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Pupillary responses during lexical decisions vary with word frequency but not emotional valence

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Abstract

Pupillary responses were examined during a lexical decision task (LDT). Word frequency (high and low frequency words) and emotional valence (positive, neutral and negative words) were varied as experimental factors incidental to the subjects. Both variables significantly affected lexical decision performance and an interaction effect was observed. The behavioral results suggest that manipulating word frequency may partly account for the heterogeneous literature findings regarding emotional valence effects in the LDT. In addition, a difference between high and low frequency words was observed in the pupil data as reflected by higher peak pupil dilations for low frequency words, whereas pupillary responses to emotionally valenced words did not differ. This result was further supported by means of a principal component analysis on the pupil data, in which a late component was shown only to be affected by word frequency. Consistent with previous findings, word frequency was found to affect the resource allocation towards processing of the letter string, while emotionally valenced words tend to facilitate processing.

Keywords: Pupillary response; Lexical decision; Word frequency; Positive, neutral, negative words; PCA

1. Introduction

The lexical decision paradigm is often used to determine the variables which affect the processes underlying word recognition. In the lexical decision task (LDT), subjects have to judge the lexicality of a presented letter string, the task being to decide as quickly as possible whether the string is a word or not a word. The time needed to solve this task, e.g., the speed of extracting relevant stimulus information from a letter string to recognize it as a word, is used as a measure of lexical access (Jacobs and Grainger, 1994). Since several studies provided evidence that lexical decisions can be executed before the letter string has been evaluated consciously, the variables that affect lexical decision performance can be seen as factors determining implicit information processing (e.g., Balota and Chumbley, 1984; Grainger and Jacobs, 1996).

One of the variables known to cause variation in LDT response times is word frequency, a measure of the frequency with which a word is used in a language (Balota and Chumbley, 1984; Gernsbacher, 1984; Monsell et al., 1989). When comparing high frequency with low frequency words in the LTD, high frequency words are recognized faster and with higher accuracy, elicit shorter fixations in reading as indicated by eye-movement research (Rayner and Duffy, 1986), and affect components of event-related potentials (Dambacher et al., 2006; Hauk and Pulvermüller, 2004; Rugg, 1990; Sereno et al., 1998), where the early components in a time window between 132 ms (Sereno et al., 1998) and 200 ms are seen as an upper time limit of lexical access (Hauk and Pulvermüller, 2004). Its reliable findings across different tasks and methods have made word frequency one of the key contributors to motivate models of word recognition (Coltheart et al., 2001; Grainger and Jacobs, 1996; Plaut and Booth, 2000). A common assumption from these models is that high frequency words can be recognized as a whole word whereas low frequency words demand additional analysis (e.g., phonological processing; Coltheart et al., 2001; for a further discussion see Barber and Kutas, 2007). Accordingly, the effects of word

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frequency have been found to affect different time windows during lexical processing, e.g., an early window around 200 ms post-stimulus presentation and a late time window between 300 and 500 ms post-stimulus presentation. Recently it was argued that the latter time window reflects post-lexical processing (Hauk and Pulvermüller, 2004). Moreover, lexico-semantic variables have been shown to affect the processing of low frequency words to a higher degree and at later processing stages (Dambacher et al., 2006; Hauk et al., 2006). Recent results from Hauk et al. (2006) suggest that word frequency might even have an effect before lexical access takes place. By showing that parallel effects of word frequency and lexico-semantic features can be observed in parallel in later time windows, the authors demonstrate that word frequency and lexical representations are accessed consecutively.

Common to most models of word recognition is the idea that visually presented letter strings do initially activate word representations in the mental lexicon which share either orthographic or phonological features. The consideration of effects of semantic information mainly includes the activation of semantic nodes via a relational network, where semantic information is supposed to enhance or inhibit subjects' performance in visual word recognition at a later processing stage (Plaut et al., 1996). An example of the influence of semantic information is the effect that emotionally valenced words have. Subjects tend to respond faster and with fewer errors in the LDT to emotionally valenced words than to neutral words, though this issue remains controversial (Bradley et al., 1994; Challis and Krane, 1988; Kuchinke et al., 2005; Matthews and Southall, 1991; StrauB, 1983; Williamson et al., 1991; Windmann et al., 2002). While Challis and Krane (1988) reported speeded responses for both positive and negative words, Kuchinke et al. (2005) found that only positive words showed the processing advantage, a result which is in accordance with a meta-analysis of seven LDT studies where no difference in the performance between negative and neutral words was observed (Siegle et al., 2002). It is important to note that all these studies differ in the way they controlled their stimulus material for factors known to affect lexical decision times.

These heterogeneous results in the behavioral data are accompanied by recent imaging results which present evidence for differences in the implicit processing of verbal affective material. In a functional magnetic resonance imaging (fMRI) study on lexical decisions using well-controlled stimulus material, Kuchinke et al. (2005) found a reliable facilitating effect of positive words (compared with neutral and negative words) on error rates and reaction times in both a behavioral pilot study and the subsequent fMRI study. Moreover, although negative words and neutral words could not be distinguished in their behavioral data, distinct brain regions were identified and associated with the processing of positive words (anterior pre-frontal cortex) and negative words (right dorsolateral pre-frontal cortex). It has previously been shown that these regions belong to a network supporting semantic processing, and the findings of Kuchinke et al. (2005) suggest that emotional valence further sub-divides this network.

