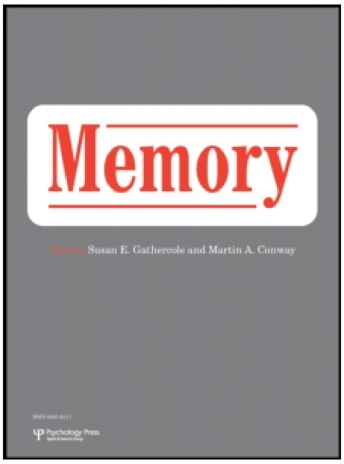

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The focus of attention in working memory: Evidence from a word updating task

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The focus of attention in working memory: Evidence from a word updating task

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Three experiments examined the cognitive costs of item switching within working memory with a novel word updating task, thereby extending previous research to the field of linguistic stimuli and linguistic-graphemic updating operations. In Experiments 1 and 2 costs for switching between working memory items were evident on the word level, and they increased with an increasing word set size (Experiment 2). In contrast, a surprisingly similar switch effect on the level of letters was not affected by word set size (Experiment 2). Experiment 3 showed that this effect is not simply based on the need for re-orienting visual spatial attention. To account for the overall picture of results, a recursive model of attentional foci is proposed. Moreover, individual working memory span appears to be associated with the accuracy of item switching, but not with its speed.

Keywords: Working memory; Attention; Focus switching; Word recognition.

In order to succeed on a variety of tasks we need to maintain small amounts of information over a short period of time. The idea of such a short-term store (with limited capacity) dates back to the 1950s (e.g., Broadbent, 1958); however, during the subsequent decades the shortcomings of this passive concept of storage were recognised. Hence, in their seminal work, Baddeley and Hitch (1974) conceptualised the ability to store information for short durations *and* to allow cognitive processes to manipulate and alter this information within the framework of *working memory* (for recent reviews see Baddeley, 2000, 2007). According to these authors working memory is a separate functional structure between sensory and long-term memory comprising (at least) three components: The central executive to perform tasks such as retrieving information from long-term memory or directing information within working memory, and two modality-specific storage devices referred to as the phonological loop and the visuo-spatial sketchpad. Later, the episodic buffer was added as a fourth component (Baddeley, 2000). Alternatively, more recent conceptualisations describe working memory as a part of long-term memory that receives particular activation. Among the most influential models of this kind is the "embedded processes model" (Cowan, 1988, 1997) sketching working memory as a preferentially accessible part of long-term memory. Crucially, this activation is considered general across domains, thus incorporating the modality-specific slave systems mentioned above (Baddeley, 2000, 2007; Baddeley & Hitch, 1974). Located within this working memory, the "focus of attention" holds those (approximately) four items that are accessible for cognitive operations at any time (= "4 ± 1-items focus of attention"; for details see Cowan, 2001, 2005). However, there is ample evidence from various experimental paradigms that at any time only one item is available as the

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target of cognitive processes (= "1-item focus of attention"; Garavan, 1998; McElree, 2001; McElree & Dosher, 1989; Oberauer, 2002). This assumption is supported by the observation that applying one single cognitive operation to the same working memory item twice in direct succession allows for faster processing than applying the same cognitive operation to two different items in succession (e.g., Garavan, 1998). In the latter case it is commonly assumed that a new target item had to be retrieved into the focus of attention first (= item switching). The observed RT difference between item repetitions and item switches is referred to as item switch costs. (The typical paradigms that have been used to assess item switch costs will be reviewed below.) In most everyday tasks (but also in many laboratory tasks) only rarely if ever is a single working memory item manipulated again and again for a longer period of time. Hence it is reasonable to assume that we often need to switch between items to make them accessible for cognitive operations. Clearly, resolving the question of the focus of attention's size is important and helps in elaborating current theories of working memory.

