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► **To cite this version:**

Hans-Christoph Nuerk, Arnaud Rey, Ralf Graf, Arthur M Jacobs. Phonographic sublexical units in visual word recognition. *Current Psychology Letters/Behaviour, Brain and Cognition*, 2000, 2, pp.25-36. hal-04450074

HAL Id: hal-04450074

<https://hal.science/hal-04450074>

Submitted on 9 Feb 2024

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Phonographic sublexical units in visual word recognition

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Abstract

Recent models of visual word recognition assume that sublexical orthographic-phonological information is organized according to an onset-nucleus-coda scheme (Plaut, McClelland, Seidenberg, & Patterson, 1996; Jacobs, Rey, Ziegler, & Grainger, 1998, but see Coltheart, Curtis, Atkins & Haller, 1993 for an alternative view). In this study we test the hypothesis that onset-nucleus-coda subsyllabic components are sublexical reading units mediating visual word recognition. We present a sublexical measure that is based on cumulated frequency of these phonology-dependent, orthographic subsyllabic components: Subcomponent Frequency (SCF). In a lexical decision task we found that SCF facilitates visual word recognition for low-frequency words, but not for high-frequency words. For nonwords, we observed that those with high-SCF are harder to distinguish from words than nonwords with low-SCF. In contrast, a standard and purely orthographic measure of sublexical structure, Bigram Frequency, did not produce an effect in our study, when SCF was controlled. Thus, we conclude that SCF is a promising first step towards indexing phonographic sublexical processing.

Introduction

Orthographic and phonological information has been shown to be strongly interdependent in visual word recognition (Stone, Vanhoy & Van Orden, 1997; Van Orden & Goldinger, 1994; Ziegler, Montant & Jacobs, 1997; Ziegler, Van Orden & Jacobs, 1997). Evidence for bi-directional orthographic-phonological influences comes from a variety of empirical phenomena, such as the pseudohomophone effect (e.g. Coltheart, Davelaar, Jonasson, & Besner; 1978; Rubenstein, Lewis, & Rubenstein, 1971; Seidenberg, Peterson, McDonald, & Plaut, 1996; Ziegler & Van Orden, & Jacobs, 1997), the bi-directional consistency effect (Jared, 1997; Jared, McRae & Seidenberg, 1990; Stone et al., 1997; Treiman, Mullenix, Bijeljac-Bibac, & Richmond-Welty, 1995; Ziegler, Montant, & Jacobs, 1997) or the multi-letter grapheme effect (Rastle & Coltheart, 1998; Rey, Jacobs, Schmidt-Weigand, & Ziegler, 1998). In recent years, when the interdependency of orthography and phonology became practically undisputed, different research groups have built connectionist word recognition models that include both, orthographic and phonological coding, such as the DRC (Coltheart, Curtis, Atkins & Haller, 1993; Coltheart & Rastle, 1994), the PDP-model of Plaut et al. (1996), and the MROM-p (Jacobs et al., 1998). These models postulate different levels of orthography and phonology and in their connection weights they quantify the functional interdependence of orthography and phonology.

Inspired by these models, we propose and test a new hypothetical answer to an old question in the domain of visual word recognition. The question is: Which are the sublexical orthographic units that mediate visual word recognition and what measure indexes those units best? A number of such sublexical units have been proposed, such as bigrams, trigrams, or the letters themselves, and measures have been derived from those assumptions such as bigram frequency, trigram frequency, or positional letter frequency (e.g. Biederman, 1966; Gernsbacher, 1984; Grainger & Jacobs, 1993; Humphreys, Evett, & Quinlan, 1990; Massaro & Cohen, 1994; Seidenberg & McClelland, 1989). However, we believe that these measures and units fall short in one important aspect of current theories and models of visual word recognition: they are purely orthographic measures and, thus, neglect the demonstrated role of phonological processes in visual word recognition. As an answer to the question about how to index sublexical units best we propose a measure that relies on units that play a functional role in the mapping from orthography to phonology in at least two of the recent connectionist models of visual word recognition. Both, the MROM-p (Jacobs et al., 1998) and the PDP-model of Plaut et al. (1996)

use the subsyllabic onset-nucleus-coda scheme to organize the mapping from orthography to phonology in monosyllabic words. Based on these three functional subsyllabic components we propose and test a new measure that indexes a sublexical structure that mediates visual word recognition: Subcomponent Frequency (SCF).

