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RESEARCH ARTICLE

On ignoring words—exploring the neural signature of inhibition of affective words using ERPs

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Abstract

In the present study event-related potentials were used to shed further light on the neural signatures of active inhibition of the (affective) content of written words. Intentional inhibition was implemented by simply asking participants ($N=32$) to ignore single words that served as primes in an affective priming (AP) task. In AP, evaluations about a priori neutral targets typically tend to shift towards the valence of preceding primes, denoting an AP effect (APE). To create a plausible cover-context emphasizing the usefulness of word inhibition, participants were asked to avoid this shift, that is, to make unbiased target evaluations. Ignoring the prime words was suggested as the most efficient strategy to achieve this aim. Effective inhibition of the words' (affective) content, as suggested by a significant APE present for words processed without any further instruction, but not for ignored ones, affected multiple stages of processing. On the neuronal level, word inhibition was characterized by reduced early perceptual (left-lateralized word-specific N170), later attentional (parietal P300), and affective-semantic processing (reduced posterior semantic asymmetry). Furthermore, an additional recruitment of top-down inhibitory control processes, which was mirrored in increased amplitudes of medial-frontal negativity, showed to be critically involved in intentional word inhibition.

Keywords Word inhibition · ERPs · Perceptual, attentional and semantic processing · Posterior semantic asymmetry (PSA) · Executive control

Introduction

To (intentionally) direct capacity-limited attentional resources to a situation or an object of interest can alter the perceptual selection of information depending on current goals and task demands. The ability to do so allows to prioritize and respond to only those aspects of the environment that are selected as relevant from a multitude of distractors competing for the control of behaviour. Facilitated access of relevant information coinciding with a simultaneous downregulation of processing of irrelevant or unwanted content protects the controlled information processing system against overload and enables adaptive behaviour (Ruz et al. 2005a).

Considerable debate has centered on the fate of deliberately unattended information, that is, information regarded not worth to be processed because it is irrelevant or even disturbing (Driver 2001; Lavie and Tsal 1994; Ruz et al. 2005a). Given the everyday importance of written material, the extent of (semantic) processing of unattended words has emerged as a question of enduring interest and controversy (Kissler et al. 2009; McCarthy and Nobre 1993; Ruz et al. 2005a, b; Schindler and Kissler 2016).[1] Although lexical and semantic processing can occur in a rather automatic fashion (Navarrete et al. 2015; Ruz et al. 2005b; Walker et al. 2017), overall word processing turns out to be considerably affected by the allocation of selective processing resources (Driver 2001; Rees et al. 1999; Ruz et al. 2005a, b). This spans from basal perceptual (McCarthy and Nobre 1993), over attentional (Holcomb 1988; Kissler et al. 2009), to higher-level

[1] Note that given systematic differences in processing across the modalities, we will mainly focus on findings on written words, leaving aside other stimulus categories (e.g., pictures; see Bayer and Schacht 2014).

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controlled (semantic) processing (Kiefer and Martens 2010; McCarthy and Nobre 1993; Ruz et al. 2005b).

For one thing, the amount of processing resources allocated to a stimulus critically depends on how much capacity is freely available. Therefore, word processing can be easily affected by means of a parallel, resource-demanding task that detracts capacity-limited selective attention from presented words. Performing a task—e.g., responding to, count, or detect repetitions—on stimuli of a given category different from words (e.g., pictures), increases attention to these, henceforth "task-relevant", stimuli. As a consequence, the overall amount of processing resources freely available decreases. Hence, fewer resources are available for the processing of other, task-irrelevant stimuli (i.e., words), likely resulting in reduced processing of these very stimuli (Ruz et al. 2005b; Schindler and Kissler 2016). Making use of the principle of feature-specific attention allocation (FSAA; Everaert et al. 2016; Spruyt et al. 2012), the processing of the meaning of words can also be altered without neglecting the word stimulus as a whole (see e.g., the Stroop effect). To be specific, attention may be directed to a non-semantic stimulus dimension of the word (e.g., font, color, or size) or to differentiable semantic dimensions within a given word (e.g., valence vs. species; Everaert et al. 2016; Spruyt et al. 2007, 2009).[2]

The amount of processing resources allocated to a given stimulus (or a particular stimulus dimension) furthermore is likely to be affected by a persons' motivation and intentions. While, typically, attentional resources are actively assigned to information declared as relevant, to ensure sufficient encoding, usually no further effort is going to be made to process irrelevant content. As a consequence, information whose status is not further defined or which is declared as irrelevant might rather passively fall outside the focus of attention. Typically in experimental settings this type of information potentially interfering with the processing of relevant stimuli is provided by simultaneously presented distractor stimuli. However, there is another ecologically valid, yet only rarely investigated, type of situation where distractor stimuli do not appear simultaneously with relevant stimuli, but instead appear alone and hamper the processing of relevant stimuli presented in close temporal proximity. This succession of events allows for—and, what is more, necessitates—proactive inhibition of the distracting event especially if this is temporary predictable (see for instance the concept of attention in time; e.g., Coull and Nobre 1998). Constituting an active intentional process in the service of current goals or task demands, this goes beyond reduced processing caused by a mere passive depletion of attentional resources assigned to a stimulus (e.g., due to a parallel, resource-demanding task). To get back to the topic at hand—the fate of, or the extent of (semantic) processing of unattended words—this leads to the question of how processing may differ between standard processed words and words that are (pro)actively inhibited.

The most straightforward way to experimentally achieve intentional word inhibition might be to simply ask participants to try to ignore the presented words (see Walker et al. 2017). However, in doing so, participants' compliance to implement this strategic instruction needs to be ensured. That is, because based on previous experience they might suspect some fraudulent intent of the experimenter, such as a later surprise recognition test on the to-be-ignored words (see Anderson and Huddleston 2012). This may result in the disregard of the Ignore instruction, which runs counter to the manipulations' principle aim. Crucially, however, this type of noncompliant behaviour can be effectively prevented by embedding the instruction to ignore the words into a broader task context that convincingly emphasizes the usefulness of word inhibition to improve task performance, thereby strengthening the motivation to implement effective ignore-attempts.