An attempt to incorporate both the 4 ± 1-item focus of attention and the 1-item focus of attention is the "concentric model" (Oberauer, 2002), which describes both assumptions as referring to "two different functional states of information in working memory" (p. 412): Some long-term memory representations are in an activated state and a subset of these is stored in the "region of direct access" (resembling the focus of attention in Cowan's model). Finally, the focus of attention in the concentric model comprises only the "one chunk that is actually selected as the object of the next cognitive operation" (Oberauer, 2002, p. 412). Only objects within the region of direct access can directly be retrieved into the focus of attention and can therefore interfere with item switching. Thus the selection of new objects becomes more difficult with larger memory loads, i.e., with more objects in the area of direct access. This assumption was supported by differential effects of memory load inside and outside the region of direct access: Switch costs increase with larger numbers of items within (Oberauer, 2002; see also Janczyk, Wienrich & Kunde, 2008, Experiment 2), but not outside the region of direct access, i.e., when they are presumably stored in the activated part of long-term memory (Oberauer, 2002; Oberauer & Göthe, 2006; see also Kessler & Meiran, 2006, Experiment 4). The experiments we report on here are based on this model and make use of the working memory updating paradigm. Therefore we continue with a brief review of variants of this paradigm.

ITEM SWITCHING WITHIN WORKING MEMORY AND ITEM SWITCH COSTS

As mentioned earlier, item switch costs are often interpreted as evidence for a 1-item focus of attention: We should not observe item switch costs if all relevant items were already inside the focus of attention. To date, item switch costs were reported from a variety of tasks. The majority of these tasks can be characterised as *working memory updating tasks* where participants initially establish various items in working memory and then update item characteristics according to cues presented while progressing through a trial. The most often employed task is the *counter updating task* (Garavan, 1998) where participants are to count the occurrences of individual instances of different (geometrical) objects. Each category is usually mapped to one counter, thus if two different object categories are used, participants need to track and update two counters concurrently. The final values are probed after a varying number of items. An illustration is given in Figure 1a. The participants know that objects of two different categories can occur, and need to establish two counters as working memory items. Having started a trial, the first object (a square) appears on the screen, prompting the participant to update the respective counter ("one square, zero circles"). Immediately after updating the counter, pressing the space bar initiates the onset of the next item (thus a self-paced progression): either another square (= repetition item: "two squares, zero circles") or a circle (= switch item: "one square, one circle"). The elapsed time from the object onset to the space bar press is recorded as the reaction time (= RT). Item switch costs are evident in the observation that RTs to repetition items are reliably shorter than RTs to switch items (e.g., Garavan, 1998; Gehring, Bryck, Jonides, Albin & Badre, 2003; Janczyk et al., 2008; Kessler & Meiran, 2006; Unsworth & Engle, 2008). Garavan (1998) initially argued that we can only attend one specific item in working memory. Upon the necessity to attend a different item, the need to re-focus attention yields the longer RTs to switch items. The difference in RTs presumably reflects the associated cognitive costs of item switching. In addition to this original interpretation, more recent research demonstrated small contributions from low-level (perceptual) priming processes (Gehring et al., 2003; Li et al., 2006) speeding up responses to repetition items and response requirements (Janczyk & Kunde, 2010). During the last years various variants of this original task have been used (e.g., Bao, Li, Chen, & Zhang, 2006; Janczyk et al., 2008; Li et al., 2006; Unsworth & Engle, 2008).

This basic paradigm has been extended using different working memory materials or updating operations. For example, *spatial updating tasks* (see Figure 1b) investigate whether item switch costs generalise to the spatial domain (Kübler, Murphy, Kaufman, Stein, & Garavan, 2003; Oberauer & Kliegl, 2006, Experiment 2). In *arithmetic memory updating tasks* (Salthouse, Babcock, & Shaw, 1991) participants typically memorise a set of starting numbers and then apply arithmetic operations to the current values (see Figure 1c). Moreover, several working memory updating tasks were combined (e.g., Kübler et al., 2003; Bao, Li & Zhang, 2007) such that, for example, participants update one counter and one spatial position at the same time. Here too, reliable cross-modality switch costs are observable and suggest a supramodal attentional limitation. In other words, all modalities investigated thus far appear to draw on a common resource (e.g., Bao et al., 2007; Cowan, 2005; Oberauer & Göthe, 2006; Oberauer & Kliegl, 2006), which yields the expectation to observe similar effects with stimuli from still different modalities. Subsequently, this assumption will be examined for verbal stimuli.

