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Reversed old/new effect for intentionally forgotten words: An ERP study of directed forgetting

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The present study investigated, using the item-method directed forgetting paradigm, whether successful intentional forgetting is reflected in brain activity, as measured by ERP. We sorted the EEG data into 4 experimental conditions based on the combination of memory instruction and behavioral outcome: TBF_F (to-be-forgotten and forgotten), TBF_R (to-be-forgotten but remembered), TBR_R (to-be-remembered and remembered, i.e. hits) and correct rejections (CR). TBR_R trials elicited a typical old/new effect (~500–750 ms poststimulus) over central and parietal regions. The TBF_F condition, however, elicited ERP that were more negative-going than ERP for CR (the reversed old/new effect). The latter may reflect the very effective inhibition of encoding and retrieval processes. This indicates that intentional processes leading to successful forgetting significantly influence brain activity.

1. Introduction

Forgetting can be viewed as a positive, adaptive strategy that prevents irrelevant or outdated information from interfering with current processing and it generally facilitates memory performance (Bjork, 1989). Selecting information to forget or disregard is often aided by explicit cues. In the item-method directed forgetting paradigm each stimulus (word) is followed by an instruction to remember (R) or to forget (F) and participants are asked to follow these cues (study phase). In the recognition test that follows, all words are re-presented, mixed with the same number of new words and subjects have to categorize each word as new or old, irrespective of previous instruction. F cues typically lead to poorer recognition memory for to-be-forgotten (TBF) items compared with to-be-remembered (TBR) items (MacLeod, 1998). This effect is referred to as the directed forgetting effect (Goernert et al., 2006). The F instruction may simply cease maintenance rehearsal, triggered after word presentation, and the TBF word decays passively in the absence of encoding effort. On the other hand, forgetting might involve active suppression (Hourihan and Taylor, 2006; Zacks et al., 1996).

Successful and unsuccessful R and F instructions are reflected in different patterns of brain activation (Wylie et al., 2008). Intentional forgetting depends on brain areas distinct from those involved in unintentional forgetting and intentional remembering (BA35, BA10/11 and BA10, BA21, BA31, BA34, BA35, respectively). Functional Magnetic Resonance Imaging (fMRI) results suggest that control processes mediated by the frontal lobes might be critical for successful forgetting. The results of an event-related potential (ERP) study support this notion (Paz-Caballero et al., 2004). The F cue elicited early enhanced positive activity in frontal and prefrontal areas, indicating strong activation of inhibitory processes. In an attempt to separate encoding effort from encoding success, Reber et al. (2002), argued that frontal regions (particularly the left inferior prefrontal cortex) might modulate processing of temporal regions (the middle temporal lobe) related to memory encoding. Ullsperger et al. (2000) found that correctly recognized TBR and TBF words resulted in qualitatively different patterns of the old/new effect, with TBF items showing less early frontal activity and the absence of the old/new effect at parietal sites. Items followed by F instruction seemed to become inhibited and less accessible and, therefore, more difficult to retrieve.

Neither of the aforementioned studies addressed the issue of whether inhibitory processes activated by the F instruction are more pronounced in a situation where TBF items are actually forgotten (TBF_F), and instead of being recognized as "old" (previously seen), they are categorized as new. In this study we investigated changes in brain activity related to the success of intentional forgetting.

2. Methods

2.1. Participants

Seventeen right-handed college and Ph.D. students (all women, mean age — 26.4) participated in the study. Handedness was confirmed with Edinburgh Inventory (Oldfield, 1971) and all participants

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were free of significant neurological dysfunction and had normal or corrected-to-normal vision. None of the participants had any previous experience of the task. All procedures were approved by Bioethics Committee of Warsaw University Medical School and the participants provided informed consent prior to the study.