Definition: Subcomponent Frequency is defined as the mean of the logarithms of orthographic onset, nucleus, and coda frequency. Orthographic onset frequency of a target word is calculated as the summed frequency of all monosyllabic words that share the same onset. Orthographic nucleus and coda frequency of a target word are calculated as the summed frequencies of all monosyllabic words that share the same orthographic nucleus or coda, respectively.

Thus, SCF represents a *phonographic* measure (Peereman & Content, 1997). It is phonology-based, as the segmentation of the syllable into onset, nucleus, coda relies on phonological properties of the language. It is orthographic, as its calculation is based on the orthographic units that correspond to phonological onset, nucleus and coda. Like for bigram frequency, cumulated frequencies of words that share the same sublexical orthographic units, are computed. However, the difference to bigram frequency is that these orthographic units are not constructed independent of phonology but rather defined by the structure of phonological subsyllabic units.

Predicted Subcomponent Frequency Effects:

This study investigates the question whether SCF indexes sublexical processing during visual word recognition. If subsyllabic components are critical reading units by which word recognition is mediated, then high-SCF should facilitate word recognition. However, sublexical phonological-orthographic effects such as consistency effects (Andrews, 1982; Backman, Bruck, Hebert, & Seidenberg, 1984; Seidenberg, Waters, Barnes, & Tanenhaus, 1984), homophone errors in semantic decision tasks (Jared & Seidenberg, 1991), multi-letter grapheme effects (Rey et al., 1998) or body neighbor effects (Ziegler & Perry, 1998) are mostly observed for low-frequency words only (but see Jared, 1997). Recognition of high-frequency words may be mainly and rapidly performed on the basis of a lexical procedure and may be less affected by a slower sublexical processing involving the conversion of sublexical orthographic units into sublexical phonological units (e.g. Jacobs et al., 1998; Coltheart et al., 1993). Therefore, we expect a facilitating SCF effect for low-frequency words but no such effect or at least a minor effect for high-frequency words.

Testing the effects of one sublexical measure and claiming that the observed effects are due to this particular sublexical measure is problematic since, by definition, most sublexical measures are highly correlated. While controlling for other established measures of visual word recognition like frequency, neighborhood and consistency, it is virtually impossible to separate SCF and bigram frequency (BF) for words. However, the measures can be disentangled for nonwords, and then be tested against each other. As BF is probably the most prominent, yet purely orthographic, sublexical measure we tested SCF while holding BF constant for nonwords. Only if SCF effects still prevail when BF is controlled, we can consider the SCF measure as a promising index for sublexical processing in visual word recognition.

For SCF, the hypotheses for nonwords are straightforward. If SCF is a relevant index for sublexical processing, then high-SCF nonwords should be more similar to words in the lexicon as they more frequently share sublexical components. Thus, high-SCF nonwords should be harder to distinguish from words in a lexical decision task than low-SCF nonwords. Similarly, if BF is a relevant index for sublexical processing then, high-BF nonwords should be harder to distinguish from words than low-BF nonwords.

Method

Participants

Forty psychology students of the Philipps-University Marburg participated in the experiment. All were native German speakers and had normal or corrected to normal vision. They received course credit for participation in the experiment.

Stimuli and Design

80 monosyllabic German 5-letter words and 80 monosyllabic 5-letter nonwords were used in the experiment. Frequency and the reference lists for computation of all other measures were taken from the CELEX-Database (Baayen, Piepenbrock, & van Rijn, 1993). For words, frequency and SCF were manipulated in 2*2 within-subject design, leading to 4 groups of 20 words each (see Table 1). Low-frequency item groups included only words with 10 or less occurrences per million while high frequency item groups consisted of words with more than 20 occurrences per million. Each frequency group was composed of one low-SCF and one high-SCF group, where all high-SCF words had higher

subcomponent frequencies than all low-SCF words. Frequency was matched between the respective SCF groups and SCF was matched between the respective frequency groups as closely as possible.

Additionally, the number of orthographic neighbors (N) was matched between stimulus groups. Furthermore, mean type and token consistency and H-consistency were calculated by generalizing the measure proposed by Treiman et al. (1995) on all monosyllabic words (for exact definition of these consistency measures see Treiman et al., 1995). In the very same way these authors calculated type and token consistency for C_1VC_2 words we computed type and token consistency for all monosyllabic onset-nucleus-coda words. All consistency measures were matched between the item groups as closely as possible (for all stimulus characteristics again see Table 1).

