamming distance of one (HD1, Coltheart, Davelaar, Jonasson, & Besner, 1977), were calculated from the Basic Dictionary of Finnish (1990/1994) by counting the number of words with the same length but differing only in the initial letter (neighborhood density) or in any single letter (HD1). Since Finnish orthography–phonology mapping is isomorphic, in the present study orthographic neighbors are equivalent to phonological neighbors. Bigram frequency, initial trigram frequency, and final trigram frequency (i.e., the average number of times that all combinations of two or three subsequent letters occur in the corpus) were obtained from the Turun Sanomat Corpus (22.7 million word tokens) using a computerized search program (Laine & Virtanen, 1999). To obtain measures of subjective frequency (i.e., familiarity) ratings, level of concreteness, and pictureability of test items, sixteen additional participants indicated on a six-point scale (from 0 to 5) their estimates for each of the target words. In addition, we asked them to estimate how often the words are seen as proper names (e.g., as a family name). Participant characteristics may also influence reaction times (Baayen & Milin, 2010), so we added participants' gender, age, and years of education as participant-level explanatory variables.

The participants were given written instructions to decide as quickly and accurately as possible whether the letter string on the screen was a real Finnish word or not by pressing the corresponding button (“yes” for words and “no” for pseudo-words) using their dominant hand. The experiment was divided into two blocks of 177 items each. The order of the items was randomized across the blocks for each participant. A practice session included thirty trials with fifteen words and fifteen pseudo-words not included in the actual experiment. There were short pauses after the practice session and between the two blocks. The experiment lasted approximately 25 min. Each stimulus was visible for 2500 msec or until a button press was made, whichever came first. Each stimulus was preceded by an asterisk in the middle of the screen for 500 msec, after which the screen was blank for 500 msec before the stimulus appeared in the same position.

The testing was performed in the Neurological department of the University Hospital of Kuopio or in the Brain Research Unit of the University of Eastern Finland.

2.3. *Data analysis*

We analyzed the data using a mixed effects model (Bates, Mächler, Bolker, & Walker, 2015). Before running the models, we orthogonalized all lexical predictors (described in *Material and procedure*) into principal components [PCs; prcomp (data, scale = T, center = T)] in order to avoid collinearity among the variables in the models. Five of the PCs explained a proportion of the variance above .05. The models included participants, items, and trial numbers as random intercepts and the five PCs and the other variables as fixed-effect predictors. We also added by-participant random slopes for the PCs into the models. Inverted-transformed reaction times (−1000/RT) were the response variable.

Before analysis, we removed trials in which the participants' response was incorrect (a response of “no” to real