Final analyses were conducted on the results of 14 subjects. Three subjects were disregarded based on behavioral outcomes: either because the number of TBF_F-type errors committed was too small, resulting in an insufficient number of EEG trials required for critical comparisons, or because the rate of TBR_F-type errors was too high (about 50%), suggesting that the subject's answers were given at random.

2.2. Stimuli

Stimuli were presented in central vision on a 19-in. FlexScan L767 EIZO LCD monitor. The set of test stimuli consisted of 160 neutral Polish nouns, 3–7 characters long. The number of words was equal in the studied and the new sets of stimuli. Moreover, the number of words was the same for both F and R conditions.

Words were written in uppercase characters, white on a black background. Their lexical frequency ranged from 50 to 172 every 500,000 (Kurcz et al., 1990). The complete set of words is listed in Appendix A.

Inquisit software was used for the presentation of visual stimuli and the measurement of the subjects' reaction times (Inquisit 1.33 Windows XP, 2004, Seattle, WA: Millisecond Software). The size of verbal stimuli ranged from 2.8×0.8 to 3.4×0.8°. Each stimulus was centered at the central fixation point, which was a small red circle (radius 0.2°).

2.3. Experimental procedure

Participants sat in an acoustically and electrically shielded dimly lit chamber at a distance of about 70 cm from the computer monitor. Responses were given by pressing keys on the response pad (Model B-830, Cedrus Corporation, San Pedro, USA). Participants responded using the index finger of the right hand.

The experiment was divided into two separate parts with a short break in between. The first part of the experiment (study phase) consisted of 80 trials and a single trial lasted 6000 ms starting with a fixation mark. After a foreperiod of 1000 ms, the stimulus was displayed for 250 ms. Then after a 1750 ms break, R or F instruction was presented for 250 ms. A set of forty different words was used in each of the two (R, F) experimental conditions. Prior to the study phase, participants were directed to follow the instruction to commit only TBR items to memory and to forget TBF items. The order of experimental trials was pseudo-random with the constraint of no more than three consecutive trials with the same type of instruction.

In the second part of the experiment (test phase), both the words presented in the first part (80 items) and new words (80 items) were displayed for a period of 250 ms. This resulted in a total number of 160 experimental trials, each 4000 ms long. The subjects' task was to decide – within 3000 ms starting from the stimulus onset – whether the word was new or had been presented during the first part of the experiment, irrespective of the R/F instruction. Again, the order of the stimuli presentation was pseudo-random with the constraint of no more than three consecutive trials with TBF/TBR stimuli and studied/unstudied stimuli.

2.4. ERP recordings

EEG data were recorded in the second part of the experiment, i.e., during the recognition test, from 11 derivations: F3, F4, C3, C4, Cz, P3, P4, Pz, O1, O2 and Oz, according to the 10/20 International System (Jasper, 1958) with Ag/AgCl GRASS scalp electrodes. All EEG channels were referenced to the linked mastoid. Electrode impedance was kept below 5 kΩ. The EEG signal was recorded using a GRASS NeuroData Acquistion amplifier (GRASS Technologies, West Warwick, USA) combined with a CED Power1401 interface (Cambridge Electronic Design, Cambridge, UK). The EEG was registered continuously at 1000 Hz sampling rate and analog-filtered in the 0.01–70 Hz frequency band. Spike 2 software for Windows (Cambridge Electronic Design, Cambridge, UK) was used in EEG acquisition. Subsequent data processing and analysis was performed using BESA 5.18 software (MEGIS Software, Munich, Germany). Data were band-pass filtered from 0.1 to 30 Hz (zero phase) off-line. Eye-blink artifacts were identified with a template-based method and corrected using the adaptive artifact correction method (Ille et al., 2002). Trials containing artifacts other than eye-blinks, identified as having voltage amplitudes greater than ±90 µV, were removed before averaging. Overall, 1.2% of trials was discarded because of artifacts. Stimulus synchronized epochs lasting from 100 ms before until 1000 ms after word onset were extracted for each subject and baseline corrected. ERP were classified on the basis of the subject's behavior into one of four subsets: TBR_R, TBF_R, TBF_F, and correct rejection (CR) trials. In general, there were not enough TBR_F trials for the averaging procedure to result in reliable ERP. In order to obtain grand-average ERP, the ERP of one type from each subject and each recording site were averaged.