< insert Table 1 about here >

Unfortunately, when frequency, SCF, N, mean type and token consistency, and H-type and H-token consistency are matched between the word stimulus groups it is impossible to hold BF constant between these groups. It generally varies with SCF. However, SCF and BF can be disentangled for nonwords. Nonwords were created by combining existing subcomponents. In a 2*2 design, SCF and BF were manipulated, while N and H-consistency were matched as closely as possible between the item groups. Consistency was generally high and comparable to words (see Table 1).

Procedure

The experiment was run on an Apple Power PC 7200/90. Subjects sat approximately 50 cm from the screen. A trial began with a fixation colon in the middle of the screen. After 500 ms the colon disappeared and a stimulus was presented in Courier 24 font. The stimulus remained visible until subjects pressed one of two keys indicating whether the stimulus was a word or a nonword. After an interstimulus interval of 500 ms the next trial began. Subjects received 16 training trials prior to the randomized 160 experimental trials. Subjects were instructed to respond as quickly and accurately as possible. Responses slower than 2000 ms were not recorded. The whole experiment took about 20 minutes.

Results

Items with overall accuracy below .67 were eliminated, i.e. responses to each item had to be correct at least twice as often as incorrect. This elimination affected only low-frequency words, but no high-frequency words and no nonwords. Three low-frequency words of the high-SCF item pool and four of the low-SCF item pool were excluded. On the basis of this item pool mean correct response times and error rates were computed and are shown in Table 2. The trimming procedure excluded scores smaller than 200 ms and greater than 3 SDs above the participant's overall response time. Analyses of variance (ANOVAs) for a general overview and t-tests for a direct test of the predicted SCF effects for each word and nonword group were separately conducted using both participants (F_1 and t_1) and items (F_2 and t_2) as random factors.

< insert Table 2 about here >

Words:

High-SCF seems to improve performance for low-frequency words, but not for high-frequency words (see Table 2). Overall ANOVAs for words reveal a frequency effect in all analyses (for RT $F_1(1, 39) = 46.48, p < .001; F_2(1, 69) = 10.31, p < .01$; for accuracy $F_1(1, 39) = 21.90, p < .001; F_2(1, 69) = 8.74, p < .01$) and an overall SCF effect in most analyses (for RT $F_1(1, 39) = 9.17, p < .01; F_2(1, 69) = 1.86, p = .18$; for accuracy $F_1(1, 39) = 8.21, p < .01; F_2(1, 69) = 5.45, p < .05$) even though no indication of an SCF-effect was observed in any analysis for high-SCF words. Consequently, an interaction or trend towards an interaction can be observed for most analyses (for RT $F_1(1, 39) = 4.68, p < .05; F_2(1, 69) = 1.23, p = .27$; for accuracy $F_1(1, 39) = 13.71, p < .001; F_2(1, 69) = 5.45, p = .08$). Direct tests of the SCF-hypotheses with t-tests confirm these results: For low-frequency words, high-SCF tends to produce faster ($t_1(39) = 3.44, p < .001; t_2(31) = 1.48, p = .07$) and more accurate ($t_1(39) = 3.89, p < .001; t_2(31) = 2.37, p = .01$) responses than low-SCF. In contrast, for high-frequency words no effect is observed in any RT or accuracy analyses (all $t < 1$).

Altogether, the results are straightforward: SCF tends to affect RT and accuracy performance for low frequency words but not for high frequency words.

Nonwords

ANOVAs for nonwords reveal a clear SCF effect, that prevails when BF is held constant. In contrast there is no hint of a BF effect when SCF is held constant. While all ANOVAs produce a clear main

SCF effect in all analyses (for RT $F_1(1, 39) = 92.64, p < .001$; $F_2(1, 76) = 23.34, p < .001$; for accuracy $F_1(1, 39) = 26.81, p < .001$; $F_2(1, 76) = 16.39, p < .001$), no indication of a BF effect can be observed in any analysis (all $F < 1$ for main effects and interactions). Direct testing of the SCF-hypotheses with t-tests confirm these results for both BF groups (see Table 2). High-SCF nonwords are harder to distinguish from words than low-SCF nonwords as they produce slower and less accurate responses in high-BF nonwords (for RT $t_1(39) = 7.41, p < .001$; $t_2(38) = 3.59, p < .001$; for accuracy $t_1(39) = 3.87, p < .001$; $t_2(38) = 2.82, p < .01$) as well as in low-BF nonwords (for RT $t_1(39) = 7.24, p < .001$; $t_2(38) = 3.75, p < .001$; for accuracy $t_1(39) = 4.05, p < .001$; $t_2(38) = 2.95, p < .01$).