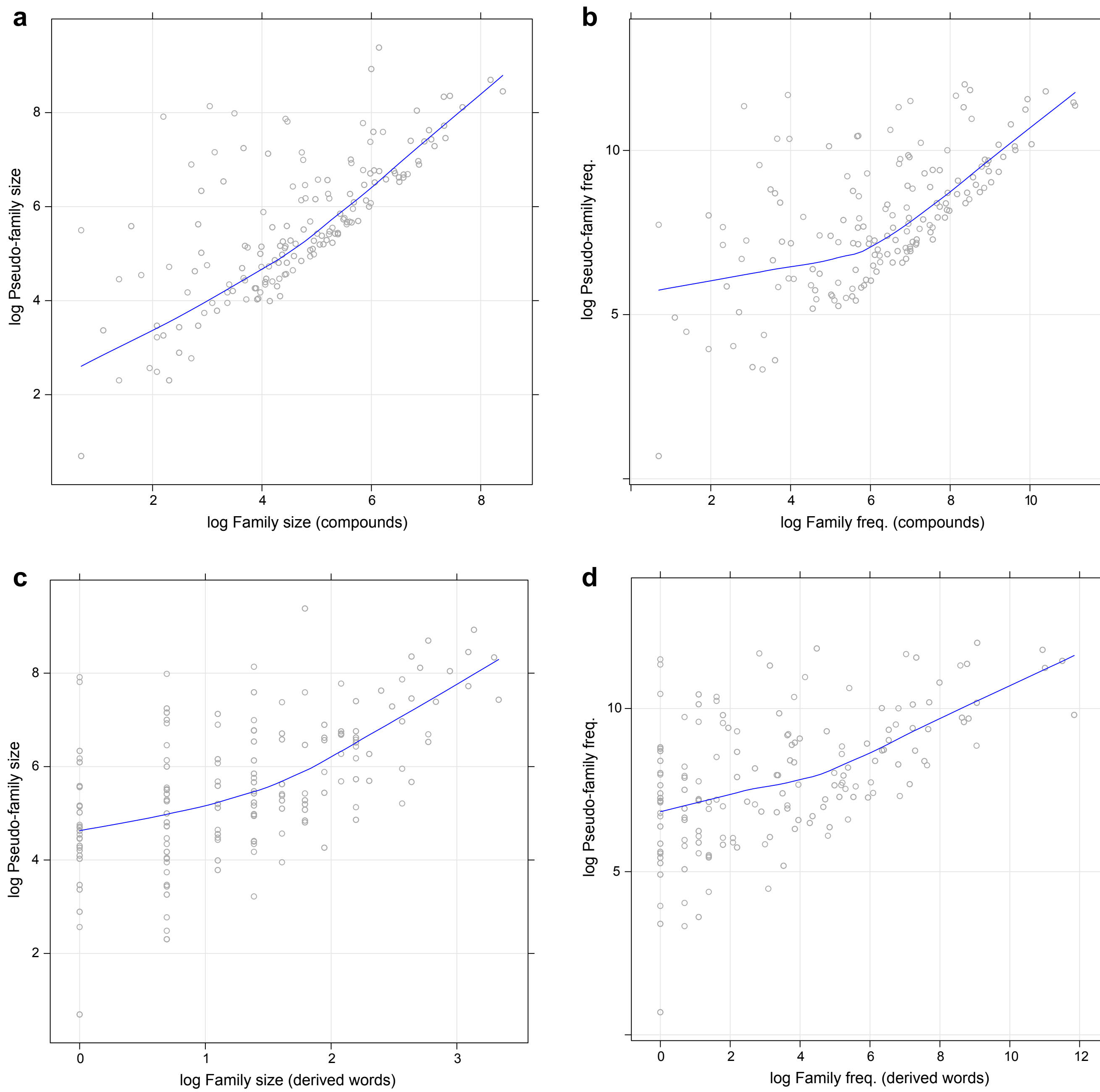

Fig. 1 — a. The relationship between logarithmically transformed morphological family size measured in compounds and pseudo-morphological family size. The blue line is a smoother fitted to the data. b. The relationship between logarithmically transformed morphological family frequency measured in compounds and pseudo-morphological family frequency. c. The relationship between logarithmically transformed morphological family size measured in derived words and pseudo-morphological family size. d. The relationship between logarithmically transformed morphological family frequency measured in derived words and pseudo-morphological family frequency.

words; young adults: 1.3%, elderly controls: 3.5%, individuals with MCI: 1.1%, and individuals with AD: 1.7% of responses) or omissions (young adults: 3.7%, elderly controls: 6.5%, individuals with MCI: 4.8%, and individuals with AD: 5.5% of responses). Following Baayen and Milin (2010), in order to improve the model and remove the influence of possible outliers, we excluded data points with absolute standardized residuals exceeding 2.5 standard deviations (1.7% of the data). Data from one participant with AD was removed from the analyses due to omissions on more than half of the test items.

In order to choose the best fitting model, we used a stepwise regression [step (model, direction = "both")] in the package "lmerTest" (Kuznetsova, Brockhoff, & Christensen, 2017), in which the models' p-values were calculated from the F test based on Satterthwaite's or Kenward-Roger approximation for the fixed effects and based on likelihood ratio test for the random effects. This function (step) performs automatic elimination of the random part followed by elimination of the fixed part. For word-type effects, *lasi*-type served as the reference for *savi*- and *vesi*-types.