The present study

In the present study we sought to systematically examine the fate of affective words that are actively ignored as per instruction. Exceeding mere behavioural results, we used the benefits of event-related potentials (ERPs) to extend the knowledge on the neural mechanisms related to visual word encoding in general and, to be more specific, the neural and temporal signature of active inhibition of their affective content.

As a plausible cover-context emphasizing the usefulness of word inhibition, we realized an affective priming (AP) paradigm. Participants made evaluative judgments about a priori neutral target ideographs preceded by affective prime words. After an initial phase of performing the standard task without specific instructions, they were made aware of the APE denoting a systematic shift of target evaluations towards the valence of the preceding primes. Participants were asked to henceforth try to avoid this shift by ignoring the primes, by simply looking through them (for further details see "Methods" section). Participants' ambition to perform successfully on the given task of making unbiased target evaluations was thought to induce sufficient motivation to implement this strategy of effective prime-word inhibition (see Degner 2009 for support for the general notion that prime-centered strategic instructions can effectively

[2] In general the efficiency of a parallel task in altering the processing of task-irrelevant stimuli (or stimulus dimensions) critically depends on a sufficiently high task load that approaches overall processing capacity. That is because perceptual processing, although being capacity-limited, proceeds automatically until it runs out of capacity (see Lavie and Tsal 1994).

reduce/increase the AP effect). As an additional benefit, the AP paradigm provides an inherent manipulation check, that is, a test of whether inhibition of the words' meaning was indeed effective. Ignoring the primes is likely to reduce the overall processing of word meaning, including the primes' emotional content. As a consequence, affective activation elicited by the primes, which is needed for an APE to occur, is likely to be attenuated (Everaert et al. 2016; Gibbons et al. 2018). Thus, a markedly reduced APE for ignored as compared to standard processed primes can serve as an indicator of effective word inhibition on the behavioural level. Note that this conceptualization focuses on processes of active inhibition rather than passive decay of task-irrelevant information. Given that primes are task-irrelevant also in the None condition, passive decay should also take place here. Therefore, all differences between the two conditions (i.e., standard processed and ignored words) can be referred to additional processes of active inhibition in the None condition.

On the neuronal level, we propose successful word inhibition to affect multiple processing stages, including early perceptual, attentional, and later affective-semantic processing (for a review on attention effects on ERPs see Luck et al. 2000). For one, as participants are given detailed instructions on ignoring the prime words right on from their onset, trying to implement this instruction is expected to trigger some kind of proactive inhibition that alters basal perceptual processing (see Luck et al. 2000). Attentional control can already operate at an early stage of processing, with increased sensory-evoked responses for attended information (Hillyard et al. 1998). Conversely, unattended or ignored/inhibited information should be subject to suppressed processing and concomitantly elicit smaller amplitudes of (rather early) ERP components associated with basal perceptual processing (see e.g., Hillyard et al. 1998; Luck 1995; Slagter et al. 2016). This might refer to parieto-occipital P1, an indicator of early perceptual processing of visual stimuli (Di Russo et al. 2002), sensitive to automatic, as well as intentional attention allocation (Bayer et al. 2012; Clark and Hillyard 1996; Hillyard and Anllo-Vento 1998; Luck et al. 2000; Smith et al. 2003). Larger amplitudes for attended as compared to unattended stimuli are thought to be due to an amplification of sensory information processing in extrastriatal areas of the visual cortex (Clark and Hillyard 1996; Di Russo et al. 2002; Hillyard and Anllo-Vento 1998; Luck et al. 2000). Efficiently ignoring the primes may reduce the overall amount of sensory information reaching the visual cortex, therefore resulting in reduced amplitudes. Furthermore, ignoring the primes may also affect amplitudes of fronto-central negativities in the N1 time range that already showed to be sensitive to task requirements and top-down attentional control (e.g., Potts et al. 2004; Vogel and Luck 2000; Waldhauser et al. 2012). Especially for words suppressed processing is likely to be mirrored in smaller amplitudes of left-lateralized occipito-temporal N170, providing a word-specific marker of low-level visuo-perceptual encoding (Bentin et al. 1999; Hauk and Pulvermüller 2004; Rabovsky et al. 2012; Simon et al. 2004). While N170 exhibits its larger amplitudes for words requiring active processing (Koppehele-Gossel et al. 2016) we suggest that instructing participants to top-down ignore the prime words will lead to reduced amplitudes.

It can be assumed that the processing of the words' affective information is not solely based on some kind of "pure", fast working emotional/affective processing, but more is likely to base on a more elaborate analysis of the words' semantics (see Blaison et al. 2012). Therefore, later-occurring markers mirroring these processes need to be focused. Successful word inhibition is further likely to dampen more controlled attentional processing as indicated by parietal P300-like deflections (Johnson Jr 1993; Kok 1997, 2001; Polich 2007) or the longer-lasting late positive potential (LPP; Schupp et al. 2006).

Both these ERP indices provide sensitive measures of the amount of attentional resources allocated to a stimulus, indicating the operation of a capacity-limited processing system (Kok 1997, 2001; Luck and Kappenman 2012; Moser et al. 2006; Polich 2007; Schupp et al. 2007). Findings of smaller amplitudes for unattended, less deeply processed words (Holcomb 1988; Kissler et al. 2009; Schindler and Kissler 2016) qualify the overall amplitudes of P300- and LPP-like deflections as sensitive markers of the amount of controlled processing resources assigned to the to-be-ignored words. Moreover late-range parietal positivities, even in response to words, already showed to be sensitive to task- and instruction effects (Kissler et al. 2009; Schindler and Kissler 2016; Waldhauser et al. 2012), with reduced amplitudes for suppressed stimuli (see e.g., Bergström et al. 2009; Mecklinger et al. 2009) emerging as a consequence of successfully applied strategic inhibition (Anderson 2004; Depue et al. 2007). Therefore, we assume active inhibition of the prime words to result in markedly reduced amplitudes of parietal positivities in the time range around P300.