Different event-related potential (ERP) studies reported modulation of ERP data in a time window of 100–400 ms after stimulus onset using the LDT paradigm (Williamson et al., 1991; go/nogo LDT: Ortigue et al., 2004) or using sub-liminal stimulus presentation (Bernat et al., 2001) which is in accordance with theories that propose an early pre-conscious stimulus evaluation along the emotional valence dimension. In their 'affective primacy hypothesis' Murphy and Zajonc (1993) describe a pre-attentive memory system which categorizes incoming information depending on whether this information is positive or negative. It is proposed that this process may occur at an early stage of perception (Anderson and Phelps, 2001; Bargh, 1992; Windmann et al., 2002). For example, using a LDT with sub-liminal stimulus presentation conditions Windmann et al. (2002) reported evidence of pre-lexical effects of emotionally negative information. Both dependent signal detection measures, the 'WORD'–'NONWORD' discrimination performance and the bias to classify a stimulus as a 'WORD', showed a significant enhancement for negative compared with neutral words, leading the authors to conclude that any visually presented verbal stimulus is initially evaluated for its emotional significance at a pre-lexical level.

In the present study the variables of word frequency and emotional valence are varied as independent factors in a lexical decision experiment. According to the model proposed by Kitayama (1990), which makes assumptions about an interaction between emotion and word frequency in word recognition, evaluative processes as well as either phonological, orthographic or morphological processes operate in parallel. Hence, emotional significance may facilitate word recognition when subjects have to process a letter string at an early processing stage, however only high frequency words benefit from the perceptual enhancement effect.

In addition to behavioral measures (reaction times and error rates), subjects' pupillometric measures were examined. Task-evoked pupillary responses have reliably been shown as sensitive to cognitive processing demands during a task (Beatty and Kahneman, 1966; Granholm et al., 1996; Just and Carpenter, 1993; Nuthmann and van der Meer, 2005) and were suggested to represent a summative index of the brain activity associated with performance in cognitive and emotional tasks (Beatty, 1982). The pupil starts to dilate within the first few hundred milliseconds after the onset of a cognitive demand. The peak pupil dilation correlates with the amount of cognitive load associated with a memory task (Beatty and Kahneman, 1966) or emotional processing (Hess, 1965; Janisse, 1974). The contribution of pupillary responses to the examination of emotional processing remains controversial. In an early study, Hess (1965) reported pupil dilations when looking at positive pictures and pupil constrictions for negative material (also see Mudd et al., 1990). On contrast, later studies found pupil dilations for emotional pictures (independent of their actual valence) compared with neutral stimuli (see Janisse, 1974; Steinhauer et al., 1983; Partala and Surakka, 2003 using emotional sounds). These results suggest that the pupil dilations are associated with the resources allocated to the processing of emotional stimuli rather than being related to the emotional valence of the stimuli.

Siegle et al. (2001) examined pupillary responses in a lexical decision task using emotionally valenced words when comparing depressed and non-depressed subjects, but did not report task-evoked peak pupil dilation measures. Instead a principal component analysis was computed (PCA) on the pupillary waveforms (Granholm and Verney, 2004; Nuthmann and van der Meer, 2005; Schluroff et al., 1986; Verney et al., 2004). The PCA technique is intended to reduce the dimensions of a pupillary response by identifying a small number of factors along the time axis which account for unique variance in the data. Derived factor scores for each condition and factor can be subjected to subsequent analyses. In Siegle et al. (2001) depressed and non-depressed subjects differed on two of five identified factors, but no effects of emotional valence for the non-depressed subjects were reported.

In the present study, word frequency is expected to affect behavioral and pupillometric measures. According to the literature, low frequency words have a lower resting level activation in the mental lexicon compared to high frequency words, and more resources have to be allocated to judge the lexicality of the letter string (Grainger and Jacobs, 1996). This resource-consuming process is known to increase reaction times and was expected to cause higher pupil dilations compared with the processing of high frequency words. With the use of well-controlled stimulus material, emotionally valenced words were expected to enhance reaction times. Although the processing of emotional pictures or sounds has been suggested to demand more cognitive resources compared with neutral items, we expect that this is not the case with the processing of emotionally valenced words in the lexical decision task. Since the evaluation of emotional significance is proposed to be an automatic process and the processing of emotional information in the lexical decision paradigm is intended to be incidental to the subjects, we suggest that emotionally valenced words do not increase pupil dilations compared with neutral words, neither in the high nor in the low frequency condition. By computing a PCA on the pupil data we intended to additionally identify components in the pupillary responses to further examine the influence of word frequency and emotional valence on the LDT.

2. Methods

2.1. Subjects

Eighteen female (aged 19–33 years) and 8 male (18–35 years) healthy psychology students (M=25.1 years, SD=4.0) from Freie Universität Berlin participated in this lexical decision experiment to partially fulfill course requirements. All twenty-six participants were right handed, native German speakers who reported no history of neurologic and affective disorders and had normal or corrected-to-normal vision.

2.2. Stimulus material

To test the hypotheses a 3×2 design was applied comprising the factors emotional valence (positive, neutral, negative), and word frequency (low and high frequency). Sixty positive, 60 neutral and 60 negative words were selected from the BAWL (Võ et al., 2006), a database which contains more than 2200 German words rated for mean emotionality and imageability on a 7-point scale. Special attention was given on the stimulus selection process to avoid the lexical decision performance being biased by orthographic word features (Graf et al., 2005). The resulting word lists were carefully selected to differ on mean valence ratings by selecting words that belonged to three non-overlapping distributions for positive (valence scores>=1.3), negative (<=−0.7) and neutral valence (between −0.7 and 0.7). In addition, word frequency was introduced as a second experimental factor to divide each of the emotionally valenced word lists into two sub-lists, each containing 30 high frequency (>=30 per million) and 30 low frequency (<=10 per million) words. These word sub-lists are comparable in their mean emotionality ratings (word statistics derived from German CELEX database, Baayen et al., 1995). Each list of the six word sub-lists consisted of 15 verbs and 15 nouns and the six word lists are matched on mean word frequency, number of letters, number of orthographic neighbors, number of higher frequency orthographic neighbors and mean imageability (see Table 1). Example stimuli from these word lists are: 'LIEBEN' ('to love'; high frequency positive), 'SCHATTEN' ('shadow'; high frequency neutral), 'BRENNEN' ('to burn'; high frequency negative), 'ZAUBERN' ('to conjure'; low frequency positive), 'PARKEN' ('parking'; low frequency neutral), 'LEICHNAM' ('corpse'; low frequency negative). A set of 180 orthographically legal and pronounceable non-words was created as randomly assigned letter strings, designed to be very word-like and matched for number of letters to the 180 target words (e.g., 'DALLE').