3. Results

Reaction times to real words were significantly slower for individuals with AD than for elderly controls (Tukey multiple comparisons of means, $p = .008$), and significantly slower for individuals with MCI than for elderly controls ($p = .043$). There was no significant difference in reaction times between individuals with AD and individuals with MCI ($p = .87$). Young adults showed significantly faster reaction times than all three elderly groups ($p < .001$). RT means (and standard deviations) were 757 msec (111) for young adults, 960 msec (177) for elderly controls, 1136 msec (257) for individuals with MCI, and 1182 msec (266) for individuals with AD.

3.1. *Principal components*

In what follows, we report PCs and their loadings sorted for each PC (the rotation matrices for these PCs).

Three of the PCs (PC1, PC2, and PC4) turned out to be significant predictors of reaction times (see the models reported in the next sections). In what follows, we interpret the principal components in terms of those variables that have the strongest negative or positive loadings on them.

PC1 reflects morphological overlap for compounds (strongest loadings). However, other variables [base frequency, surface frequency, pseudo-family size (final position overlap), and morphological overlap for derived words] had loadings that were close to those for morphological overlap for compounds, but morphological overlap constituted the two highest loadings (.319 and .324) on PC1, and they did not load well on any of the other four components (see Table 2).

PC2 (Table 3) seems to reflect pseudo-family size and frequency for overlap in the internal position (strongest positive loadings). The strongest negative loadings of PC2 (bigram frequency, orthographic Hamming distance of one, final trigram frequency and orthographic neighborhood density) are all form-based.

PC3 (Table 4) reflects pseudo-family frequency and size for internal positions like PC2, but, unlike for PC2, bigram and trigram frequencies are in the same direction as pseudo-family frequency and size (i.e., they all have negative loadings on PC3).

PC4 (see Table 5) has strong negative loadings for pictureability, concreteness, and familiarity rating.

PC5 (see Table 6) has strong negative loadings for neighborhood density and Hamming distance of one, as well as a strong positive loading for initial trigram frequency.

3.2. *Effect of aging*

PC1 and PC4 were significant predictors of RTs in the young adult group. In the model for young adults (shown in Table 7), PC1 and PC4 have negative estimates, showing that morphological overlap for compounds, base frequency, surface frequency, pseudo-family size (final position overlap), morphological overlap for derived words, pictureability, and concreteness of words are facilitatory variables influencing RTs. The number of allomorphs was also a significant predictor.

For elderly controls (Table 8) PC1, PC4, and number of allomorphs were significant predictors, as in the young adult group. However, in contrast to the young adults, PC2 (with a strong positive loading of pseudo-family size and frequency for overlap in the internal position, as well as strong negative loadings of other form-based orthographic predictors) also

Table 2 – The rotation matrix for PC1.

	PC1
Length	−.186
Concreteness	−.134
Pictureability	−.067
As proper name	−.013
Final trigram freq.	.011
Hamming distance of one	.020
Neighborhood density	.021
Initial trigram freq.	.035
Bigram freq.	.066
Pseudo-family freq. (internal)	.134
Pseudo-family size (internal)	.181
Familiarity rating	.211
Family freq. (derived words)	.218
Pseudo-family freq.(final)	.242
Pseudo-family freq. (initial)	.268
Family size (derived words)	.288
Pseudo-family size (final)	.288
Base freq.	.305
Surface freq.	.310
Pseudo-family size (initial)	.318
Family freq. (compounds)	.319
Family size (compounds)	.324

Table 3 – The rotation matrix for PC2.