As a neuronal marker of reduced affective-semantic processing of ignored words, we additionally considered the recently introduced posterior semantic asymmetry (PSA; Koppehele-Gossel et al. 2016, 2018b, c). This temporoparietal left–right ERP asymmetry index of negative polarity peaks around 300 ms into word processing and neatly tracks the degree of semantic activation from single written words, with larger amplitudes as depth of semantic encoding increases. Previous results support the PSA to provide a relatively pure measure of the effort made to encode a words' semantic content, without typifying a mere attention effect (Koppehele-Gossel et al. 2016, 2018b, c; see also Gibbons et al. 2014). As participants are prompted to ignore the prime words to avert being influenced by their affective content (that is, some type of semantic information), to be effective, inhibition needs to incorporate reduced processing of the words' semantics. Therefore, we expect that trying to ignore the prime words markedly reduces the overall effort made to encode their semantics, resulting in smaller amplitudes of the PSA.[3]

Exceeding a mere passive reduction of processing resources, (pro)actively ignoring/inhibiting the prime words is further likely to be accompanied by increased top-down control processes. Given the rather passive experimental situation that does not provide any distraction from the highly salient prime words, active recruitment of inhibitory resources should be needed to enable successful word inhibition. On a neuronal level this might be mirrored in larger amplitudes of the medial-frontal negativity (MFN) that is related to activity in anterior cingulate cortex (ACC), a brain area critically involved in monitoring and control processes (Botvinick et al. 2001, 2004; Gehring and Willoughby 2002; Johnson Jr et al. 2004; Waldhauser et al. 2012). Activation in prefrontal areas known to be important for executive control functions (such as the ACC) is associated with the active (suppressive) control of unwanted stimuli (Anderson 2004; Depue et al. 2007). ERPs related to activity in these regions, such as MFN, have been assumed to mirror the operation of an inhibitory network indexing cognitive control mechanisms (Bergström et al. 2009). Those ERPs have repeatedly been associated with strategic inhibitory control mechanisms eliciting larger amplitudes for stimuli (even words) when intentionally suppressed (see e.g., Bergström et al. 2009; Mecklinger et al. 2009; Waldhauser et al. 2012). Therefore, we predict MFN, related to an upregulation of cognitive control functions (Friedman 2012; Johnson Jr et al. 2004; Nessler et al. 2007), to increase if participants intentionally try to suppress the processing of the prime words (see also Gibbons et al. 2014).

To sum up, we expect that the intentional, active inhibition of the affective word content (implemented by a straightforward instruction to ignore the primes and supported by a reduced APE) will be accompanied by reduced perceptual, attentional, and controlled semantic processing. On the neuronal level, this is supposed to be reflected in reduced amplitudes of indicators of overall early perceptual processing like parieto-occipital P1 and left-lateralized word-specific N170, later attention-sensitive parietal P300- or LPP-like deflections, as well as semantics-specific left-lateralized PSA. Furthermore, successful word inhibition is expected to be accompanied by the recruitment of inhibitory control processes, which should evoke larger amplitudes of MFN, an index of executive control.

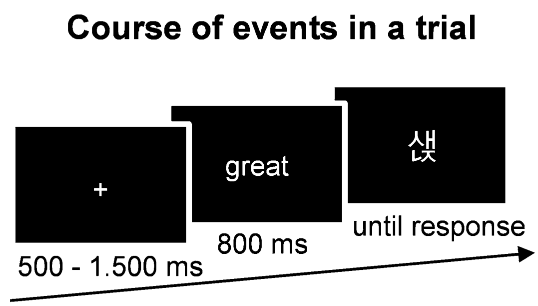

Fig. 1 Schematic illustration of the course of events in a trial of the AP cover task

Methods

Participants, stimuli, and procedure

32 volunteers [5 male, mean age 24 years (*SD* = 3.5)] participated in the study for partial course credit. All were naïve as to the purpose of the study, reported no history of neurological or psychiatric disorders and had normal or corrected-to-normal vision. All participants gave written informed consent. The study was approved by the local ethics committee.

90 German adjectives (30 negative, 30 neutral, 30 positive; Schwibbe et al. 1994) displayed in Arial, font size 24 served as the to-be-ignored words, that is, as primes in the AP cover-task.[4] 360 randomly selected Korean ideographs (size 6 × 6 cm) served as to-be-evaluated a priori neutral targets. Stimuli were shown white-on-black in the centre of a 23″ TFT monitor positioned 60 cm from the subject's eye. Upon arrival, participants were informed about the study which was introduced as an investigation of the neural correlates of the processing of abstract symbols. Then, EEG was prepared. In the course of the AP cover-task (see Fig. 1) participants rated their liking of a priori neutral targets (displayed until response) that were preceded by a 800-ms

[3] Note that in looking for a word-specific indicator of semantic processing, we did not expect any effects on centro-parietal N400 that is not specific to words. N400 is typically elicited by violations of context-induced expectations (Kutas and Federmeier 2011; Lau et al. 2013). Context violation, however, is not part of our design, presenting participants with single words.

[4] For the purpose of the AP cover task, words differed significantly in mean valence (all $t(58) > 26.80$, $p < .001$), but neither in word frequency nor word length (all $t(58) < 0.96$, $p > .34$). Emotional words were matched for arousal, $t(58) = 0.40$, $p = .70$, but were more arousing than neutral ones (both $ts > 9.30$, $ps < .001$). Note that for subsequent analyses, data were collapsed across word valence, as no differential effects were expected (see also Kissler et al. 2009). This assumption was verified by additional control analyses that ensured instruction effects on ERPs to indeed not depend on word valence (see Supplementary material 1).

negative, neutral or positive prime word. Target ratings were made on a six-point Likert-type scale ranging from 1/do not like at all to 6/like it very much, by pressing marked keys on a standard keyboard.