2.3. Procedure

The experiment took place in a medium-illuminated room (background luminance about 500 lx). Subjects seated themselves

Table 1
Summary statistics for the stimulus sets, including emotional valence, word frequency per million (F), mean letter length, number of orthographic neighbors (N), number of higher frequency orthographic neighbors (HFN), and imageability

		Emotional valence		F		# Letters		N		HFN		Imageability	
Word type		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
High frequency	Positive	1.86	0.37	64.37	21.25	6.93	1.48	1.33	1.49	0.33	0.61	4.60	1.39
	Neutral	−0.06	0.45	63.96	24.82	7.20	1.30	1.70	1.78	0.37	0.81	3.99	1.27
	Negative	−1.83	0.31	56.94	17.25	7.10	1.56	1.53	1.36	0.27	0.52	4.30	1.01
Low frequency	Positive	1.81	0.40	4.27	2.71	6.57	1.22	1.37	1.30	0.57	0.77	4.30	1.76
	Neutral	0.10	0.41	4.19	2.63	6.63	1.10	0.97	1.25	0.30	0.60	4.63	1.47
	Negative	−1.85	0.35	4.05	2.87	6.87	1.14	1.07	1.34	0.43	0.86	4.31	1.09

M = mean, SD = standard deviations.

in a comfortable chair with their head stabilized in a chin rest (approximately 0.6 m distance between their eyes and the computer screen). Pupil data were recorded with a video-based IView X Hi-Speed eye tracker (SensoMotoric Instruments, Teltow, Germany). An infrared sensitive camera recorded pupil diameters at a sampling rate of 240 Hz. The experimental session started with written instructions on the computer screen, followed by the calibration of the subjects' left eye and a training trial consisting of 10 items (which were not part of the stimulus material).

The 360 test items were randomly assigned on the computer screen using Presentation 9.0 software (Neurobehavioral Systems, Albany, Canada) including the IVIEW X interface to synchronize trial presentation and pupil data recording. A single trial started with the presentation of a fixation cross (+) in the centre of the screen for 1000 ms. The fixation cross was replaced by an experimental item which remained on the screen until button press with a maximum trial duration of 2500 ms. The item presentation was followed by the re-appearance of a fixation cross for 1000 ms for a continuous pupil recording in the time window of 1500 ms post-stimulus onset. Subjects were instructed to respond as quickly and accurately as possible, by pressing the left mouse button for 'WORD' and the right mouse button for 'NONWORD'. The mapping between fingers and mouse buttons was changed after half of the subjects.

Following each trial the presentation of a smiley indicated a self paced period were subjects were allowed to blink, a procedure which is known to minimize blinking artifacts during the experimental trial (Schlemmer et al., 2005). The new trial started with the next fixation cross.

Items were presented in black color 'Arial 24' uppercase font displayed on a grey background (RGB: 150, 150, 150) to minimize differences in luminance during stimulus presentation. Word stimuli subtended a horizontal visual angle of 0.92° and range horizontally from 1.72° to 5.72° (three to ten letters) on the 17″ computer screen. The test phase lasted approximately 25 min during which pupil raw data were recorded.

2.4. Data preparation and analysis

Pupil data were prepared using a computer algorithm written in MATLAB (version 6.5) that discarded trials with major blinks or linearly interpolated smaller artifacts on a trial by trial basis in the time window between 200 ms before stimulus onset and 1500 ms post-stimulus onset. Raw pupillary raw data were sampled down to a 60 Hz and smoothed using a 7-point weighted average filter. In addition all trials were checked visually for undetected artifacts. Because of excessive blinking or recording artifacts 3.1% (ranging from 0% to 14.7% per subject) of all trials were discarded. Pupillary artifacts were not systematically distributed across experimental conditions. Baseline pupil diameter was defined as the average pupil diameter recorded during the 200 ms (fixation cross) preceding the stimulus onset and subtracted from the raw pupil diameter. Peak dilations were computed as the maximum baseline-corrected pupil diameter during a trial. In addition to the artifact removal, pupil data were discarded for trials that contained erroneous responses and reaction time outliers (more than 2 standard deviations apart from individual mean reaction time). Averaged peak dilations, reaction times and error data per experimental condition and subject were submitted to a two-way repeated measures analysis of variances (rmANOVA) comprising the within-subject factors 'emotional valence' (positive, neutral, negative) and 'word frequency' (high vs. low). Significance level was set at alpha = 0.05 and a Greenhouse–Geisser correction was applied if necessary.

The PCA was computed on the average stimulus locked trials per condition and subject. Each of the 91 time points in the time window between stimulus onset and 1500 ms post-stimulus onset was submitted to a PCA as a dependent variable which was followed by a varimax rotation. Two criteria were set to extract the factors, an eigenvalue greater than 1 (Kaiser-criterion) and a significant contribution to the accounted variance as revealed by the visual inspection of a screeplot. The derived factor scores per subject and condition were submitted to a rmANOVA for each factor.

3. Results

Only correct responses were considered for the reaction time analysis and latencies more than two standard deviations apart from the individual mean reaction time were excluded from all subsequent analyses (outliers = 4.9%).

