Words are made of letters, and yet sometimes it is easier to identify a word than a single letter. This word superiority effect (WSE) has been observed when written stimuli are presented very briefly or degraded by visual noise. We compare performance with letters and words in three experiments, to explore the extents and limits of the WSE. Using a carefully controlled list of three letter words, we show that a WSE can be revealed in vocal reaction times even to undegraded stimuli. With a novel combination of psychophysics and mathematical modeling, we further show that the typical WSE is specifically reflected in perceptual processing speed: single words are simply processed faster than single letters. Intriguingly, when multiple stimuli are presented simultaneously, letters are perceived more easily than words, and this is reflected both in perceptual processing speed and visual short term memory (VSTM) capacity. So, even if single words come easy, there is a limit to the WSE.

Keywords: reading, word processing, Theory of Visual Attention (TVA), word superiority effect, visual processing speed, visual short term memory
report of letters in words compared to single letters, Jordan and Bevan, 1994). Both phenomena obviously reflect a “word superiority” in processing, and although the word-nonword effect has received the most attention in the experimental literature, the word-letter effect may be the most thought-provoking one: Even if words consist of single letters, and even if there are strong indications that individual letters must be processed for a word to be recognized, words enjoy a processing advantage compared with single letters. Following the IAM (McClelland and Rumelhart, 1981), most will agree that the word advantage is due to top–down effects on word recognition, that are absent or smaller for single letters. It is not clear, however, if this processing advantage may affect the threshold for visual processing of words and letters, or whether it is mainly reflected in the perceptual processing speed. It is also not known how word and letter processing may differ at the level of visual short term memory (VSTM). Can words be encoded as units or wholes in the sense that they are treated like entities in VSTM?

In the current study, we investigate these questions using classical psychophysical paradigms with words and letters as stimuli, and methods based on a Theory of Visual Attention (TVA; Bundesen, 1990). TVA is a theoretical framework for understanding and investigating attentional effects at the behavioral (e.g., Peers et al., 2005; Starrfelt et al., 2009; Vangkilde et al., 2011) and neurophysiological level (Bundesen et al., 2005). TVA-based experiments employ unspeeded, accuracy-based measures of perception and attention, and use computational modeling to derive several attentional parameters unconfounded by response times, from one single task. We focus on three of these parameters in the experiments reported here: (1) \(t_0\), the threshold of conscious perception measured in milliseconds; (2) \(C\), the speed of visual processing measured in items processed per second; and (3) \(K\), the capacity of VSTM measured in number of items. The parameters are illustrated in Figure 1, right panel. Parameters \(C\) and \(t_0\) can be estimated both in tasks presenting a single stimulus, and in paradigms with multiple stimuli (whole report).

This study contains three experiments, each including both letter and word stimuli. The first, a computerized naming task, was used to familiarize subjects with the stimuli. In the second experiment, we compared performance with single words and letters at a range of exposure durations. This allowed us to investigate whether the WSE was present in a task where stimuli were to be reported (in contrast to the traditional forced choice tasks), and if so, whether the WSE is reflected either in the threshold for conscious processing \((t_0)\) or the perceptual processing speed \((C)\), or both. In the third experiment we used a classical whole report paradigm with multiple stimuli, to estimate the capacity of VSTM (i.e., the \(K\)-value) for words and single letters. The speed \(C\) and threshold \(t_0\) were also estimated in the whole report paradigm,

**MATERIALS AND METHODS**

All experiments were conducted in a semi-darkened room, and subjects were seated ~100 cm from a 19” CRT monitor running at 160 Hz.

**SUBJECTS**

Twenty-one bachelor students (six male; mean age 23, range 19–36) at the University of Copenhagen participated in this study for course credits. All provided written, informed consent.