The AP cover-task consisted of two blocks containing 180 trials each.[5] In the first experimental block, 180 trials of the standard AP task were run, without any further instruction on how to handle the primes. Leading over to the main issue of interest, prior to the second experimental block detailed instructions carving out the usefulness of subsequent intentional inhibition of the prime words were displayed: first, participants were explicitly made aware of the APE. They were asked to henceforth try to avoid this systematic shift of target ratings towards the valence of the preceding primes, and instead strive to ensure unbiased target evaluations. Ignoring the prime words—by simply looking through them—was suggested as the most effective, therefore to be applied, strategy to achieve this aim. Participants' ambition to perform successfully on the given task was assumed to induce sufficient motivation to implement effective prime-word inhibition.

Participants were discouraged from closing their eyes or removing their gaze as this would become obvious in the EEG data, causing uselessness of their data for analyses.[6] They repeatedly were asked to take self-paced breaks both within as well as between the two experimental blocks. The experiment was programmed and run under Presentation 19.0 (Neurobehavioral Systems Inc., Berkeley, USA). It lasted for about 60 min.

EEG recording

EEG was recorded continuously from 60 active Ag/AgCl scalp electrodes of the international 10% system (Chatrian et al. 1988) using a digital ActiCap/BrainAmp system (Brain Products, Gilching, Germany). Data were sampled at 500 Hz and recorded with a bandpass filter from 0.1 to 70 Hz. Recording was online-referenced to FCz and re-referenced offline against algebraically linked mastoids (TP9, TP10). The ground was placed between AFz and AF4. Impedances were kept below 5 kΩ. Offline analyses were conducted using VisionAnalyzer 2 software (Brain Products, Gilching, Germany). Vertical and horizontal ocular correction was performed according to Gratton et al. (1983), based on electrodes located below and above the right eye and the outer left and right canthi, respectively. The continuous EEG was filtered (low pass: 40 Hz, 48 dB/octave attenuation; see e.g., Widmann et al. 2015) and segmented into − 100, 800 ms epochs relative to prime word onset. Epochs were baseline-corrected with respect to the − 100, 0 ms interval and screened for artifacts. Bad channels were replaced by the average of neighbouring channels. Epochs still containing amplitudes exceeding ± 100 µV were rejected. On average, the artifact-induced dropout of epochs was less than 5% for all participants and conditions with no significant differences between the instruction conditions, $t(31) = 1.832$, $p = .08$. For ERP analyses, epochs were averaged across prime word valence and participants.

Data analysis

Mean target ratings in the AP cover task were subjected to a 2 × 3 repeated measures ANOVA with factors instruction (none, ignore) and prime valence (negative, neutral, positive) and followed up by Bonferroni-corrected paired within-subject *t* tests (p_c indicate Bonferroni-corrected *p* values). Results of this analysis served as an inherent manipulation check of whether inhibition of the words' meaning was indeed effective (see "Introduction"). As derived above, we expected the effect of prime valence on target ratings to be clearly evident for standard processed prime words, but markedly reduced or even absent for ignored ones. Greenhouse–Geisser correction for violation of sphericity was applied where appropriate.

Identification of exact timing and topography of the ERP components of interest was guided by previous findings and determined by the empirically observed amplitude maximum of the grand-grand-averaged ERP waveform collapsed across all participants, instructions, and prime valences. Based on this principle, we quantified parieto-occipital P1 as the mean amplitude between 85 and 130 ms post prime onset, averaged over a seven-electrode away ranging from PO7 to O2 (for similar timing and topography, see e.g., Bayer et al. 2012; Scott et al. 2008). Word-specific N170 that showed a clear peak around 170 ms at lateral posterior electrodes was quantified as mean amplitude between 150 and 200 ms after prime-word onset at electrodes PO7 and PO8 (for a similar quantification of N170, see e.g., Bentin et al. 1999; Hauk and Pulvermüller 2004; Luck 2014). Centro-parietal P300 with a peak at electrode Pz was assessed between 230 and 380 ms after word onset (for similar timing and topography see e.g., Hruby and Marsalek 2002; Polich 2012). The PSA was

[5] Prime valence was balanced within blocks, with primes drawn randomly from a combined list of 30 negative, neutral, and positive adjectives each. After emptying the list, primes were replaced and drawn again. During the course of the experiment each prime word was presented four times. Target stimuli were drawn randomly and rated exactly once.

[6] We carefully monitored the recorded data during data acquisition to ensure that participants in fact adhered to the instruction. Furthermore ensuring that our ERP (between instruction) effects were not simply due to mere eye-movement artifacts a direct comparison of vEOG and hEOG channel activity for the duration of prime presentation (0–800 ms) between the None and the Ignore condition revealed no significant differences between conditions, both $t(31) < 1.13$, $p > .270$.

computed as the averaged difference of left-side minus right-side ERP activity of homologous temporoparietal electrodes (TP7–TP8, CP5–CP6, P7–P8, and P5–P6) between 230 and 380 ms after word onset. This exactly replicates the timing and topography of PSA as reported in Koppehele-Gossel et al. (2016, 2018b, c). Marking the additional recruitment of top-down control processes, MFN showed a clear overall amplitude maximum at medial frontal electrode Fz, where it was quantified as mean amplitude between 380 and 580 ms (for similar timing and topography, see e.g., Johnson Jr et al. 2004; Waldhauser et al. 2012). To test for potential effects of intentional word inhibition on mental processes assumed to be mirrored in the defined components of interest, mean amplitudes of P1, N170, P300, PSA, and MFN (quantified as described above) were subjected to paired two-tailed *t* tests with factor instruction (none, ignore).

Results

Behavioural data: the AP paradigm as an inherent manipulation check

Analyses of target ratings revealed a significant main effect of factor prime valence, $F(2,62)=4.62$, $p=.032$, $\varepsilon=0.61$, $\eta_p^2=.13$, denoting an overall APE (collapsed across instructions). Although the significant linear trend, $F(1,31)=5.08$, $p=.031$, $\eta_p^2=.14$, suggested target ratings to gradually increase with increasing positivity of the primes, subsequent *t* tests did not reveal any significant differences in target ratings depending on the primes' valence, all $t(31)<2.25$, all $p_c>.09$.