3. Results

3.1. Behavioral data

Mean reaction times (RTs) and response rates for TBR_R (mean number of trials: 30.9, range: 21–39), TBF_R (mean number of trials: 23.6, range: 11–30), TBF_F words (mean number of trials: 16.4, range: 12–32) and correctly recognized new words (correct rejections, CR; mean number of trials: 74.3, range: 60–79) are presented in Fig. 1. Repeated measures MANOVA with the "condition" factor (TBR_R,

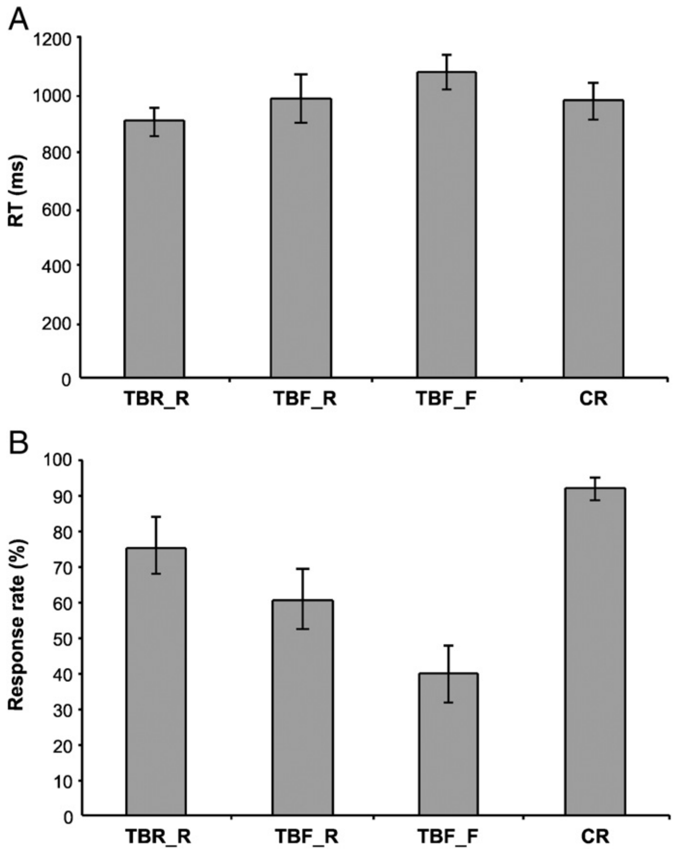

Fig. 1. Mean reaction times (A) and response rates (B) for all experimental conditions. Error bars represent ±SD.

TBF_R, TBF_F, CR) was performed on mean RTs. This revealed the statistical significance of the "condition" factor ($F(3,11)=8.61$, $p<.005$). Participants responded faster to TBR_R items than to TBF_R ($p<.005$), TBF_F ($p<.001$) and correctly rejected new items ($p<.05$), as shown by pair-wise comparisons. In addition, reactions to TBF_R words were significantly faster than those to TBF_F ($p<.005$). Moreover, RTs to TBF_F items were also slower than RTs to correctly rejected new items ($p<.05$). Thus, correct retrieval of TBR words was associated with much shorter RTs than correct retrieval of TBF words. On the other hand, responses to TBF_F items were the slowest among all analyzed RTs.

Recognition rates for correct responses were analyzed using repeated measures MANOVA with the "condition" factor (TBR_R, TBF_R, CR). The main factor was significant ($F(2,12)=17.267$, $p<.001$). Additional analyses contrasting correct responses to TBR and TBF words revealed that the recognition rate for TBR words was significantly ($p<.005$) higher than that for TBF words, clearly indicating the effectiveness of F/R instruction.