	PC2
Bigram freq.	−.390
Hamming distance of one	−.350
Final trigram freq.	−.330
Neighborhood density	−.320
Length	−.226
Initial trigram freq.	−.224
Pseudo-family size (final)	−.124
Pseudo-family freq.(final)	−.052
Family freq. (compounds)	−.042
Family size (compounds)	−.039
Family freq. (derived words)	−.036
Family size (derived words)	−.034
Surface freq.	−.023
Base freq.	−.008
Pseudo-family size (initial)	.070
Familiarity rating	.093
As proper name	.102
Pseudo-family freq. (initial)	.113
Concreteness	.275
Pictureability	.296
Pseudo-family size (internal)	.296
Pseudo-family freq. (internal)	.316

Table 4 – The rotation matrix for PC3.

	PC3
Pseudo-family freq. (internal)	−.469
Pseudo-family size (internal)	−.434
Bigram freq.	−.365
Final trigram freq.	−.334
Initial trigram freq.	−.271
Pseudo-family size (final)	−.127
Pseudo-family freq. (final)	−.124
Familiarity rating	−.030
Family size (derived words)	−.011
Pictureability	−.009
Neighborhood density	.027
Concreteness	.036
Hamming distance of one	.055
Base freq.	.127
Pseudo-family size (initial)	.128
Family size (compounds)	.140
As proper name	.141
Family freq. (compounds)	.154
Surface freq.	.164
Family freq. (derived words)	.164
Pseudo-family freq. (initial)	.166
Length	.243

Table 6 – The rotation matrix for PC5.

	PC5
Neighborhood density	−.550
Hamming distance of one	−.513
Pseudo-family freq. (internal)	−.187
Pseudo-family size (internal)	−.182
Pictureability	−.021
Pseudo-family freq. (initial)	−.014
Pseudo-family size (initial)	−.008
Family freq. (compounds)	.005
Family size (compounds)	.008
Family freq. (derived words)	.023
Familiarity rating	.025
Concreteness	.044
Family size (derived words)	.046
Surface freq.	.048
Pseudo-family size (final)	.072
Base freq.	.074
Final trigram freq.	.080
Pseudo-family freq. (final)	.101
Bigram freq.	.182
As proper name	.212
Length	.245
Initial trigram freq.	.439

reached significance. In addition, years of education was a significant predictor of RTs for healthy older adults.

3.3. *Effect of pathology*

For individuals with MCI (Table 9), the same PCs that were found to be significant for elderly controls were significant predictors: PC1, PC2, and PC4, as well as education. However, the number of allomorphs was not significant.

Individuals with AD (Table 10) showed no effect of education, but all other significant predictors were the same as those found for elderly controls.

Table 5 – The rotation matrix for PC4.

	PC4
Base freq.	−.131
Pseudo-family freq. (internal)	−.094
Surface freq.	−.091
Pseudo-family size (internal)	−.090
Pseudo-family freq. (initial)	−.001
Family freq. (derived words)	.009
Family size (derived words)	.015
Pseudo-family size (final)	.056
Pseudo-family size (initial)	.064
Initial trigram freq.	.102
Family size (compounds)	.105
Family freq. (compounds)	.108
Length	.122
Pseudo-family freq. (final)	.143
As proper name	.148
Bigram freq.	.156
Final trigram freq.	.162
Hamming distance of one	.185
Neighborhood density	.203
Familiarity rating	.305
Concreteness	.542
Pictureability	.590

In the next sections, we summarize how all of the significant predictors are related regarding a) form-based versus semantic-based components of morphological processing, and b) the effect of neurodegenerative disease on morphological processing.

3.4. *Contribution of years of education and number of stem allomorphs*

We found a facilitating effect of years of education on the speed of word recognition in individuals with MCI and the healthy elderly control group. This means that the more years of education a person had, the faster her/his recognition of words was. However, in individuals with AD, years of education did not predict word recognition speed. The range of years of education was similar for all groups: AD (mean = 10.8 years, SD = 4.2, range = 5–19), MCI (mean = 10.4 years,

Table 7 – Estimated coefficients, standard errors, and t- and *p*-values for the mixed model fitted to the latencies elicited for 99 *i*-final words in the lexical decision experiment for young adults.