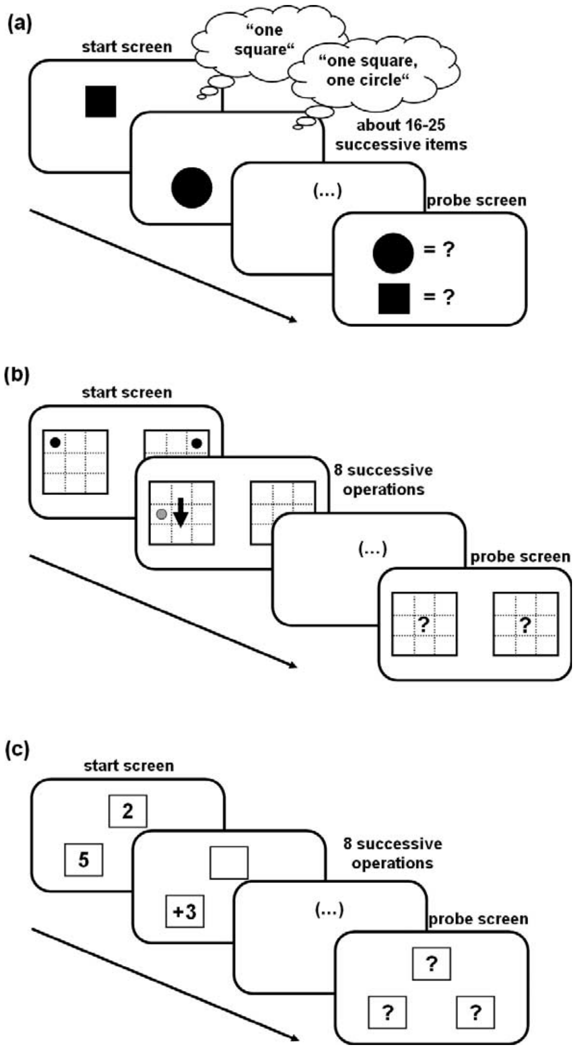

Figure 1. Examples of several working memory updating tasks: (a) counter updating task, (b) spatial updating task, and (c) arithmetic memory updating task. (See text for further explanations.)

USING VERBAL MATERIALS AND UPDATING OPERATIONS: THE WORD UPDATING TASK

Although it may be assumed that, for example, the counter updating task requires a verbal representation of the current working memory items, the updating operation itself is arithmetic. In contrast, the word updating task we introduce here requires a verbal representation, while the relevant updating operation has a language-based characteristic as well. There are at least three reasons why it is important whether or not findings from other working memory updating tasks generalise to this particular combination of stimuli and operations. First, linguistic stimuli (i.e., words) and updating operations deserve particular interest, since working memory in the sense of Baddeley (2000, 2007)—especially the phonological loop—has often been related to psycholinguistic research, e.g., language in general (Gathercole & Baddeley, 1993), word learning (Gathercole, 2006), writing (Grabowski, 2010; Kellogg, 1999), or specific language impairment (Gathercole & Baddeley, 1990; Janczyk, Schöler, & Grabowski, 2004). Second, existing working memory updating tasks make use of (arbitrary) typical laboratory stimuli. For example, the stimuli in the counter updating task are typically simple geometrical figures and the updating operations do not directly affect the numbers that represent the current content of working memory. Indeed there is some evidence that when life-long learned stimuli are used, these are processed differently compared to arbitrary ad hoc stimuli. For example, in a study by Colzato, Raffone, and Hommel (2006), typical laboratory-like stimuli with arbitrary meanings yielded only initially indications of binding which vanished over time. In contrast, life-long learned stimuli exhibited stable and robust binding and this difference was related to the absence or presence of long-term representations of the particular stimuli. Words are probably best suited to assess whether such differences apply to working memory updating as well, since they clearly have life-long learned meaningful representations associated with mental lexicons in long-term memory, and these representations are even twofold: semantic (lexem aspect) and grammatical (lemma aspect), the latter including phonological information (Levelt, 1989). Finally, words are composed of (again) meaningful smaller units on successive levels: In the case of written words, strokes combine to letters that combine to words (or articulatory features combine to sounds that combine to words, respectively). While a rectangle in a counter updating task also consists of several smaller pieces (four lines), the particular structure of the part–whole relationship of words and letters is due to their linguistic nature. This multiple-level structure prompts an interesting research question: Intuitively, a word looks like the typical working memory item, and we thus can expect costs when switching between words in an appropriate updating task. However, it might be the case that single letters (or even other units like syllables) are represented as distinct working memory items. In this case we should expect similar costs when two successive updating operations (within a word repetition) require a switch on such a finer-grained level (see introduction to Experiment 1).