3.2. Event-related potentials

The numbers of EEG segments averaged to obtain ERPs for of the four experimental conditions were following: TBR_R — mean number of trials: 30.5, range: 21–39, TBF_R — mean number of trials: 22.5, range: 11–30, TBF_F words — mean number of trials: 16.3, range: 12–31 and CR — mean number of trials: 74.3, range: 60–79). For statistical analyses, a latency window of interest was defined as ~500–750 ms poststimulus. The component was defined as the largest deflection in a predefined time window within the ERP response, averaged across subjects and conditions. The grand-average ERP elicited in the recognition phase by studied and unstudied items are presented in Fig. 2A. For illustrative purposes, differential potentials, i.e., the differences between the ERP for TBR_R, TBF_R, TBF_F conditions and the ERP for CR were calculated and they are shown in Fig. 2B.

Raw ERPs for each of the four experimental conditions (TBR_R, TBF_R, TBF_F and CR) were analyzed in the time window 500–750 ms. We were interested to see whether the TBR_R and TBF_R conditions resulted in a reliable and significant old/new effect and whether the TBF_F condition yielded a significantly different pattern of results, as suggested by visual inspection of Fig. 2A and B. Therefore, repeated measures MANOVA was performed with the following factors: "condition" (4 levels: TBR_R, TBF_R, TBF_F, CR), "region" (3 levels: left hemisphere, midline, right hemisphere) and "electrode site" (3 levels: C, P, O). This demonstrated a significant "condition"×"region" interaction ($F(6,8)=4.04$, $p<.05$) while other factors and their interactions were insignificant. The left hemisphere was the only region in which the four experimental conditions yielded significant differences ($F(3,11)=4.39$, $p<.05$), whereas for the right hemisphere and the midline region the "condition" factor did not reach the level of statistical significance. Therefore, only ERP recorded in the left hemisphere were analyzed further. A repeated measures MANOVA with "condition" factor (4 levels: TBR_R, TBF_R, TBF_F, CR), and "electrode site" factor (3 levels: C, P, O) demonstrated the statistical significance of the "condition"×"electrode site" interaction ($F(6,8)=4.04$, $p<.005$) indicating that the four experimental conditions differed for some, but not all, recording sites. Significant differences between conditions were present in central and parietal recordings ($F(3,11)=6.74$, $p<.005$ and $F(3,11)=5.89$, $p<.05$, respectively). Pair-wise comparisons revealed that ERP for TBR_R words statistically differed from ERP for CR in both central ($p<.001$) and parietal ($p<.001$) recordings: ERP for TBR_R were more positive-going than ERP for CR (i.e., the old/new effect). Interestingly, ERP for TBF_F stimuli were more negative-going in comparison to ERP for CR ($p<.05$ and $p<.005$, for central and parietal sites, respectively). We have named this phenomenon the reversed old/new effect. Topographical distributions of the old/new effect and the reversed old/new effect are presented in Fig. 2C.

ERP for TBF_R words did not differ from ERP for correctly recognized new words. In other words, no old/new effect was observed for TBF_R stimuli at either the parietal or central recordings sites.

4. Discussion

Forgetting is often viewed as memory failure (Schacter, 1999) and it has been hypothesized to result from various processes including interrupted consolidation, passive decay, interference and retrieval failure. In contrast, intentional forgetting may be thought of as an adaptive memory function that helps to reduce interference in the processing and retrieval of relevant information (Wylie et al., 2008).