Analysis of the reaction times revealed significant main effects: emotional valence [$F(2,50) = 13.071$, $P < 0.001$, $\eta^2 = 0.343$] and word frequency [$F(1,25) = 66.232$, $P < 0.001$,

Table 2
Lexical decision performance data, including reaction times in ms (RT), percent error (% Error), peak dilations in mm, and factor scores as derived by principal component analysis on pupil data

		Behavioral data				Pupil data		Factor scores					
		RT		% Error		Peak dilations		Factor 1		Factor 2		Factor 3	
Word type		*M*	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD	*M*	SD
High frequency	Positive	723	130	1.98	2.81	0.17	0.09	−0.02	0.96	0.10	0.98	−0.13	0.86
	Neutral	747	141	1.73	2.81	0.17	0.10	0.03	1.11	0.05	1.03	−0.03	1.02
	Negative	749	140	1.31	2.18	0.17	0.09	0.05	1.01	−0.03	1.07	−0.06	0.91
Low frequency	Positive	769	142	2.66	2.99	0.18	0.09	−0.07	0.88	−0.07	1.08	0.09	1.06
	Neutral	820	153	5.00	4.46	0.19	0.09	0.01	1.03	0.02	1.01	0.09	1.15
	Negative	779	141	6.68	5.04	0.18	0.10	0.00	1.08	−0.07	0.91	0.04	1.05

M = mean, SD = standard deviations.

$\eta^2=0.726$]. The frequency effect showed the expected pattern with shorter latencies for high frequency words. A series of Bonferroni-corrected pairwise *t*-tests revealed that the emotional valence effect was driven by faster responses for positive ($P<0.001$) and negative ($P=0.036$) words compared with neutral words (see Table 2). In addition, the interaction between emotional valence and word frequency was significant [$F(2,50)=8.060$, $P=0.001$, $\eta^2=0.244$]. Additional rmANOVAs were conducted to further examine this interaction (Fig. 1). High frequency words showed an effect of emotional valence [$F(2,50)=6.131$, $P=0.004$, $\eta^2=0.197$] due to faster responses for positive words compared with neutral ($P=0.020$) and negative words ($P=0.016$), whereas the emotional valence effect in the low frequency condition [$F(2,50)=14.987$, $P<0.001$, $\eta^2=0.375$] revealed that positive and negative words yielded shorter reaction times than neutral words (both P's<0.001).

Analyzing the error data confirmed these observations. Again, both factors showed significant main effects: (1) emotional valence [$F(2,50)=4.520$, $P=0.016$, $\eta^2=0.153$] owing to a higher error rate for negative words compared with positive words ($P=0.010$); and (2) word frequency [$F(1,25)=27.173$, $P<0.001$, $\eta^2=0.521$] showing that low frequency words caused more errors than high frequency words. In addition to the main effects the two-way interaction between emotional valence and word frequency reached significance [$F(2,50)=8.907$, $P<0.001$, $\eta^2=0.263$]. Follow-up rmANOVAs revealed that different to the reaction time data no effect of emotional valence was observed in the higher word frequency condition [$F(2,50)<1$, $\eta^2=0.021$], while low frequency negative words showed an effect of the emotional valence manipulation [$F(2,50)=9.961$, $P<0.001$, $\eta^2=0.285$] caused by lower error rates for positive words than neutral ($P=0.038$) or negative words ($P=0.001$).

Similar to the analysis of the behavioral data, pupil data showed a significant main effect of word frequency on peak dilations [$F(1,25)=6.944$, $P=0.014$, $\eta^2=0.217$]. The frequency effect was reflected by higher peak dilations in the low frequency condition (Fig. 2). Neither the main effect of emotional valence [$F(2,50)<1$, $\eta^2=0.013$] nor the interaction term between emotional valence and word frequency reached the significance level in the pupillary data [$F(2,50)<1$, $\eta^2=0.005$].

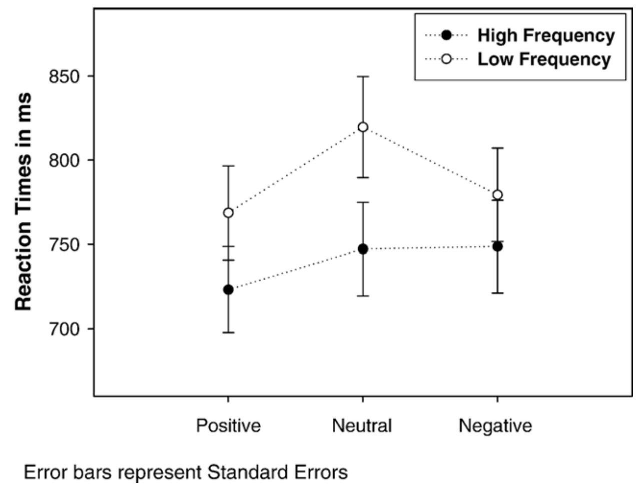

Fig. 2. Lexical decision performance responses as a function of high and low frequency for positive, neutral and negative words error bars represent standard errors.

Computing a PCA with the average waveforms per condition and subject identified 4 factors comprising eigenvalues over one. Visual inspection of the screeplot revealed that only the first three factors differed from the rest. These three factors accounted for 98.196% of the overall variance. Thus, a second PCA was conducted limiting the number of factors to three (accounted variance: factor 1 — 35.39%; factor 2 — 16.97%; factor 3 — 45.91%). A plot of the factor loadings obtained after a varimax rotation is depicted in Fig. 3, where the number of a factor represents its order along the time line (and not the initial factor structure according to the accounted variance). Only factor loadings above 0.4 will be considered for interpretation. The first factor is loading primarily at the beginning of the waveform between 0 and 700 ms, possibly representing early pupillary responses to the presentation of the stimulus (e.g., the