Fixed effects	Estimate	Std.Error	*t*-value	*p*-value
(Intercept)	−1.31	.05	−26.36	<.001
Allomorphs	−.034	.015	−2.3	.024
PC1	−.021	.004	−5.179	<.001
PC4	−.042	.008	−5.224	<.001
Random effects				
Groups	Name	Variance	Std.Dev.	Corr
Item	(Intercept)	.009	.095	
Subject	(Intercept)	.032	.179	
	PC1	4.765e−05	.007	.08
Residual		.055	.235	
Number of obs. 2862; Item, 99; Subject, 31.				

Table 8 – Estimated coefficients, standard errors, t- and *p*-values for the mixed-model fitted to the latencies elicited for 99 *i*-final words in the lexical decision experiment for elderly controls.

Fixed effects	Estimate	Std.Error	*t*-value	*p*-value
(Intercept)	−.72	.157	−4.574	<.001
Allomorphs	−.022	.01	−2.14	.035
PC1	−.011	.003	−4.122	<.001
PC2	−.011	.005	−2.223	.029
PC4	−.02	.006	−3.687	<.001
Education	−.024	.011	−2.237	.041
Random effects				
Groups	Name	Variance	Std.Dev.	
Item	(Intercept)	.003	.057	
Subject	(Intercept)	.026	.16	
Residual		.033	.181	
Number of obs. 1595; Item, 99; Subject, 17.				

Table 10 – Estimated coefficients, standard errors, t- and *p*-values for the mixed-model fitted to the latencies elicited for 99 *i*-final words in the lexical decision experiment for individuals with AD.

Fixed effects	Estimate	Std.Error	*t*-value	*p*-value
(Intercept)	−.876	.051	−17.017	<.001
Allomorphs	−.018	.009	−2.008	.048
PC1	−.011	.003	−4.097	<.001
PC2	−.011	.004	−2.718	.008
PC4	−.018	.005	−3.751	<.001
Random effects				
Groups	Name	Variance	Std.Dev.	Corr
Trial	(Intercept)	.001	.034	
Item	(Intercept)	.002	.049	
Subject	(Intercept)	.045	.212	
	PC1	4.138e−05	.006	.83
Residual		.026	.162	
Number of obs. 1879; Item, 99; Subject, 21.				

SD = 3.5, range = 6–17), elderly controls (mean = 13.7 years, SD = 3.7, range = 8–20). Thus, more formal education has a positive effect on word recognition speed in the preclinical, prodromal stage of AD, but this is no longer the case when the disease progressed further. The concept of cognitive reserve has been proposed to explain the apparent behavioral compensation mechanism that has been linked to education (Scarmeas et al., 2003; Stern, 2012; Stern, Alexander, Prohovnik, & Mayeux, 1992). Our results with healthy older adults and people with MCI support this idea. The lack of a correlation for people with AD does not necessarily mean that individuals with AD do not have cognitive reserve. However, it might be that at some point in this neurodegenerative disease, the effect of education provides a weaker benefit.

Stem allomorphy is a morphological variable denoting how complex a word's paradigm (all inflected forms) is. More allomorphs reflect greater complexity. Young adults and two older adult groups (elderly controls and individuals with AD) showed faster reaction times to words with more stem allomorphs in their inflectional paradigms compared to words with fewer stem allomorphs, replicating the results obtained by Nikolaev et al. (2014) and Nikolaev et al. (2018) for young adults. Nikolaev et al. (2018) explain why greater complexity leads to faster responses: since there is variation in the form (stem allomorphy), but no variation in the meaning, activation of multiple forms, and, at the same time, activation of the same meaning should result in activation of a broader neuronal network for words with higher stem allomorphy compared to words with no stem variants. When a participant initiates a word-recognition response following the detection of a stimulus, the possibility of parallel pathways to the motor system facilitates response latency by utilizing the principle of the fastest racer or the fastest group of racers (Miller & Ulrich, 2003; Raab, 1962; Schröter, Frei, Ulrich, & Miller, 2009). However, an alternative explanation is suggested by discriminative learning (e.g., Baayen, Chuang, & Blevins, 2018), which does not require constructs such as stem, morpheme, or allomorph, and according to which greater morphological complexity of words is a more effective discriminative cue for readers or listeners.