**STIMULI AND MASKS**

The stimuli were the same in all three experiments and were presented in lower case Arial font (point size 40) in white on a black background. The order of tasks and stimulus conditions was counterbalanced across subjects. The letter-condition featured 25 letters of the alphabet (w excluded) with the average letter subtending 0.52° (width; range 0.11–0.92) by 0.83° (height; range 0.69–0.97) of visual angle. For the word-condition, 25 high-frequency, three-letter words were chosen so they could not be predicted by identifying only one letter of the word (see Appendix for a list of stimuli). A printed list of the stimuli was present during all experiments, for easy reference. The average word subtended 1.92° (width; range 1.32–2.41) by 0.99° (height; range 0.69–1.20) of visual angle. Masks were rectangular white-on-black pattern masks (2.46° by 2.12° of visual angle) constructed of letter fragments, thus covering both letters and words completely.

![Figure 1](https://example.com/figure1.png)

**FIGURE 1** | Illustration of observed data and model fit for letter and word processing in a single subject in Experiments 2 (left) and 3.
MATHEMATICAL MODELING

The results from Experiments 2 and 3 were analyzed using Bundesen's theory of visual attention (TVA; Bundesen, 1990). According to TVA, stimuli in the visual field compete in a race for access to a limited visual short-term store of \( K \) items. Specifically, the speed at which a stimulus \( x \) in the visual field races for access to VSTM is given by,

\[
v_x = \frac{C}{\sum_{z \in S} w_z} \]

where \( C \) is the overall speed of visual processing and \( w_x \) is the attentional weight of stimulus \( x \) which is divided by the sum of attentional weights across all stimuli in the visual field, \( S \). In other words, the competition for access to VSTM is represented by the attribution of attentional weights such that a stimulus with a high weight will be processed faster (i.e., have a higher probability of being represented in VSTM) than a stimulus with a low weight.

In the special case in which only a single stimulus is presented in the visual field \( v_x = C \) (i.e., no competition) and the probability that the stimulus gets represented in VSTM is given by

\[
p = 1 - e^{-v_x(t_0 - t)} \text{ for } t > t_0
\]

where \( t \) is the exposure duration of the stimulus and \( t_0 \) is the threshold of conscious perception. That is, if the exposure duration of the stimulus is shorter than \( t_0 \) the probability that the stimulus will be represented in VSTM is zero. However, if the exposure duration is longer than \( t_0 \) the probability will follow an exponential function (see Figure 1, right panel, for two examples).

In a single stimulus experiment attentional weights and \( K \) cannot be estimated resulting in a simple model with only two free parameters, \( C \) and \( t_0 \). However, with larger display sizes the complexity of the model increases as does the number of free parameters (see Dyrholm et al., 2011, for a full specification of the model). In Experiment 3, we used a display size of six stimuli resulting in a model with 13 free parameters. Five parameters were used to characterize a probability distribution of the storage capacity of VSTM. Hence the \( K \)-value reported in the result section is the expected \( K \) given a particular probability distribution for each individual participant. Another five parameters were used to estimate the attentional weights (\( w \)-values) at each of the six stimulus locations (one attentional weight was fixed at a value of 1). The remaining three free parameter were used to estimate the threshold of conscious perception, \( t_0 \); the speed of visual processing, \( C \); and the sensory decay in the unmasked trials. In both Experiments 2 and 3, the individual data were fitted by an improved maximum likelihood fitting procedure using the LibTVA toolbox for MatLab (Dyrholm et al., 2011).

EXPERIMENT 1. STIMULUS FAMILIARISATION

Experiment 1 was a computerized naming task, used to familiarize subjects with the stimuli employed in Experiments 2 and 3. Half the subjects (\( n = 11 \)) performed the letter task first. Stimuli were randomly selected and presented at the center of the screen with an inter-trial interval of 1 s from response to the next stimulus. Subjects were instructed to name the stimuli as quickly as possible, without making errors, and reaction times (RTs) were measured using a voice key. The letter and word conditions included 50 and 100 trials, respectively, and 10 practice trials were included in each condition. RTs below 200 ms and above 900 ms were considered voice key errors and were removed from the data. On average 5.6% (SD = 5) of the letter trials and 2.4% (SD = 2.7) of the word trials were removed.