Crucially, the instruction × prime valence interaction was significant, too, $F(2,62)=5.60$, $p=.014$, $\varepsilon=0.70$, $\eta_p^2=.15$. Follow-up one-way ANOVAs separately for instructions revealed a significant main effect of prime valence in the None condition, $F(2,62)=6.04$, $p=.015$, $\varepsilon=0.59$, $\eta_p^2=.16$. It was driven by a significant linear trend, $F(1,31)=6.51$, $p=.016$, $\eta_p^2=.17$, suggesting target ratings to gradually increase with increasing positivity of the primes. Indeed, target ratings were more positive after positive as compared to negative, $t(31)=2.55$, $p_c=.05$, $d_z=0.3$, as well as neutral primes, $t(31)=2.62$, $p_c=.05$, $d_z=0.3$. The neutral–negative difference failed to reach significance, $t(31)=1.93$, $p_c=.19$. Conversely, and in line with our predictions, there was no effect of prime valence in the Ignore condition, $F(2,62)=0.27$, $p=.767$. Thus, while there was a significant APE for standard processed prime words, words intentionally inhibited did not exert any systematic influence on target ratings. This pattern of results supports the notion that inhibition of the prime words' meaning including their emotional content indeed was effective. Note that the Ignore condition always constituted the second experimental block. This was necessary because once participants are debriefed about the APE in the course of receiving the Ignore instruction, standard processing of the primes in a subsequent block will no longer be feasible. Crucially, given this, one might critically suspect the absence of an APE in the Ignore condition to be a mere habituation effect caused by increasing familiarity with the primes. However, to anticipate, results of additional analyses proved this concern to be unfounded. To further portion the time domain, we subdivided the 180 trials of both experimental blocks into two runs (first run and second run) each. A 2 × 2 repeated-measures ANOVA with factors instruction (none and ignore) and run (first run and second run) yielded a significant instruction effect on the APE that preserved despite a mere time on task effect. While the APE indeed decreased with increasing absolute time on task, this effect was clearly due to the observed instruction effect instead of a mere time-on-task/habituation effect. While there was a clear main effect of factor Instruction, $F(1,31)=6.78$, $p=.014$, $\eta_p^2=.18$, with a significantly reduced APE between the instructions, effects involving factor Run (not the main effect and nor interaction instruction × run) did not reach significance, both $F(1,31)<3.4$, $p>.08$, with no significant reductions of the APE within instructions (for further information as well as a graphical illustration see Supplementary material 2). Thus, this supports the notion that the absence of the APE in the Ignore condition indeed results from efficiently ignoring the prime words' emotional content, instead of being a mere time-on-task/habituation effect.

Instruction effects on ERPs

To test for the hypothesis that intentionally ignoring the primes affects multiple stages of processing, namely early perceptual, attentional, and later affective-semantic processing, as well as controlled inhibitory processes, we directly compared mean ERP amplitude for standard processed and to-be-ignored prime words by means of paired two-tailed *t* tests. To anticipate the results, in line with our predictions visual inspection of the ERP time course already indicated reduced overall depth of processing of ignored words (as mirrored in smaller amplitudes of ERPs related to perceptual, attentional, as well as semantic processing) to come along with an additional recruitment of top-down control processes (mirrored in larger amplitudes of MFN).

First, analyses of early attention-sensitive P1 did not yield any significant differences between ignored and standard processed words as there were no significant amplitude differences between the two instruction conditions, $t(31)=0.624$, $p=.537$. Conversely, word-specific N170 showed to be affected by the Ignore instruction: a

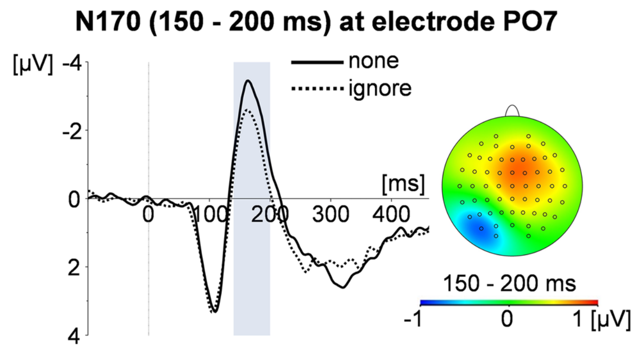

Fig. 2 Word induced N170 (150–200 ms) at left occipito-temporal electrode PO7 separated by instruction conditions. The map depicts the difference activity between standard-processed and ignored words

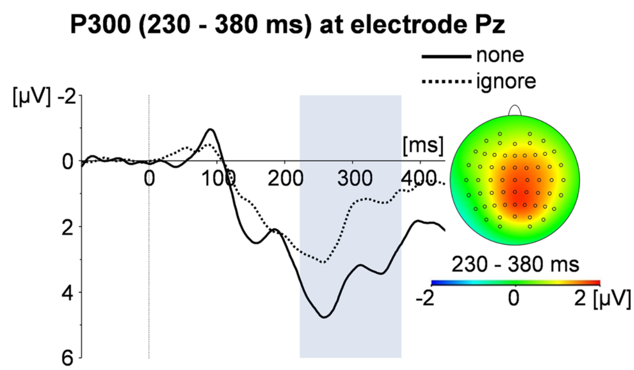

Fig. 3 Word induced P300 (230–380 ms) at centro-parietal electrode Pz separated by instruction conditions. The map depicts the difference activity between standard-processed and ignored words