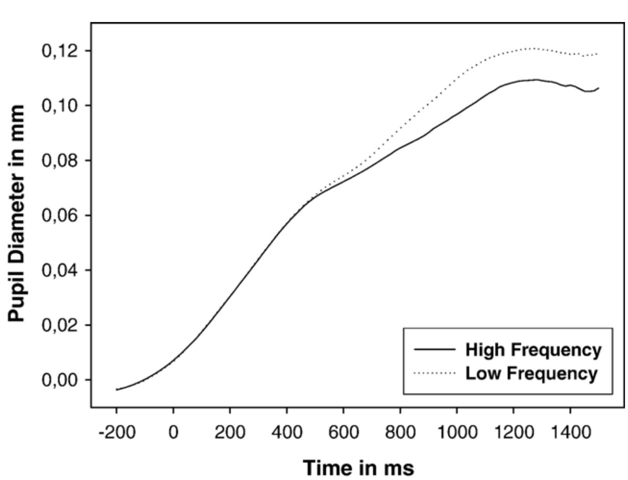

Fig. 1. Stimulus-locked mean pupillary responses during lexical decision performance as a function of high and low frequency word.

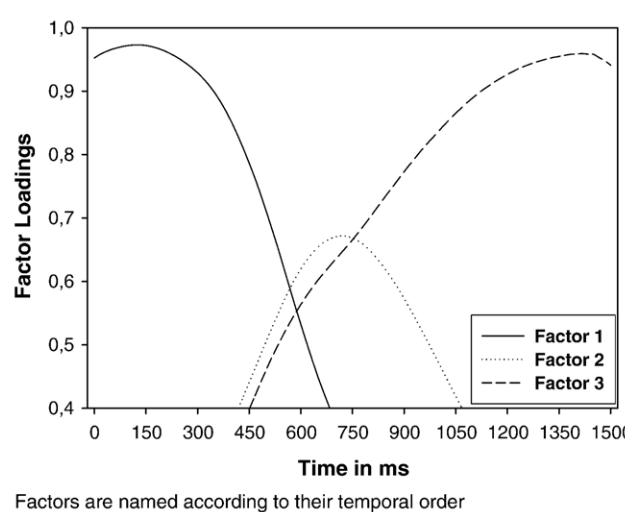

Fig. 3. Factor loadings for the three extracted factors from principal components analysis on the pupil data. Factors are named according to their temporal order.

light reflex or attentional processes).[1] Factor scores were obtained according to the factor loadings for each subject and condition. A two-way rmANOVA was computed on the factor scores of the first factor. Neither the variables 'emotional valence' and 'word frequency', nor the interaction reached significance (all F's < 1). The second factor is loading in the interval between 400 ms and 1050 ms and is assumed to mirror the phase of pupil dilation in preparation of the response (with a mean reaction time for all subjects around 765 ms).[1] Again, the second factor was not affected by the independent variables (all F's < 1.8). The third factor reflects the pupil responses in the late interval starting at 450 ms when the pupil curves reach their peak and start to constrict. Since one has to consider the latency of the pupil reaction (a lag of 300–400 ms), this factor might reflect processes of response selection and execution as well as later post-processing stages.[1] For the third factor, the rmANOVA revealed a significant main effect of word frequency [$F(1,25) = 7.619$, $P = 0.011$, $\eta^2 = 0.234$] with higher factor scores for low frequency words, but no effect of emotional valence or the interaction between these two variables (Table 2).

4. Discussion

In the present study, we asked whether emotional valence influences word recognition, even when subjects do not have to pay attention to the emotional content of the stimuli for executing the task. The use of well-controlled stimulus material comprising positive, neutral and negative high and low frequency words in a lexical decision paradigm lead to three important findings. First, as a main result emotional valence was found to significantly enhance lexical decision performance. This conclusion was supported by faster reaction times for positive and negative words when subjects had to decide upon the lexicality of a presented letter string. In addition, our results confirmed the expected processing advantage for high frequency words compared to low frequency words.

Second, a significant interaction effect was observed between emotional valence and word frequency. While responses to low frequency words were affected by both emotional word categories (positive and negative words), the processing of high frequency words seems to be influenced only by positive valence. These findings challenge the hypotheses of the Kitayama model (Kitayama, 1990) in that the effect of emotionally valenced words is also evident in the low frequency condition (even to a higher degree according to the effect size measures η^2). Taken together the behavioral findings support the idea that emotional valence has a strong and early influence on reaction times and error rates in implicit word recognition. Because word frequency has been shown to affect lexical decision times as early as 120–160 ms after stimulus onset (Assadollahi and Pulvermüller, 2001; Sereno et al., 1998), the observed interaction effect may be interpreted as further evidence for an early effect of emotional content in the LDT (Ortigue et al., 2004; Williamson et al., 1991). Alternatively, it should be noted that interactive effects of word frequency with lexico-semantic features have been observed at post-lexical processing stages (e.g., Hauk et al., 2006), and the possibility appears that the interaction between word frequency and emotional valence in the present study points to late effects of emotional content in the LDT. Especially, influences of negative valence might be discussed in this direction. Negative content affected only the processing of low frequency words which are in general discussed to be processed more slowly, while positive content had an effect on the fast processed high frequency words too.

It seems obvious that the use of well-controlled stimulus material in addition with the manipulation of word frequency served to overcome the heterogeneities of previous studies regarding the processing of positive and negative words in the LDT. It is possible to observe the processing advantage of emotionally valenced words when looking at a mixture of high and low frequency words (or only low frequency words), but the advantage for negative words disappears when only high frequency words are examined (see Kuchinke et al., 2005). Because emotional valence and emotional arousal are thought to represent two orthogonal dimensions that constitute the affective space (Lang et al., 1990; Bradley et al., 1992; Osgood et al., 1957), one might hypothesize that the emotional arousal of negative words accounts for this effect. A recent study by Matthews and Barch (2004) did not find effects of emotionally arousing words in an explicit recognition memory paradigm. Since the stimulus material in the present study was not controlled for the arousal dimension, we cannot answer this question yet.