Table 9 – Estimated coefficients, standard errors, t- and *p*-values for the mixed-model fitted to the latencies elicited for 99 *i*-final words in the lexical decision experiment for individuals with MCI.

Fixed effects	Estimate	Std.Error	*t*-value	*p*-value
(Intercept)	−.562	.114	−4.922	<.001
PC1	−.009	.003	−3.218	.002
PC2	−.013	.005	−2.643	.01
PC4	−.018	.006	−3.078	.003
Education	−.039	.01	−3.708	.001
Random effects				
Groups	Name	Variance	Std.Dev.	
Item	(Intercept)	.003	.056	
Subject	(Intercept)	.03	.174	
Residual		.061	.248	
Number of obs. 2227; Item, 99; Subject, 24.				

The effect of stem allomorphs was not modulated by age (healthy younger *vs* older adults) but it was modulated by disease type. Unlike the control groups, individuals with MCI did not show sensitivity to the number of stem allomorphs. Lõo, Järvikivi, and Baayen (2018) also reported that speakers of Estonian (a close relative of Finnish) aged 21–67 years old were sensitive to the inflectional paradigm size of the test items regardless of their age. Inflectional paradigm size is similar to morphological family size in that both measures are semantic in nature, whereas stem allomorphy reflects less semantic and more form-based aspects of morphology (since there is no variation in meaning across the stem allomorphs, but only variations in form). This further suggests that in AD, form-based aspects of morphology are preserved. However, our participants with MCI appear to be showing deterioration of some form-based aspects of morphology.

4. Discussion

The effect of morphological family on word processing has two sources. Utilizing a simple word recognition task that allowed us to test individuals with dementia, we found that reliance on these sources changes with age (cf. Mulder, et al., 2015; Milin et al., 2017). On the one hand, morphological neighbors share semantics, which facilitates recognition of a written word when family members are also activated through semantic convergence. All of the groups showed an effect of morphological family on word recognition speed (PC1, see Table 2). On the other hand, words that share orthography may not be part of the same morphological family, but may influence word recognition in a similar way. In the current study, older adults (including individuals with MCI or AD) were found to rely on both semantic-based morphological neighbors and form-based neighbors (pseudo-morphological family members, which had strong positive loadings on PC2, see Table 3) for quickly recognizing words. Further evidence that word recognition speed in older adults is influenced by orthographic aspects of the word comes from the significant impact of variables such as bigram and trigram frequency (i.e., the average number of times that all combinations of two subsequent letters, regardless of their position in a word, or three subsequent letters in the initial or final position occur in the corpus), which had strong negative loadings on PC2. Words with higher bigram or trigram frequencies were recognized more slowly than words with lower bigram or trigram frequencies. This is likely the result of greater lexical competition for words with higher bigram frequency. According to Milin et al. (2017), the more a bigram is shared across lexomes, the less effective it will be as a discriminative cue.

We hypothesized that the effect of overlapping orthography may differ depending on where the overlap occurred in the pseudo-morphological family members. Indeed, Fig. 2 [1] shows that word-final and word-internal pseudo-morphological family clustered with real morphological family measured in compounds, and word-initial pseudo-morphological family clustered with real morphological family measured in derived words.