Again, the results are straightforward: Nonwords with subcomponents that are frequent in the language are much harder to distinguish from words than nonwords with infrequent subcomponents. In contrast, BF does not appear to affect nonword performance in our study. When SCF is controlled, nonwords with high-frequent bigrams are no harder to distinguish from words than nonwords with low-frequent bigrams.

Discussion

The result of this study suggests that using phonological-orthographic coupling for a new phonographic sublexical measure SCF may eventually produce a promising index of sublexical processing in visual word recognition. For nonwords, SCF seems to be an even more promising index of sublexical processing than BF as the SCF effect prevails when BF is held constant, but not vice versa. Thus, the confound with the most prominent other sublexical measure BF cannot explain the SCF effect obtained in this study¹. Other alternative explanations of the SCF effect can also be excluded. For example neighborhood is naturally correlated with SCF, as mostly orthographic neighbors share two of three subcomponents. As N was controlled, this confound does not account of the results. Similarly, alternative explanations based on possible confounds of SCF with HFN, subcomponent consistency can also be excluded in the present study. Although not all possible alternative explanations can be excluded in one experiment (e.g. Ziegler, Rey, & Jacobs, 1998), we believe that many of the most established alternative explanations (BF, N, HFN, consistency) cannot explain the SCF effect in this study. Therefore, the SCF effect obtained here, for both, nonwords and in most analyses for words, provides additional evidence for the hypothesis that the onset-nucleus-coda organization of the syllable plays a functional role in visual word recognition as proposed by

recent computational models (e.g. Plaut et al., 1996; Jacobs et al., 1998). In accordance with the MROM-p and the DRC (Coltheart et al., 1993; Coltheart & Rastle, 1994) is the fact that high-frequency words are not sensitive to SCF, because their recognition might be mainly and rapidly performed on the basis of a lexical procedure and their recognition does less rely on sublexical orthography-to-phonology translation. Nonwords with high-SCF are harder to reject in a lexical decision task. This is consistent with the view that they produce more orthographic and phonological lexical activation than low-SCF words, making it harder to distinguish high-SCF nonwords from words (c.f. Grainger & Jacobs, 1996; Jacobs et al., 1998). In contrast, a purely orthographic BF measure did not have any effect on response performance for nonwords, when SCF was controlled.

As the importance of interdependency of orthographic and phonological information in visual word recognition has often been established in recent years (Stone et al., 1997; Van Orden & Goldinger, 1994; Ziegler et al., 1997; Jared, 1997; Jared et al., 1990; Treiman et al., 1995; Peereman & Content, 1997; Rey et al., 1998), we suggest that any index of sublexical processing should also take this interdependency into account and should not purely rely on orthography. The SCF measure presents an alternative for monosyllabic words that acknowledges the importance of phonological processing in visual word recognition.

Although SCF seems to be a promising new index for sublexical processing, some issues need to be discussed for future research. First, it seems that the issue of phonographic reading units is a language-specific issue and that it strongly depends on the relation between orthography and phonology in each language. Two recent translingual studies illustrate this point showing that both, German developing readers and developmental dyslexics had less problems in reading non-words than paralleled English children (Landerl, Wimmer & Frith, 1997; Wimmer & Goswami, 1994). These results indicate that German young readers probably use a smaller unit-sized orthography-to-phonology mapping. Therefore, it seems not unlikely that unit-size of subsyllabic components skilled adult readers use to mediate reading does differ between languages (e.g., Rey et al, 1998).

Second, we tested in this study the psychological validity of onset, nucleus, and coda units following recent models of visual word recognition (Jacobs et al., 1998; Plaut et al., 1996). However,

other partitions have been proposed. Some of them favor an onset-rime partition, where nucleus and coda are not separated (Zorzi, Houghton, & Butterworth, 1998). Others do assume a segmentation based on single graphemes (Coltheart et al., 1993; Rastle & Coltheart, 1999). These alternative segmentations provide therefore additional phonographic hypotheses. As SCF is naturally confounded with onset-rime frequency or grapheme frequency, future studies should disentangle these alternative account of SCF to investigate if the frequency of larger phonographic units (onset-rime), or the frequency of smaller units (graphemes) could account for the SCF effect. However, the main purpose of this study was to generally establish the idea that the frequency of phonographic subsyllabic units of visual word recognition plays an important role in visual word recognition. Future research may investigate the size and levels at which frequency of sublexical phonographic units determine visual word recognition.