EXPERIMENT 2. SINGLE ITEM REPORT

Experiment 2 tested identification of single stimuli flashed briefly at the center of the screen. Letters and words were presented in separate blocks of 160 trials. In total, subjects ran 320 trials per condition, and the first and second blocks for each stimulus type were preceded by 30 and 15 practice trials, respectively. In each trial, a single stimulus was chosen randomly and presented for one of eight exposure durations (6–80 ms, randomly intermixed). The stimulus was terminated by a pattern mask shown for 500 ms. Participants were instructed to make an unspeeded report of the stimulus, if they were “fairly certain” of its identity. Responses were recorded by the experimenter. To ensure foveal presentation, participants were required to focus on a centrally placed cross and then initiate the trial by pressing the right mousebutton.

The analysis first compared the proportions of correct responses for the different exposure durations for the two stimulus conditions. Then, participants’ performance was modeled individually by TVA (see section Mathematical Modeling for details). This resulted in separate parameter estimates for visual processing speed (\( C \)) and threshold of conscious perception (\( t_0 \)) for all participants. Parameter estimates for letters and words were compared in paired-samples \( t \)-tests (see Table 1).

EXPERIMENT 3. WHOLE REPORT

Experiment 3 was designed to measure the participants’ ability to perceive multiple independent stimuli simultaneously. Words and letters were presented in different blocks of 120 trials. There were four blocks in all. In every trial, six stimuli were chosen randomly without replacement from the stimulus sets described above. Stimuli were presented for one of six exposure durations (30–200 ms, randomly intermixed), and followed by either six pattern masks (500 ms), or a blank screen prolonging the effective exposure duration by a visual afterimage. Stimuli were shown at six locations on the circumference of an imaginary circle with a radius of 4.6° of visual angle centered on fixation (given this radius and the size of the words and letters used crowding effects between stimuli are minimal, see Kyllingsbæk et al., 2007). Again the instruction was to make unspeeded reports of the items which the subject was “fairly certain” of having seen, and responses were recorded by the experimenter. The first and second blocks for each stimulus type were preceded by 36 and 12 practice trials, respectively.

In the analysis, the raw scores (items correctly reported) for the different exposure durations were compared for the two stimulus conditions. Then, the performance of individual subjects was modeled by TVA (see section Mathematical Modeling for details) resulting in parameter estimates for speed of visual processing (\( C \)), threshold of conscious perception (\( t_0 \)), and capacity of VSTM (\( K \)), and attentional weights for each of the six stimulus
positions. These weights were used to characterize any bias of attention toward the left or right visual hemifield by calculating a laterality index, \( w_{\text{index}} \), given as the ratio between the sum of the three weights in the left visual hemifield and the sum of all six attentional weights. This index ranges from zero (absolute right-sided bias) to one (absolute left-sided bias) with 0.5 indicating perfectly unbiased attentional weighting between the hemifields. An additional parameter was included to estimate the sensory decay in the unmasked trials; see Bundesen (1990). The mean estimates of \( C \), \( t_0 \), \( K \), and \( w_{\text{index}} \) across subjects were compared for the letter and word conditions using paired-samples \( t \)-tests (see Table 1).

**RESULTS**

A summary of performance in the word and letter conditions in each experiment can be found in Table 1.

**EXPERIMENT 1. STIMULUS FAMILIARISATION**

Mean RTs (SDs) were significantly longer for single letters, \( M_{\text{LetterRT}} = 476 \text{ ms (37)} \), than for words, \( M_{\text{WordRT}} = 441 \text{ ms (45)} \), see Table 1 for statistics. This difference was significant in 15/21 individual subjects. To be certain this was not attributable to the fact that there were more trials in the word condition, we also made this comparison with only the first 50 word trials. The RT advantage for naming words was slightly smaller when looking only at the first 50 word trials, \( M_{50\text{WordRT}} = 447 \text{ ms (48)} \), but the difference was still highly significant, \( t_{(20)} = 3.75, p = 0.001 \).