In this study we aimed to identify changes in brain activity – as revealed by ERP – related to the successful and unsuccessful retrieval of words that were intended to be either forgotten or remembered. F and R instructions proved to work efficiently: recognition rate was significantly higher for TBR than TBF words. The pattern of electrophysiological results was determined both by instruction type and memory performance. We observed a typical old/new effect for TBR words that were correctly recognized. However, the old/new effect was absent for TBF words that were – despite the F instruction – successfully retrieved (i.e., TBF_R items). Interestingly, actually forgotten TBF words yielded ERPs that were more negative-going in comparison to ERPs for correctly rejected new items (the reversed old/new effect). Thus, our findings may be viewed as a kind of continuum with the old/new effect for TBR_R items on one side, the reversed old/new effect for TBF_F items on the other side and no effect for TBF_R items in between.

ERP studies of recognition memory have consistently reported a left parietal old/new effect that differentiates correctly recognized old and new stimuli (e.g. Opitz and Cornell, 2006; Vilberg et al., 2006; for review, Friedman and Johnson, 2000). The parietal old/new effect is directly related to conscious recollection of test items (Curran and Friedman, 2004; Wilding and Rugg, 1997). This effect indexes the amount of information recollected in response to a test item and is modulated according to the level of episodic detail elicited by the item. It demonstrates greater amplitude when elicited by test items associated with full, relative to partial, recollection (Vilberg et al., 2006). In addition, evidence from animal studies (Aggleton and Brown, 1999), studies on amnesic patients (Holdstock et al., 2002) and neurocomputational models (Norman and O'Reilly, 2003) suggests that the process of recollection, reflected in ERP as the parietal old/new effect, is specifically dependent on the hippocampus.

Our results for TBF_R words, though based not on a very high number of EEG segments, are in line with the findings of Ullsperger et al. (2000), who also reported the absence of the parietal old/new effect for correctly retrieved TBF words. It should be stressed that item-method forgetting paradigm, used in their and our study, is based on the direct assumption that F instruction causes inhibition of normal encoding processes. When subject views a word (in the study phase) he/she does not know in advance which instruction will follow. Thus, the best strategy is to rehearse this word and initiate encoding. This encoding is stopped at the time of presentation of F instruction. In other words, subjects react to F instruction by blocking the processing of the material associated with such an instruction. Paz-Caballero et al. (2004) observed early frontal and prefrontal activity, related specifically to the F instruction. That finding could reflect inhibitory processes activated by F instruction. It was suggested that frontal and prefrontal activity may serve to limit parietal activity, which is otherwise associated with maintaining the item representation (Wylie et al., 2008). This, to some extent, may explain the absence of an old/new effect for TBF_R words.

Nevertheless, mechanisms proposed to account for directed forgetting effects include not only differential encoding of TBF and TBR items but also repression-like process at the time of retrieval that prevents TBF items from being recovered (Anderson and Neely, 1996; Geiselman and Bagheri, 1985; Zacks and Hasher, 1994). However, in case of TBF_R items, F instruction was not very effective