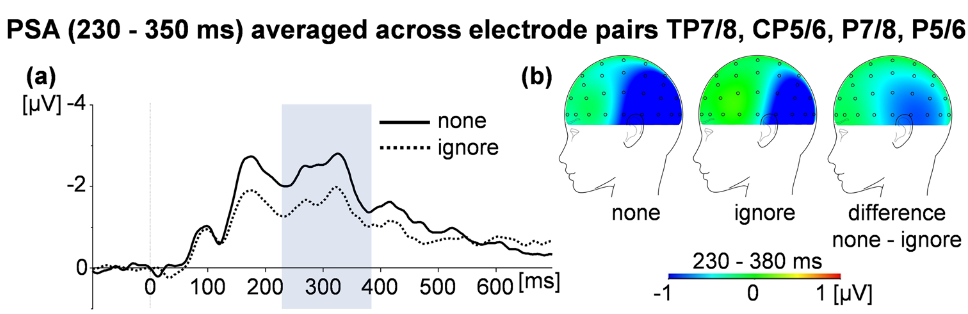

Fig. 4 **a** Word induced PSA (230–380 ms) quantified as the difference of left-side minus right-side activity, averaged across homologous temporoparietal electrode pairs TP7/8, CP5/6, P7/8, and P5/6, presented separately for the two instruction conditions. **b** Topographic distribution of the lateralized difference activity (left minus right) separated by instruction condition. The rightmost hemispheric map depicts the difference activity of the PSA amplitude between standard-processed (no instruction) and ignored words (ignore instruction)

first analysis of mean N170 amplitude revealed the characteristic strong left-lateralization, with larger amplitudes at PO7 as compared to its right-side homologue PO8, $t(31) = 6.80$, $p < .001$, $d_z = 1.2$. Therefore, subsequent analysis was performed for PO7. N170 was significantly smaller for ignored as compared to standard processed words, $t(31) = 2.77$, $p = .009$, $d_z = 0.5$. Although there were no instruction effects on early P1, this suggests the intentional inhibition of word processing to already operate at early stages of basal perceptual processing (see Fig. 2).

Also, the later-occurring parietal P300 showed to be significantly reduced for ignored words, $t(31) = 5.69$, $p < .001$, $d_z = 1.0$ (see Fig. 3). Extending basal perceptual processing, this indicates that also later stages of controlled attentive processing are affected by intentional inhibition.

As a more specific marker of reduced affective-semantic processing of ignored words, temporoparietal PSA also exhibited significantly smaller amplitudes for ignored as compared to standard processed words, $t(31) = 3.76$, $p = .001$, $d_z = 0.7$ (see Fig. 4).

Finally, we tested for the assumption that trying to effectively inhibit the words' processing does not only result in reduced depth of processing, but is additionally accompanied by increased top-down control processes. Supporting this, a paired two-tailed *t* test of mean *MFN* amplitude revealed larger amplitudes for ignored words, that is, words participants were asked to inhibit, $t(31) = 4.57$, $p < .001$, $d_z = 0.8$ (see Fig. 5).

As with the behavioural data, we ensued additional analyses to rule out the possibility that reduced amplitudes of ERP components of interest for ignored words are due to a mere habituation effect with increasing time on task. Therefore, as it was done with the behavioural data we further subdivided both experimental blocks (none and ignore) in two halves each and checked for mere time-on-task effects. As becomes obvious in Supplementary material 3, similar to the analyses performed for the APE the observed ERP effects overall did not arise from a mere time-on-task/habituation effect. Instead, they can be

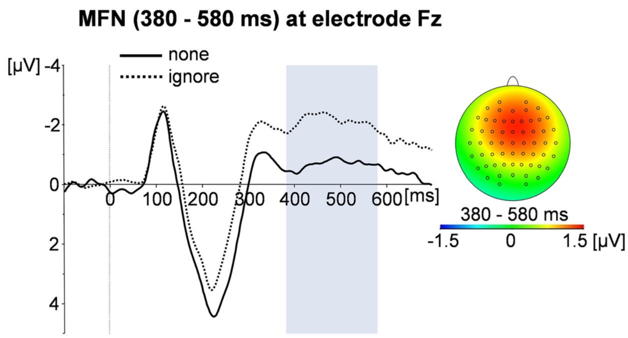

Fig. 5 Word induced MFN (380–580 ms) at fronto-central electrode Fz, denoting larger amplitudes for ignored as compared to standard-processed words. The map depicts the difference activity between standard-processed and ignored words

assumed to accrue from the observed instruction effect, that is, effective inhibition of to-be-ignored words but not, standard processed words.

Discussion

In the present study we examined the neural signature of active inhibition of the affective content of written words using the benefits of ERPs. Word inhibition was straightforwardly implemented by simply asking participants to ignore written words that served as primes in an AP cover-task. Successful word inhibition was accompanied by markedly reduced perceptual, attentional, as well as more controlled semantic processing. Furthermore it was characterized by an additional recruitment of frontally located top-down control mechanisms.

Providing an inherent manipulation check of the effectiveness of the inhibition of the words' (affective) meaning, the APE (that is, the systematic shift of target ratings depending on the valence of preceding primes), which was clearly evident for targets following standard processed words, was absent for to-be-ignored ones. Thus, we suggest intentionally ignoring the prime words reduced the overall processing of the words' meaning, or at least, to be more specific, their emotional content. As a consequence, prime-induced affective activation which is needed for an APE to occur is likely to be reduced, causing absence of the APE (Everaert et al. 2016; Gibbons et al. 2018).

Note that, at a side stage, our findings valuably contribute to the ongoing debate on the effects of depth of prime processing in the context of AP (e.g., Everaert et al. 2016; Gibbons et al. 2018; Hashimoto et al. 2012; Murphy and Zajonc 1993; Rotteveel et al. 2001; Rotteveel and Phaf 2004). They are well in line with a theoretical framework only recently proposed by Everaert et al. (2016; see also Gibbons et al. 2018), in which two types of processes are suggested to be necessary for an APE to occur: first, the prime affect needs to be processed to some extent, giving rise to more or less intense affective activation (type-1 processes). Second, this affective activation might then be transferred to the neutral target, thereby causing prime-congruent target evaluations (type-2 processes). While there is broad consensus on the involvement of type-2 processes of affect misattribution in AP (see e.g., Payne et al. 2005), up to now our knowledge on type-1 processes is much more limited. Our finding of the APE being absent for intentionally ignored prime words emphasises the importance of type-1 processes in AP: we propose that reduced depth of prime-word processing—as indicated by reduced amplitudes of ERPs reflecting multiple processing stages (see below)—including the encoding of the primes' emotional content, causes reduced prime-induced affective activation (i.e., type-1 processes). As it has been argued (Everaert et al. 2016; Gibbons et al. 2018), type-1 processes are logically necessary for an APE to occur. Therefore, the present finding of the absence of an APE in the Ignore condition with it being present in the standard condition can most parsimoniously be explained in terms of reduced type-1 processes of affective activation in the former condition.