**EXPERIMENT 2. SINGLE ITEM REPORT**

Figure 2, left panel, displays the raw scores (mean proportion of correct reports) for the two stimulus conditions at each exposure duration. Overall, words were identified significantly better than letters at all exposures from 19 to 37 ms. Participants were generally better at identifying words than letters, and significantly so in all conditions where floor effects (performance at exposures below the perceptual threshold) or ceiling effects (where performance were close to a 100% for both stimulus types) were not present. This difference was further qualified by the TVA-based parameter estimates.

### Table 1 | Performance and statistics across conditions for Experiments 1–3.

| Parameter        | Letters (Mean (SD)) | Words (Mean (SD)) | \( t \) (20) | \( P \) | \( r \) | \( d \) |
|------------------|---------------------|-------------------|-------------|-------|-------|-------|
| **EXPERIMENT 1** |                     |                   |             |       |       |       |
| Reaction time    | 476 (38)            | 441 (46)          | 4.94        | <0.001| 0.74  | 0.78  |
| **EXPERIMENT 2, SINGLE ITEM REPORT** |                   |                   |             |       |       |       |
| \( t_0 \)        | 14.2 (7.1)          | 11.8 (3.3)        | 1.71        | 0.103 | 0.42  | 0.40  |
| \( C \)          | 677 (24.1)          | 114.4 (40.4)      | −5.50       | <0.001| 0.36  | −1.36 |
| **EXPERIMENT 3, WHOLE REPORT** |                   |                   |             |       |       |       |
| \( t_0 \)        | 39.2 (12.9)         | 45.1 (18.7)       | −1.53       | 0.142 | 0.42  | −0.36 |
| \( C \)          | 33.0 (15.6)         | 14.4 (7.3)        | 8.04        | <0.001| 0.81  | 1.07  |
| \( K \)          | 3.9 (0.5)           | 2.5 (0.4)         | 13.19       | <0.001| 0.48  | 2.94  |
| \( w_{\text{index}} \) | 0.72 (0.14)         | 0.60 (0.21)       | 2.96        | <0.01 | 0.57  | 0.60  |

Units for individual parameters: Reaction time (ms), \( t_0 \) (ms), \( C \) (items/s), \( K \) (items), and \( w_{\text{index}} \) (unitless).

**FIGURE 2 | Comparison of raw scores.** (A) Experiment 2: Proportion correct for letters and words at the different exposure durations. (B) Experiment 3: Number of items correctly reported for words/letters at the different exposure durations. **\( p < 0.01 \), ***\( p < 0.001 \).
A comparison of the mean TVA-estimates (across subjects) of \( t_0 \) and \( C \) in the two conditions (see Table 1) revealed that the mean \( t_0 \) values for letters (14.2 ms) and words (11.8 ms) were not significantly different. In contrast, the perceptual processing speed, the \( C \)-value, was significantly higher for words (14.4 items/s) than letters (68 items/s). This performance pattern is illustrated for a single, representative subject in Figure 1, left panel.

**EXPERIMENT 3. WHOLE REPORT**

A comparison of the raw scores (items correctly reported, see Figure 2, right panel) showed that significantly more letters than words were reported at all exposure durations except for the shortest (30 ms), where performance in both conditions was close to zero. Indeed, the TVA-based modeling revealed that \( t_0 \) was above 30 ms for both stimulus types, and not significantly different between letters and words (see Table 1). In contrast, processing speed (\( C \)) was significantly higher for letters (33.0 items/s) than words (14.4 items/s) in this experiment. In addition, the analysis revealed that significantly more letters (3.9 letters) than words (2.5 words) were retained in VSTM (\( K \)). See Figure 1, right panel, for an illustration of a single subject’s performance and parameter estimates for the whole report of letters.

**GENERAL DISCUSSION**

We investigated normal performance with single letters and short simple words in three experiments, aiming to explore the extents and limits of the WSE. In a naming task, we found that mean RTs were significantly shorter for words than letters. In our second experiment, single item report, we replicate the classical effect that words are identified better than letters with brief, masked presentation. Testing a range of stimulus durations, we found significantly better performance with single words than single letters at a several exposures between the perceptual threshold and ceiling performance.