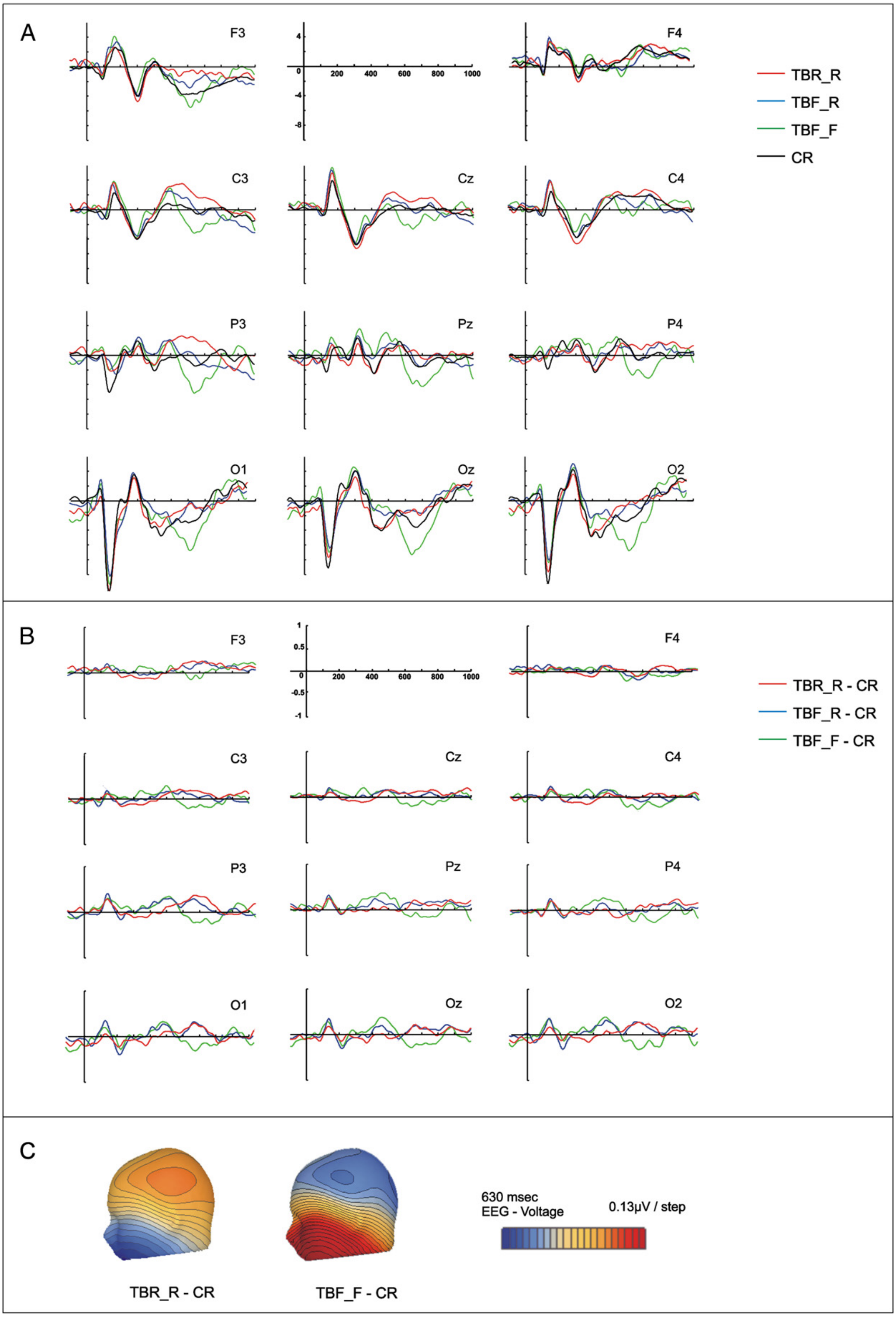

Fig. 2. Grand-average ERP for four experimental conditions (A). Differential ERP for three comparisons: TBR_R–CR, TBF_R–CR, TBF_F–CR (B). Topographical distribution of brain activity for TBR_R–CR (left) and TBF_F–CR (right) comparisons (C).

as indicated by the behavioral results: subjects were able to properly retrieve those items. Assuming that encoding processes were similar for all TBF items, evidence for the involvement of retrieval inhibition in directed forgetting effects comes from comparing ERPs for TBF_R and TBF_F items. In the analyzed time window, amplitudes of ERPs for TBF_R words were higher than amplitudes of TBF_F words. It might be expected that larger retrieval effort necessary to release TBF items from inhibition would be reflected in higher activation of structures involved in retrieval processes. Successful forgetting (TBF_F), on the other hand, may result either exclusively from successful inhibition of encoding processes, triggered by F instruction or from inhibition of both encoding and retrieval processes. Altogether, these inhibitory influences may lead to the reversed old/new effect for TBF_F stimuli.