The neural signature of intentional word inhibition: reduced depth of processing is supplemented by increased top-down inhibitory control

Asking participants to effectively ignore the presented prime words, on the neuronal level we found evidence for markedly reduced early perceptual, attentional, as well as later affective-semantic processing, with smaller amplitudes of N170, P300, and PSA for ignored versus standard processed words. Furthermore, larger amplitudes of MFN for ignored words point to an additional recruitment of higher-level inhibitory control resources in terms of a strategic component of increased top-down control processes in situations of proactive inhibition. This valuably extends and complements previous findings on the neural signature of reduced word processing caused by a rather passive depletion of attentional resources (for instance, due to a parallel task. See e.g., Kissler et al. 2009; McCarthy and Nobre 1993; Ruz et al. 2005b; Schindler and Kissler 2016).

Reduced amplitudes of word-specific N170 marking low-level visuo-perceptual encoding (e.g., Hauk and Pulvermüller 2004; Rabovsky et al. 2012) for ignored words suggest intentional inhibition to already operate at early stages of basal perceptual processing.This is well in line with previous findings that showed N1 to be sensitive to task requirements and top-down attentional control attempts(Potts et al. 2004; Vogel and Luck 2000; Waldhauser et al. 2012). On the contrary, however, Kissler et al. (2009) did not report any differential early basal processing (in the N1 range) for attended as compared to passively viewed words, with the latter being assumed to be less intensely processed. This divergence however may be due to task specifics. While increasing attention to words defined as task-relevant perhaps might not (consistently) affect early perceptual encoding, active inhibition of the words' semantic content in the present design might do: our detailed instructions to ignore the prime words right on from their onset likely have triggered processes of rather proactive inhibition, ending up in reduced basal perceptual encoding. Given the high salience of the (to-be-ignored) prime words, successful word inhibition in the given experimental context might even crucially depend on such an early attentional set, being established as a top-down bias already prior to stimulus presentation (see also Coull and Nobre 1998; Potts et al. 2004).

Marking more controlled processing stages, smaller amplitudes of parietal P300 for ignored words suggest intentional word inhibition to be accompanied by an overall reduced allocation of capacity-limited higher-level processing resources (e.g., Kok 1997, 2001; Luck and Kappenman 2012). This matches previous findings of parietal P300/LPP to be sensitive to task-/instruction effects (Kissler et al. 2009; Schindler and Kissler 2016; Waldhauser et al. 2012). It further nicely complements reports of larger P300/LPP amplitude for task-relevant, intentionally attended words, compared to task-irrelevant, unattended words (Kissler et al. 2009; Schindler and Kissler 2016). Taken together, controlled attentive word processing (as mirrored in P300-/LPP like deflections) turns out to be sensitive to top-down intentional control attempts in general: for one the processing of words declared as relevant is actively promoted by means of greater allocation of attentional resources (facilitation aspect of selection; Neill 1977; Neumann and DeSchepper 1992; Tipper and Cranston 1985), whereas, as a by-product, irrelevant words may rather passively fall outside the focus of attention (Kissler et al. 2009; Schindler and Kissler 2016; see also Everaert et al. 2016). On the other hand, providing some kind of protective mechanism, controlled processing resources can also be actively drawn away from stimuli not intended to be processed as they interfere with current goals or task demands (inhibition aspect of selection; Keele and Neill 1978; Li et al. 2017; Neill 1977; Neumann and DeSchepper 1992; Tipper and Cranston 1985).

Yielding fairly clear-cut evidence for reduced affective-semantic processing; intentionally ignored words elicited markedly smaller amplitudes of the PSA. This may trace back to an intentionally triggered top-down controlled strategic reduction of resources invested, that is, the general effort made to activate the words' meaning (Koppehele-Gossel et al. 2016, 2018b, c). Crucially, reduced processing of the words' semantics, especially its emotional content, is what is required for word inhibition to be effective in terms of enabling unbiased target evaluations: if the primes' emotional content/their valence information (which actually is a form of semantic information) is not processed (at all), it consequently cannot produce target evaluations consistent with the primes' valence. Notably, up to now attention-, task-, and depth-of-processing effects on ERP indicators more specifically related to semantic processing have been largely neglected or overseen. This may be due to the fact that the representation of semantics relies mainly on left-hemisphere temporal neural activity (Price 2012). Critically, ERP indices of left-lateralized semantic processes might not be easily visible in conventional unlateralized ERP waveforms, as they are masked by bilateral, most likely language-unspecific activity (Koppehele-Gossel et al. 2016; see also Luck 2014, for the overlap problem in ERPs). In being a lateralized difference measure, the PSA eliminates such non-language related activity probably reflecting general attentional processes (see also Luck 2014). Thereby it carves out more semantics-specific effects (Koppehele-Gossel et al. 2016, 2018c). In the present case this refers to processes related to the downregulation of semantic processing in the Ignore condition that are not obviously manifested in the raw ERP waveform. Notably, in the present study we were able to accurately replicate timing and topography of the PSA (Koppehele-Gossel et al. 2016, 2018b, c).[7] Extending previous results and confirming our hypotheses, the PSA emerged as a sensitive measure of intentional top-down inhibition of semantic processing. This further legitimates it as a useful, graphically easily accessible real-time tool that visualizes time course and magnitude of lateralized, specifically semantic processing of single words (see also Koppehele-Gossel et al. 2018a).

Finally, as it was expected we found larger amplitudes of late-range MFN associated with cognitive control functions (Friedman 2012; Johnson Jr et al. 2004; Nessler et al. 2007) for intentionally ignored words. This points to an active recruitment of inhibitory resources mirroring the involvement of more controlled, top-down driven processes in intentional inhibition. Given the rather simple experimental situation that does not provide any distraction from the highly salient prime words, active recruitment of top-down control processes is likely to be essential for word inhibition to be finally successful, at least in the present experimental design (see also Herbert et al. 2012, for related findings on picture processing; Waldhauser et al. 2012).