In Experiments 2 and 3, we have adopted a novel approach to the investigation of the WSE by taking advantage of the TVA framework (Bundesen, 1990). This provides us with a more detailed picture of the factors underlying this effect, as we can derive several measures from one and the same task, and thus disentangle the contribution of e.g., perceptual processing speed and the threshold for perception. The combination of single item and whole report experiments further enables us to map out the perceptual process from the beginning of encoding the first word or letter, to the level where multiple word or letter representations are encoded in VSTM.

TVA-based modeling of data from Experiment 2 revealed that single words are processed significantly faster than letters, whereas the perceptual threshold did not differ between the two types of stimuli. In the third experiment, a classic whole report with multiple stimuli, a different pattern of performance emerged: Processing speed was faster for letters than words. Also, the capacity of VSTM, \( K \), was significantly higher for letters than words.

**EXTENTS AND LIMITS OF THE WORD SUPERIORITY EFFECT**

Our findings indicate that the WSE is more general than previously reported. When presented in isolation, at the center of the visual field, single words are identified better than single letters at all exposure durations between the perceptual threshold and ceiling performance. The effect is also apparent in simple vocal reaction times to unmasked stimuli, perhaps indicating that words enjoy “superiority” not only at perceptual levels of processing. However, although single words are perceived and reported better and faster than single letters, words do not enjoy the same advantage when multiple stimuli are presented simultaneously. In such cases, single letters are processed faster than words, and, in addition, more single letters than whole words can be encoded into VSTM. Also, there is a general decrease in processing speed for both stimulus types from the single item to the whole report experiment. It is well-known that both errors and RTs increase with eccentricity (Eriksen and Schultz, 1977; Carrasco et al., 1995), and thus this speed dependence on eccentricity is not unexpected.

The WSE has typically been reported in experiments using brief, masked displays of single stimuli (e.g., McClelland and Johnston, 1977), and forced choice responses. The type of masking or degradation required to evoke this effect has been widely debated (Johnston, 1981; Prinzmetal, 1992; Jordan and Bevan, 1994), and most studies have used the one exposure duration where subjects perform above 75% correctly (Pollatsek and Rayner, 2005). Our results suggest that this may not be necessary, as the WSE, at least when measured with a report task rather than forced choice, is evident over a range of exposure durations. Using a two-alternative forced-choice paradigm comparing performance with postmasked words and single letters, Jordan and de Bruijn (1993; see also Jordan and Bevan, 1994) found that word superiority persisted only when the same size masks were used for both words and letters but disappeared when the width of the masks were adjusted to the actual width of the individual stimuli. This latter approach, however, may inadvertently have resulted in a letter benefit as certain letters could easily be excluded just by the size of their masks. Hence, we used similar masks for both letters and words. Even if the WSE we observed in Experiment 2 could potentially be explained by the mask we used, this does not necessarily make the effect less interesting. Also, mask attributes cannot explain why the effect is reversed in Experiment 3, where the same stimuli and masks were employed.

In addition, the results of Experiment 1 indicate that words are processed more efficiently than single letters even when they are unmasked. Cattell (1886) was the first to record such a word superiority in vocal naming times, but the phenomenon has not been studied to any large degree, although it does, in our opinion, deserve further investigation. For instance, it is possible that some of the word advantage in RTs may have its roots on other levels of processing than in visual perception, and may perhaps be related to the ease of phonological retrieval. The relative speed of lexical and sublexical processing has been investigated within the framework of the Dual Route Cascaded model of reading (Coltheart et al., 2001). Sublexical processing (letter-sound translation processes) is slower than lexical (whole word) processing, and this may be related to the RT difference we observe between single letters and words. It may also be the case, however, that the advantage in visual processing speed observed for words...
VSTM is known to have a capacity of about four items (Sperling, 1960). Stimuli were presented outside the central visual field (at 4.6° from fixation). Although previous work indicates that there is little crowding between stimuli at this eccentricity (Kyllingsbæk et al., 2007), “within stimulus crowding” (i.e., lateral masking) may have affected the processing of words in this condition. It is worth noticing, however, that if we count the number of words encoded in the word condition in Experiment 3, we do see a WSE: While our subjects could only encode a mean of 2.5 (i.e., 2 or 3) three-letter words at the longest exposure duration, this of course translates to them having encoded between six and nine letters. This is clearly superior to their performance in the letter condition, where the mean capacity was about four letters. Thus, the WSE may be said to be present also in the whole report condition, but not to the same extent as in the single item task.