One may claim that the effectiveness of F instruction may also be viewed in the light of attentional mechanisms engaged to expunge TBF words from the memory and to prevent their reactivation (Zacks et al., 1996). Zacks and coworkers argued that attentional inhibition may have the function of preventing the return of attention to a previously rejected item, whether that item is an external stimulus, event or even a thought. Hence, when the processes triggered by F instruction win the race against the intention to remember, it may be so because F instruction activates attentional control mechanisms. Thus, the reported here the reversed old/new effect may also reflect some late effects of such attention inhibition.

Supplementary interpretation of the reversed old/new effect comes from a recent ERP study on recollection and familiarity (Woodruff et al., 2006). ERP were classified on the basis of subjects' responses related to their confidence that test items were old or new, irrespective of recollective details. Woodruff et al. (2006) reported that ERP for unconfident old stimuli were more negative-going than ERP for confident new, confident old and unconfident new stimuli. Therefore, an alternative partial explanation of our reversed old/new effect, observed for TBF_F items, may be the subjects' lack of confidence about the familiarity of the stimuli presented previously at the study phase of the experiment and followed by F instruction. This explanation may also be supported by our behavioral results. Correlation between RT and response confidence is well documented elsewhere (Murdoch, 1974; Jacobs et al., 2006). Fast responses are expected when subjects are confident that they had previously seen the stimulus (hits) or, inversely, when subjects are confident that they had not seen the stimulus (correct rejections). The pattern of our RT results is in agreement with this notion. RT for TBF_F words were the slowest of all conditions, probably reflecting the lack of subjects' confidence whether a TBF_F item is old or new. However, it is not possible to separate the lack of subjects' confidence from two other factors that might contribute to longer RTs for successfully forgotten words. TBF_F words might be thought of as items incorrectly categorized by subjects as new words and RT of any incorrect response is longer than RT of the correct one (Jacobs et al., 2006). The second factor which might be responsible for significant slowing subjects' reaction is retrieval inhibition.

There are two reasons to claim that our reversed old/new effect is not related to the late, posteriorly distributed negative-going slow wave (late posterior negativity — LPN), frequently found in studies of episodic memory (Johansson and Mecklinger, 2003). Firstly because all reported ERP effects (the typical old/new effect and the reversed one) were observed in the same time window (~500–750 ms poststimulus). LPN, however, starts around 1000 ms poststimulus, i.e., it peaks after the parietal old/new effect (Curran et al., 2007). Secondly, LPN manifest itself as a greater negativity to old then new items which is not the case either for TBR_R or TBF_R items in our study.

In summary, the classical old/new effect might be viewed as an electrophysiological marker of successful encoding, storage and retrieval of studied information. The reversed old/new effect, on the other hand, seems to reflect intentional and effective inhibition, leading to exclusion from memory these items that were supposed to be forgotten and were actually forgotten. However, on the basis of our present findings it is not possible to determine which stage of information processing was inhibited: encoding, retrieval or both.

It would be interesting to investigate whether forgotten – but not intentionally – items, i.e., stimuli that were supposed to be remembered but were forgotten (TBR_F), elicit ERP similar or dissimilar to TBF_F items. Comparison of ERPs for intentionally and incidentally forgotten items may shed more light on the reported here ERPs effects and their interpretations because – in contrast to intentional forgetting – unintentional forgetting does not include inhibition of encoding but is just a memory failure.