We should note that the present ERP correlates of word inhibition may be limited to situations in which proactive

[7] Although up to now reports of the PSA are limited to work of our research group, this replication of timing and topography is worth mentioning given the ongoing debate on reproducibility of major findings in psychological science, calling for replication studies (Makel et al. 2012; Maxwell et al. 2015; Open Science Collaboration, 2012, 2015).

inhibition can be achieved, that is, all stimuli uniformly can be inhibited right from their onset. They may not cover situations of reactive inhibition where, for example, a (nonpredictable) stimulus is preattentively identified as threatening/aversive and then, based on this assessment, prevented from entering higher levels of controlled attentional processing. In this respect, it is interesting to see that all our ERP effects of the Ignore instruction were not modulated by valence of the words (see Supplementary material 1), which is better in line with the proactive mechanisms intended by our experimental manipulation, rather than with reactive inhibition. This is because reactive inhibition should only be applied to affective but not to neutral words, because only affective prime words carry information that can affect target judgments. Our data, however, did not indicate any differences in ERP instruction effects between valent and neutral stimuli.

Further research suggestions and conclusion

Further research may take a closer look on whether the depth of processing of words depending on their—task-specifically defined—situational status (relevant, not defined/indefinite, irrelevant, or even interfering) perhaps also manifests in gradual modulations of ERPs sensitive to different stages of processing. Information explicitly declared as task relevant is likely to be intentionally attended to ensure sufficient encoding. As a consequence, depending on the total amount of capacity-limited processing resources available, irrelevant information whose status is not further specified/defined might rather passively fall outside the focus of attention. Again, even less effort is going to be made to process information explicitly declared as irrelevant. Finally, content obviously interfering with current goals and task demands, or information participants were explicitly asked to inhibit, should be processed least. Constituting a potential qualitative difference, additional top-down suppressive processes are likely to operate in this latter case.

With respect to time-on-task/habituation effects potentially contaminating the observed instruction effects on the APE and the ERP components of interest, one might criticize the repeated presentation of prime words (four times over the entire course of the experiment). Indeed, previous findings have shown that word-elicited ERPs are sensitive to repetition/habituation effects (see e.g., Renoult et al. 2012). Therefore although we were able to rule out the possibility that the observed instruction effects were mere time-on-task/habituation effects (see Supplementary material 2 and 3), future research on the ERP correlates of word inhibition should strive to avoid stimulus repetitions whenever feasible. This, however, would require a sufficiently large stimulus database (e.g., of at least 360 normed, highly valent German adjectives) which, to the best of our knowledge, is not yet available.

One might suspect the observed effects to not solely result from a successful implementation of the Ignore instruction per se but more, at least in parts, from a reduced amount of processing resources available due to the parallel task of ignoring the primes. Actually, the given paradigm cannot differentiate between these two potential explanations: if participants really try to follow the instruction, that is, provide resources for inhibition/the secondary task, they actually will be able to ignore the primes. Future research should try to shed further light on this aspect, for instance by comparing behavioural and ERP data between an ignore instruction condition and a condition implementing a resource-demanding parallel task with no further instructions with respect to the primes. Also effects of an alternative instruction on how to handle the primes, for instance, specifically attend to them, may provide a promising approach for future research: if the same behavioural and prime ERP effects are found in the ignore and the attend condition (both are secondary tasks), they will reflect general effects of the dual task/instruction. If, however, prime ERP amplitude reductions are only found in the ignore condition, these could be more confidently referred to a specific effect of ignoring the primes.

With respect to the AP paradigm which, one should note, in the present study merely served as a plausible cover context to increase participants' effort to ignore the prime words, some further interesting future suggestions should be mentioned. For instance, focusing on the characteristics of the prime words one could directly compare highly versus weakly valent (but not neutral) prime words. Despite the prime words' valence (differentiating between negative and positive), potential effects of their arousal, that is, the degree of activation associated with a stimulus (see e.g., Hinojosa et al. 2009) may be of particular interest. A systematic variation of the arousal dimension of the valent primes (note that as per definition neutral primes necessarily are non-arousing) may provide valuable insight into the processes functionally involved in AP: for one, stronger effects of high- than low-arousing valent primes would support the notion that the amount of prime elicited affective activation—assumed to increase with increasing arousal—is critical for an APE to occur (see Everaert et al. 2016; Gibbons et al. 2018; see also first paragraph of the discussion section; see Herring et al. 2015 for related findings in congruency based AP). Conversely, if AP is reduced for highly arousing valent primes compared to weakly arousing valent primes, this would argue in favor of affect misattribution to take place: high arousal may ease the binding of prime-induced affect to the primes, making affect misattribution and, hence, prime-congruent target evaluations less likely. Furthermore, although we clearly focused on instruction effects on the processing of the prime words, intentionally ignoring them may not solely affect prime processing but also the processing of the to-be-evaluated targets (for findings on the relevance of target processing in AP see e.g., Eder and Deutsch 2015; Gibbons et al. 2014, 2018; Hashimoto et al. 2012). Thus, a focus on target processing may provide an additional promising future approach that can help to further examine the processes involved in AP.

Using the benefits of ERPs we were able to shed further light on the fate of words that are actively ignored. This valuably enhances the knowledge on the neural mechanisms related to word encoding in general and, to be more specific, on the neural signature of intentional, active inhibition of the (affective) content of written words. Word inhibition was characterized by reduced early perceptual (left-lateralized occipital N170), later attentional (parietal P300), as well as affective-semantic (PSA) processing. Furthermore, an additional recruitment of top-down-driven inhibitory control processes (as mirrored in increased amplitudes of fronto-central MFN) showed to be crucially involved in intentional word inhibition.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee (Ethikkommission am Institut für Psychologie der Universität Bonn; Ethical committee, Department of Psychology, University of Bonn); ethical approval #15-08-10 and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study. The data and significant program code on which this paper is based are available from the corresponding author upon request.

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