Another possible explanation is based on theories of the asymmetry of positive and negative affect which suggest that positive material is better elaborated and interconnected in the cognitive system (Ashby et al., 1999; Isen, 1985). Isen (1985) proposed that emotional material is organized differently in memory according to its valence. Especially positive material may be better elaborated and interconnected in the cognitive system than negative material which supports the spreading of activation in the relational network (Ashby et al., 1999; Isen, 1985). Accordingly, the fMRI study by Kuchinke et al. (2005) observed different brain regions associated with the processing of positive words and negative words, and it seems possible that positive and negative word stimuli may not only differ in terms of their organization in memory, but that their processing is also supported by functionally distinct cortical networks.

Another important finding concerns the pupil data. While word frequency has been shown to affect the pupillary responses, emotionally valenced words did not in the LDT. The word frequency effect was reflected by higher peak pupil dilations when processing low frequency words. This result is in accordance with models of word recognition (e.g., Coltheart et al., 2001; Grainger and Jacobs, 1996), wherein the processing of low frequency words are proposed to consume more resources. Low frequency words differ from high frequency words in terms of a lower activation resting level in the mental

[1] It should be noted that the interpretation of the PCA factors is rather speculative on the basis of their temporal sequence (see Nuthmann and van der Meer, 2005) and that future studies are required to analyze the relation of the three-factorial structure to stimulus luminance or response selection processes (see Discussion).

lexicon which is associated with a slower and more demanding lexical access in the LDT (Rubenstein et al. 1970; Grainger and Jacobs, 1996). Further, pupillary responses are seen as an indicator of the resources allocated towards a task (Beatty, 1982). At present, no other study on pupil dilation has reported a word frequency effect.

In contrast to the processing of emotional pictures (Janisse, 1974, Steinhauer et al., 1983) and emotional sounds (Partala and Surakka, 2003) the incidental processing of emotionally valenced words in the lexical decision paradigm did not increase pupil dilations. Looking at the present results, it is unlikely that processing emotionally valenced words in the lexical decision task is associated with additional resource allocation to affective information. Although it is difficult to draw conclusions from null effects, this result fits well with the assumption of an early 'automatic' evaluation process which categorizes incoming stimuli regarding their emotional valence and enhances their likelihood to reach awareness (Anderson and Phelps, 2001). According to this hypothesis, a processing facilitation not associated with additional resource-consuming processes can be expected for emotionally valenced words. In contrast, the possibility exists that resource-free automatic evaluation processes that enhance lexical access may reduce cognitive effort. This would lead to decreased peak pupil dilations for emotionally valenced words compared with neutral words. On a descriptive level this effect was observed for low frequency words (see Table 2) but did not reach significance in the present study.

The following explanations might also be responsible for the present null effects of emotional valence in the pupillary responses. One example is the analyzed time window of 1500 ms. Siegle et al. (2001) reported differences in the 4000 ms interval post-stimulus onset related to sustained processing of personally relevant affective words. Thus, pupil dilations in a later time window might differ depending on the emotional valence of the words, although this does not seem very likely given the present waveforms of the pupillary responses which started to decrease after they reached their peak dilations around 1200 ms post-stimulus onset. Partala and Surakka (2003) also reported emotional valence effects in a late time window 2000 ms post-stimulus offset when subject listened to affective sounds. The results of Siegle et al. (2001) and Partala and Surakka (2003) support the idea of late post-perceptual processing which is enhanced for affective material — whereas the present study focused on the early and incidental effects of emotional valence.

A second explanation regards the lexical decision paradigm. It could be argued that the relatively long stimulus presentation duration (until button press) favors non-automatic processes that overshadow the initial effects of emotional valence, but this should also affect the RTs. Pupil data and behavioral data (like reaction times) are often seen as different sides of the information processing approach: reaction times and error rates reflect speed and accuracy while pupil dilation is primarily a measure of the cognitive resources required by the task (Nuthmann and van der Meer, 2005). Although this differentiation requires further testing, it is probable that emotional valence does not influence the processing demands in the LDT, but does influence the temporal component of lexical access.[2] In this case, emotional valence would not modulate the observed familiarity of a word stimulus (like word frequency does), but may lower the criterion to respond 'WORD'. If emotional valence changes the decision criterion in an LDT, this would lead to speeded responses without affecting the activation demands. A similar explanation was proposed by Windmann et al. (2002) who found evidence for a bias to respond 'WORD' due to the stimulus' emotional valence under the process dissociation paradigm. Their explanation for a more liberal response criterion is an inborn tendency to categorize an event with high survival value as familiar, which at the same time reduces the chance of missing it. As is evident in the present data, speeded responses to answer "WORD" for negative words correspond with more errors in the low frequency condition. This seems to be a trade-off.

Computing a PCA in the present study replicated the common factor structure with three temporal components (e.g., Granholm and Verney, 2004; Nuthmann and van der Meer, 2005). Similar to these studies, the experimental variation in the present study mainly affected a component around the time of the response. Only word frequency was shown to have an effect on this last factor, with higher factor loadings in the low frequency condition. This finding replicates the pattern which is visible in the pupil curves (Fig. 2) and is found by significant differences in the peak pupil dilations. Since the late component started to show relevant factor loadings around 450 ms post-stimulus presentation (and one has to consider the latency on the pupil reaction) this result on the third factor might be related to the resource-consuming processes around the time of lexical access. This fits very well with the expected time window reported in the ERP literature, but it is also possible that this late factor is affected by post-lexical processing as have been proposed for low frequency words (see Barber and Kutas, 2007). Thus, the possibility exists that the observed effect on the third factor simply reflects the shifted temporal characteristics in processing low frequency words. To solve this problem, further studies on pupillary responses using the PCA technique have to show its appropriateness in the interpretation of the temporal resolution of extracted factors, especially when they are related to early processing stages.