In sum, the phonology-based orthographic (i.e. phonographic) sublexical measure SCF seems to be a promising and easily computable index of sublexical processing whose translingual unit-size validity seems worth being tested further. Conceptually, it provides additional evidence for the coupling of orthographic and phonological codes during reading.

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Footnote

1. One group of nonwords (high SCF/ low BF) seems to be very homogenous in that they have either of two bigrams in common – IE or ZW. This is due to the fact that it is very hard to construct nonwords in the mixed (high SCF/ low BF, and low SCF/ high BF) groups, particularly in the high SCF/ low BF group. Hence, one could argue that the SCF effect may be due to properties of these particular bigrams that are irrespective of bigram frequency, for example visual properties. While this argument explains perfectly for the SCF effect in the low BF group, it does not hold for the SCF effect in the high BF group. The bigrams used there are quite different and more heterogeneous, but still we find an SCF effect. This suggests that it is rather unlikely that the SCF effect in general can be explained by the visual properties of these particular bigrams, but leaves the question open whether different interactions with respect to that specific group of nonwords could be produced in other experiments. We thank Glyn Humphreys for putting our attention on this alternative account for the performance with stimuli of the high-SCF/ low-BF nonword group.

Authors' notes

This research was supported by grants from the German Research Foundation (DFG: Deutsche Forschungsgemeinschaft) to Arthur M. Jacobs supporting Ralf Graf and Hans-Christoph Nuerk (Teilprojekte 7 und 8 der Forschergruppe: Dynamik kognitiver Repräsentationen), and by grants from the Fyssen Foundation and the French Ministry of Education and Research (#95124, programme Sciences Cognitives) to Arnaud Rey. We thank Katja Oßwald, Kai Richter and Siegfried Gauggel for their precious help in the realization of this study. We also wish to thank Max Coltheart and Glyn Humphreys for helpful comments on an earlier version of this article. Correspondence should be addressed to Hans-Christoph Nuerk, who is now at the University Hospital of the RWTH Aachen, Department of Neurology – Section Neuropsychology, Pauwelsstr. 30, D-52057 Aachen, Germany. E-Mail may be sent to Hans-Christoph Nuerk (hcnuerk@post.klinikum.rwth-aachen.de).

Table 1: Characteristic of Words and Nonwords: Means for Different Stimulus Groups

WORDS	high Freq		low Freq	
	high SCF	low SCF	high SCF	low SCF
Log Frequency	1.88	1.91	0.60	0.50
SCF	4.08	3.38	4.09	3.11
N	1.40	1.20	1.75	1.60
log BF	3.73	3.32	3.62	3.07
Type Consistency	0.95	0.93	0.94	0.91
Token Consistency	0.91	0.93	0.88	0.92
H-Type Consistency	0.20	0.23	0.26	0.30
H-Token Consistency	0.14	0.15	0.20	0.24
NONWORDS	high BF		low BF	
	high SCF	low SCF	high SCF	low SCF
log BF	3.47	3.41	2.69	2.67
SCF	4.18	2.73	4.06	2.76
N	0.45	0.45	0.30	0.30
H-Type Consistency	0.23	0.31	0.13	0.25
H-Token Consistency	0.17	0.17	0.04	0.14

Table 2: Mean Correct Response Times (RT) in ms and Percentage of Errors (%Err) with the Standard Errors in Brackets for Different Stimulus Groups Computed Over Subjects

WORDS	high Freq		low Freq	
	high SCF	low SCF	high SCF	low SCF
Mean RT	566 (15)	570 (14)	587 (16)	610 (16)
%Err	4.5 (1.0)	5.4 (1.3)	7.2 (1.2)	12.4 (1.9)
NONWORDS	high BF		low BF	
	high SCF	low SCF	high SCF	low SCF
Mean RT	649 (17)	600 (16)	646 (17)	596 (16)
%Err	5.2 (1.0)	1.0 (0.4)	5.4 (1.0)	1.7 (0.5)