**CONCLUSION**

We have shown that the WSE, at least for simple short words, can be revealed in vocal reaction times, and that part of this superiority is probably caused by increased visual processing speed for words compared to letters. This fits neatly with previous observations of the WSE, and the interpretation that top–down connections may enhance processing of letters in words, while single letter processing may rely more on bottom-up signals. A novel finding is that the WSE is significant at a range of exposure durations, which means that at least in our paradigm, the meticulous search for a given performance level is not necessary to reveal the effect. Rather, words seem to be processed better or faster than letters from the threshold of perception. When several stimuli are presented simultaneously, we find the opposite result: letters are processed faster than words, and more letters than words can be encoded in VSTM. This indicates that words are not treated as units in VSTM.

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### APPENDIX

#### WORD STIMULI

All words are high frequency Danish words, with high neighborhood-size. At least two neighbor words were included in the list for all stimuli, thus making it necessary to process at least two, and for most words all three letters in the word to identify it correctly.

| Stimulus | Freq. pr mill. \( ^a \) | \( N_{\text{size}} \) \( ^b \) | Wordclass | Neighbour-stimuli in list |
|----------|------------------|------------------|----------|------------------|
| bag      | 266              | 25               | Noun; prep | 3                | bog; dag; tag |
| bog      | 107              | 23               | Noun     | 2                | bag; tog     |
| dag      | 791              | 23               | Noun     | 3                | bag; dig; tag |
| den      | 9259             | 28               | Det.; pron. | 2           | det; din     |
| det      | 15358            | 22               | Det.; pron. | 2           | den; dit     |
| dig      | 427              | 21               | Pron.    | 4                | dag; din; dit; mig |
| din      | 267              | 24               | Pron.    | 4                | den; dig; dit; min |
| dit      | 111              | 24               | Pron.    | 3                | det; dig; din |
| fad      | 23               | 19               | Noun     | 3                | far; fod; mad |
| far      | 212              | 24               | Noun     | 2                | fad; for     |
| lod      | 29               | 18               | Noun     | 3                | fad; for; mod |
| for      | 9336             | 22               | Conj.    | 3                | far; fod; mor |
| han      | 4556             | 21               | Pron.    | 3                | hun; kan; man |
| hun      | 2070             | 17               | Pron.    | 2                | han; kun     |
| kan      | 4058             | 15               | Verb     | 3                | han; kun; man |
| kun      | 970              | 14               | Adv.     | 2                | hun; kan     |
| mad      | 85               | 18               | Noun     | 4                | fad; man; med; mod |
| man      | 3146             | 17               | Pron.; noun | 4         | han; kan; mad; min; |
| med      | 9204             | 15               | Prep.; adv. | 2          | mad; mod     |
| mig      | 1123             | 18               | Pron.    | 2                | dig; min     |
| min      | 684              | 20               | Pron.    | 3                | din; man; mig |
| mod      | 907              | 16               | Noun; prep | 4                | fod; mad; med; mor |
| mor      | 244              | 19               | Noun     | 2                | for; mod     |
| tag      | 78               | 22               | Noun; verb | 3               | bag; dag; tog |
| tog      | 290              | 15               | Noun     | 2                | bog; tag     |

|                | Mean          | SD            | Median |
|----------------|---------------|---------------|--------|
|                | 2544.04       | 4019.46       | 684    |

\( ^a \) Bergenholz (1992).

\( ^b \) Number of words in the Danish dictionary (www.ordnet.dk/ddo) differing from the target by only one letter. Values kindly calculated by the Danish Lexicographic Society.