[2] Computing non-linear (quadratic) regressions with emotional valence as the regressor and RTs and peak dilations as dependent variables revealed that the quadratic emotional valence term was significant in the RT analysis (beta = − 0.130; $P = 0.080$) but not in the peak dilation analysis (beta = − 0.053; $P = 0.483$). Thus, emotional valence explained more variances in the RTs than in the peak dilations. To further examine whether emotional valence contributes to observed differences in the RTs above and beyond pupil dilation a hierarchical regression model was computed. RTs (as the dependent variable) and peak dilations and PCA factor scores (factor 3) were entered in the first level and emotional valence and word frequency in the second level. Only word frequency had a significant regression coefficient in the peak dilations (beta = 212.215; $P = 0.023$) and the factor scores (beta = − 34.551; $P = 0.073$), while emotional valence did not reach significance (all Ps > 0.258). Again, this analysis did not reveal an effect of emotional valence on RTs that was mediated by pupillary variables. The results support the notion of RTs and pupil dilations being different aspects of information processing but will still need further investigations.

In summary, the behavioral results of the present study indicate interactive effects of emotional valence and word frequency in visual word recognition. Enhanced perceptual processing of positive and negative words is associated with facilitated responses in the LDT. This processing advantage is most pronounced for processing low frequency words. The results extend the classical findings of orthographic or phonological effects in the LDT by showing that basic semantic properties, like emotional valence, affect lexical decision times. As a result of measuring pupil dilations during the processing of this task, emotionally valenced words appear to modulate the speed with which a verbal stimulus is processed, whereas low frequency words have been shown to affect the allocation of additional resources as indexed by higher pupil dilations. Measuring pupil data has been shown to be an appropriate method for creating and testing hypotheses even in situations where the experimental variation is incidental to the subjects.

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References

Anderson, A.K., Phelps, E.A., 2001. Lesions of the human amygdala impair enhanced perception of emotionally salient events. Nature 411, 305–309.

Ashby, F.G., Isen, A.M., Turken, U., 1999. A neuropsychological theory of positive affect and its influence on cognition. Psychological Review 106 (3), 529–550.

Assadollahi, R., Pulvermüller, F., 2001. Neuromagnetic evidence for early access to cognitive representations. NeuroReport 12, 207–213.

Balota, D.A., Chumbley, J.I., 1984. Are Lexical Decisions a Good Measure of Lexical Access? The Role of Word Frequency in the Neglected Decision Stage. Journal of Experimental Psychology. Human Perception and Performance 10 (3), 340–357.

Barber, H.A., Kutas, M., 2007. Interplay between computational models and cognitive electro-physiology in visual word recognition. Brain Research Reviews 53, 98–123.

Bargh, J.A., 1992. The ecology of automaticity: toward establishing the conditions needed to produce automatic processing effects. American Journal of Psychology 105, 181–199.

Beatty, J., 1982. Task-evoked pupillary responses, processing load, and the structure of processing resources. Psychological Bulletin 91, 276–292.

Beatty, J., Kahneman, D., 1966. Pupillary changes in two memory tasks. Psychonomic Science 5, 371–372.

Bernat, E., Bunce, S., Shevrin, H., 2001. Event-related potentials differentiate positive and negative mood adjectives during both supraliminal and subliminal visual processing. International Journal of Psychophysiology 42 (1), 11–34.

Bradley, M.M., Greenwald, M.K., Petry, M.C., Lang, P.J., 1992. Remembering pictures: pleasure and arousal in memory. Journal of Experimental Psychology. Learning, Memory, and Cognition 18 (2), 379–390.

Bradley, B.P., Mogg, K., Williams, R., 1994. Implicit and explicit memory for emotional information in non-clinical subjects. Behaviour Research and Therapy 32 (1), 65–78.

Challis, B.H., Krane, R.V., 1988. Mood induction and the priming of semantic memory in a lexical decision task: asymmetric effects of elation and depression. Bulletin of the Psychonomic Society 26, 309–312.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., Ziegler, J.C., 2001. DRC: a dual-route cascaded model of visual word recognition and reading aloud. Psychological Review, 108, 204–256.

Dambacher, M., Kliegle, R., Hofmann, M., Jacobs, A.J., 2006. Frequency and predictability effects on event-related potentials during reading. Brain Research 1084 (1), 89–103.

Gernsbacher, M.A., 1984. Resolving 20 years of inconsistent interactions between lexical familiarity and orthography, concreteness, and polysemy. Journal of Experimental Psychology. General 113, 256–281.

Graf, R., Nagler, M., Jacobs, A.M., 2005. Faktorenanalyse von 57 Variablen der visuellen Worterkennung. Zeitschrift für Psychologie 213 (4), 205–218.

Grainger, J., Jacobs, A.M., 1996. Orthographic processing in visual word recognition: a multiple read-out model. Psychological Review 103 (3), 518–565.

Granholm, E., Verney, S.P., 2004. Pupillary responses and attentional allocation problems on the backward masking task in schizophrenia. International Journal of Psychophysiology 52, 37–52.

Granholm, E., Asarnow, R.F., Sarkin, A.J., Dykes, K.L., 1996. Pupillary responses index cognitive resource limitations. Psychophysiology 33, 457–461.

Hauk, O., Pulvermüller, F., 2004. Effects of word length and frequency on the human event-related potential. Clinical Neurophysiology 115, 1090–1103.

Hauk, O., Davis, M.H., Ford, M., Pulvermüller, F., Marslen-Wilson, W.D., 2006. The time course of visual word recognition as revealed by linear regression analysis of ERP data. NeuroImage, 30 (4), 1383–1400.