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Appendix A

List of Polish words used in the experiment and their translation to English

TBR		TBF		NEW		NEW	
KWADRAT	Square	BRZEG	Shore	ARTYKUŁ	Article	WIEDZA	Knowledge
FOTEL	Armchair	CZAJNIK	Kettle	AUTOBUS	Bus	WIĘŹ	Attachment
GAZETA	Newspaper	DROGA	Road	CHMURA	Cloud	WYJĄTEK	Exception
OGNISKO	Campfire	DRUKARZ	Printer	TEATR	Theater	ZACHÓD	West
GROCH	Pea	EKRAN	Screen	DZIECKO	Child	ŻAGLE	Sails
KUBEK	Mug	KASZA	Groats	FLAGA	Flag	ŻYCIE	Life
LAMPA	Lamp	KŁADKA	Footbridge	GAŁĄŹ	Branch	DOM	House
WAZON	Vase	KOMIKS	Comics	TEMAT	Topic	FILM	Movie
NATURA	Nature	KRAJ	Country	KLASA	Class	GOLF	Golf
OBRAZ	Picture	KROWA	Cow	SEN	Dream	PIEŚŃ	Song
OCEAN	Ocean	LOS	Fate	KOLARZ	Cyclist	KINO	Cinema
TRAWNIK	Lawn	MYŚL	Thought	KOMÓRKA	Cell	KIŚĆ	Bunch
CHODNIK	Pavement	PAPIER	Paper	ZAWÓD	Job	GIEŁDA	Stock
PUDŁO	Box	PIÓRNIK	Pencil box	KORYTO	Trough	KOSMOS	Space
ROWER	Bicycle	PIÓRO	Pen	KOSZYK	Basket	KRESKA	Line
SAD	Orchard	MUZEUM	Museum	UBRANIE	Clothes	LAS	Forest
SZAFA	Wardrobe	PODRÓŻ	Trip	KRZEW	Bush	ŚWIECA	Candle
TORBA	Bag	RZEKA	River	DYWAN	Carpet	MĄDROŚĆ	Wisdom
WYSPA	Island	LITERA	Letter	ŁĄKA	Meadow	METRO	Underground
TWARZ	Face	ZASŁONA	Curtain	NÓŻ	Knife	OKULARY	Glasses
POSIŁEK	Meal	ZATOKA	Gulf	MIOTŁA	Broom	PANEL	Panel
KARTKA	Page	DOLINA	Valley	MOTOR	Motorcycle	PIĘTRO	Storey

(continued on next page)

Appendix A (*continued*)

TBR		TBF		NEW		NEW	
SUFIT	Ceiling	JEZIORO	Lake	WĄWÓZ	Gorge	PLECAK	Backpack
KURTKA	Jacket	KOMIN	Chimney	NOWOŚĆ	News	PŁOT	Fence
BIURKO	Desk	KONTUR	Outline	NAMIOT	Tent	POMOC	Aid
DYNIA	Pumpkin	KSIĄŻKA	Book	KIMONO	Kimono	JABŁKO	Apple
FASOLA	Bean	LINIJKA	Ruler	PARKIET	Parquet	POZYCJA	Position
GÓRA	Mountain	PRALKA	Washer	WÓZEK	Cart	SKLEP	Shop
ZEGAR	Clock	PLAŻA	Beach	RAKIETA	Rocket	TANGO	Tango
JAGODA	Berry	POCIĄG	Train	STRUNA	String	SZKOŁA	School
MORZE	Sea	PODKŁAD	Foundation	SAMOLOT	Airplane	TENIS	Tennis
GITARA	Guitar	STÓŁ	Table	KRASNAL	Dwarf	OKNO	Window
ŁYŻKA	Spoon	ŚLIWKA	Plum	PIASEK	Sand	UCZEŃ	Student
PODŁOGA	Floor	TORY	Train tracks	STAN	State	PASEK	Belt
WIADUKT	Overpass	ZESZYT	Notebook	SZKŁO	Glass	WIADRO	Bucket
RYNEK	Market	BLAT	Worktop	BUTELKA	Bottle	WŁOSY	Hair
PORANEK	Morning	CZYN	Deed	SZOSA	Highway	NAUKA	Science
TALERZ	Plate	KĄT	Angle	TĘCZA	Rainbow	WZÓR	Pattern
KOC	Blanket	MURARZ	Bricklayer	TRAMWAJ	Tram	ZABAWKA	Toy
DOMINO	Domino	OKŁADKA	Cover	KLEPKA	Tile	ZAKUPY	Shopping

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