Both word-initial and word-final pseudo-morphological families had strong positive loadings on PC1 (Table 2), a component that was a significant predictor of RTs for all participant groups. Word-internal pseudo-morphological family had strong positive loadings on PC2, which was a significant predictor for older adults (including individuals with MCI or AD), but did not reach significance for young adults. Fig. 2 shows that pseudo-morphological family with the overlap in the internal position clusters more distantly with regular morphological neighbors (compounds) than word-final pseudo-morphological family. The reason why the orthographic overlap in the internal position is more isolated from regular morphological members is that in Finnish, there are fewer three-constituent compounds (e.g., *sana* 'word' in haku*sana*lomake 'entry form', lit. *search word form*, word-internal overlap) than two-constituent compounds (e.g., *sana*kirja 'dictionary,' lit. *word book*, word-initial overlap, or yhdys*sana* 'compound,' lit. *combining word*, word-final overlap). Also, there are fewer derived words as final constituents

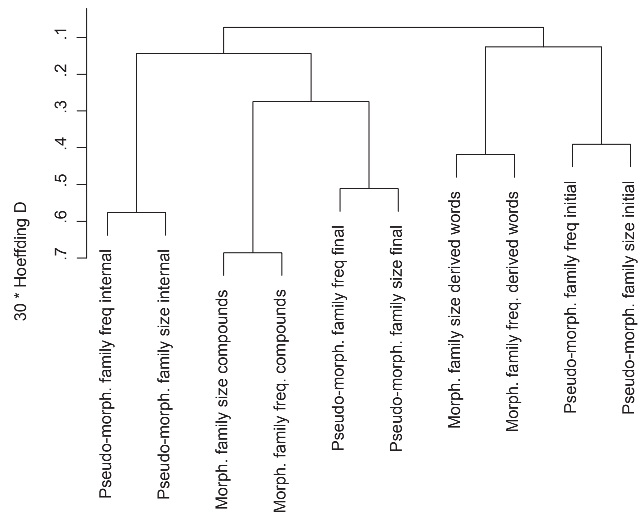

Fig. 2 – Hierarchical cluster analysis (using D statistic) for (pseudo)morphological family variables based on the experimental words. Pseudo-morphological family was calculated according to the word position, in which the family member and target word overlapped: in word-initial position, word-internal position, or word-final position.

of a compound (e.g., *sana*sto 'vocabulary' in agraari*sana*sto 'agrarian vocabulary') than just derived words (e.g., *sana*sto, word-initial overlap). In addition, word-internal overlap also contains many words that are only orthographically but not semantically related (e.g., aikalais*ana*lyysi 'contemporary analyses', where a letter string *sana* in the internal position is just a coincidence of two adjacent constituents of the compound: *aikalais* and *analyysi*). Thus, word-internal pseudo-morphological family does not always reflect anything that looks like a morpheme (since it crosses morphemic boundaries) and is thus more form-based than word-initial and word-final pseudo-morphological families.

Although we controlled for a number of variables known to affect word recognition speed, it is in principle possible that a mixed design with 99 experimental items has somewhat limited statistical power (Lõo, Järvikivi, Tomaschek, Tucker, & Baayen, 2018) for detecting certain relationships. It is important, then, that additional studies attempt to investigate this issue further using a new set of stimulus words and in other languages.

5. Conclusion

Alzheimer's dementia is often characterized by reduced access to the semantic system. The current study examined the impact of morphological family and orthographic neighbors on word recognition among healthy younger and older adults and individuals with Alzheimer's dementia or Mild Cognitive Impairment. A novel finding from the current study is that this reduced access to the semantic system may be accompanied by increased reliance on word form for word recognition. However, people with Mild Cognitive Impairment and cognitively healthy elderly also showed increased reliance on form-based measures for recognizing words. This

[1] We calculated a hierarchical cluster analysis (using D statistic: Hoeffding, 1948) for 10 morphological and pseudo-morphological family measures based on the words used in the experiment.

demonstrates that an increased reliance on form-based aspects of language processing in Alzheimer's disease is not necessarily due to a partial loss of access to semantics, but might be explained in part by a common age-related change in the processes involved in written word recognition.

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