Hess, E.H., 1965. Attitude and pupil size. Scientific American 212, 46–54.

Isen, A.M., 1985. Asymmetry of happiness and sadness in effects on memory in normal college students: comment on Hasher, Rose, Zackes, Sanft, and Doren. Journal of Experimental Psychology General 114 (3), 388–391.

Jacobs, A.M., Grainger, J., 1994. Models of visual word recognition — sampling the state of the art. Journal of Experimental Psychology. Human Perception and Performance 20, 1311–1334.

Janisse, M.P., 1974. Pupil size, affect and exposure frequency. Social Behavior and personality 2 (2), 125–146.

Just, M.A., Carpenter, P.A., 1993. The intensity dimension of thought: pupillometric indices of sentence processing. Canadian Journal of Experimental Psychology 47, 310–339.

Kitayama, S., 1990. Interaction between affect and cognition in word perception. Journal of Personality and Social Psychology 58, 209–217.

Kuchinke, L., Jacobs, A.M., Grubich, C., Võ, M.L., Conrad, M., Herrmann, M., 2005. Incidental effects of emotional valence in single word processing: an fMRI study. Neuroimage 28, 1022–1032.

Lang, P.J., Bradley, M.M., Cuthbert, B.N., 1990. Emotion, attention, and the startle reflex. Psychological Review 97, 377–398.

Matthews, G., Southall, A., 1991. Depression and the processing of emotional stimuli: a study of semantic priming. Cognitive Therapy and Research 15 (4), 283–302.

Matthews, J.R., Barch, D.M., 2004. Episodic memory for emotional and nonemotional words in schizophrenia. Cognition and Emotion 18 (6), 721–740.

Monsell, S., Doyle, M.C., Haggard, P.N., 1989. Effects of frequency on visual word recognition tasks: where are they? Journal of Experimental Psychology. General 118, 43–71.

Mudd, S., Conway, C.G., Schindler, D.E., 1990. The eye as music critic: pupil response and verbal preferences. Studia Psychologica 32, 23–30.

Murphy, S.T., Zajonc, R.B., 1993. Affect, cognition, and awareness: affective priming with optimal and suboptimal stimulus exposures. Journal of Personality and Social Psychology 64 (5), 723–739.

Nuthmann, A., van der Meer, E., 2005. Time’s arrow and pupillary response. Psychophysiology 42, 306–317.

Ortigue, S., Michel, Ch.M., Murray, M.M., Mohr, Ch., Carbonnel, S., Landis, T., 2004. Electrical neuroimaging reveals early generator modulation to emotional words. NeuroImage 21, 1242–1251.

Osgood, C., Suci, G., Tannenbaum, P., 1957. The Measurement of Meaning. University of Illinois, Urbana.

Partala, T., Surakka, V., 2003. Pupil size variation as an indication of affective processing. International Journal of Human-Computer Studies 59, 185–198.

Plaut, D.C., McClelland, J.L., Seidenberg, M.S., Patterson, K.E., 1996. Understanding normal and impaired word reading: computational principles in quasiregular domains. Psychological Review 103, 56–115.

Plaut, D.C., Booth, J.R., 2000. Individual and developmental differences in semantic priming: empirical and computational support for a single-mechanism account of lexical processing. Psychological Review 107, 786–823.

Rayner, K., Duffy, S.A., 1986. Lexical complexity and fixation times in reading: effects of word frequency, verb complexity, and lexical ambiguity. Memory & Cognition 14, 191–201.

Rubenstein, H., Garfield, L., Millikan, J.A., 1970. Homographic entries in the internal lexicon. Journal of Verbal Learning and Verbal Behavior 9, 487–494.

Rugg, M.D., 1990. Event-related brain potentials dissociate repetition effects of high- and low-frequency words. Memory & Cognition 18, 367–379.

Schlemmer, K., Kuhlke, F., Kuchinke, L., van der Meer, E., 2005. Absolute pitch and pupillary response: effects of timbre and key color. Psychophysiology 42, 465–472.

Schluroff, M., Zimmermann, T.E., Freeman Jr., R.B., Hofmeister, K., Lorscheid, T., Weber, A., 1986. Pupillary responses to syntactic ambiguity of sentences. Brain and Language 27, 322–344.

Sereno, S.C., Rayner, K., Posner, M.I., 1998. Establishing a time-line of word recognition: evidence from eye movements and event-related potentials. NeuroReport 9, 2195–2200.

Siegle, G.J., Granholm, E., Ingram, R., Matt, G., 2001. Pupillary response and reaction time measures of sustained processing of negative information in depression. Biological Psychiatry 49, 624–636.

Siegle, G.J., Ingram, R.E., Matt, G.E., 2002. Affective interference: explanation for negative information processing biases in dysphoria? Cognitive Therapy and Research 26, 73–88.

Steinhauer, S.R., Boller, F., Zubin, J., Pearlman, S., 1983. Pupillary dilation to emotional visual stimuli revisited. Psychophysiology 20, 472.

Strau, E., 1983. Perception of emotional words. Neuropsychologia 21, 99–103.

Verney, S.P., Granholm, E., Marshall, S.P., 2004. Pupillary responses on the visual backward masking task reflect general cognitive ability. International Journal of Psychophysiology 52, 23–36.

Võ, M.-L., Jacobs, A.M., Conrad, M., 2006. Crossvalidating the Berlin affective word list (BAWL). Behavior Research Methods 38 (4), 606–609.

Williamson, S., Harpur, T.J., Hare, R.D., 1991. Abnormal processing of affective words by psychopaths. Psychophysiology 28 (3), 260–273.

Windmann, S., Daum, I., Güntürkün, O., 2002. Dissociating prelexical and postlexical processing of affective information in the two hemispheres: effects of the stimulus presentation format. Brain and Language 80 (3), 269–286.