In sum, the behaviour of linguistic stimuli and updating operations clearly deserves closer investigation, and the present work presents a first step towards this goal. In particular, we introduce a novel *word updating task* that has been constructed in analogy to arithmetic memory updating tasks, but uses both linguistic stimuli (requiring a verbal representation) and linguistic updating operations. To this end we made use of orthographic neighbours, i.e., words that differ only in one letter (e.g., ‘‘land’’ and ‘‘sand’’). During a trial, participants are presented with new letters together with the information of which letter they shall substitute in the given word. The resulting word in turn is the new content of the respective working memory item (to which subsequent letter substitutions can apply). Details are given below in the method section of the respective experiments.

Subsequently we will report on three experiments using this word updating task. Experiment 1 was carried out to show that this task proves fruitful to study item switching in working memory. Experiment 2 was run to generalise the findings from Experiment 1 to a different set of words and to investigate further predictions from the concentric model of working memory (Oberauer, 2002), to analyse the characteristics of the letter position switch costs found in Experiment 1 in greater detail, and to relate individual working memory capacity to item switching. Finally, Experiment 3 was run to rule out that the letter position switch costs were simply due to a necessary re-orientation of visual spatial attention.

EXPERIMENT 1

Experiment 1 was run as a first test of the word updating task's appropriateness to investigate item switching. Participants started with memorised sets of German words at the beginning of each trial. For nine subsequent items they were then informed which letter in which word they should replace with a given new letter, thereby transferring the old word into a new one. All initial, intermediate, and final words actually exist in the German language, thus no pseudo-words were used throughout the reported experiments. Participants pressed the space bar once they finished an updating process, and the time elapsing from letter onset to the press of the space bar was considered indicative of the duration of the updating process. In analogy to other working memory updating tasks, the updating operation can either be applied to a word in the same frame as before, thus to the word directly resulting from the previous update (= repetition item), or to a word associated with a different frame than before (= switch item). If the region of direct access and the focus of attention (Oberauer, 2002) are indeed supramodal (Bao et al., 2007; Cowan, 2005; Oberauer & Göthe, 2006; Oberauer

& Kliegl, 2006), item switch costs should occur with this task (i.e., shorter updating times for repetition items than for switch items). In addition the word updating task allows analysis of whether similar switch costs occur when the to-be-replaced letter appears at a different position within the word than in the previous item (obviously, this can only be meaningfully assessed for word repetition items). Based on the rationale outlined in the introduction, such a finding would suggest that, within a given word, the next ongoing cognitive operation can only be applied to one single letter position.

Method

Participants. A total of 14 (advanced) students (10 female) from Martin Luther University Halle-Wittenberg volunteered in this experiment (mean age: 25;11 years). Participants were naïve regarding the hypotheses underlying this experiment, and were native speakers of German.

Design. Participants worked on a word-updating task. The following description of a trial is illustrated in Figure 2 (the following details in parentheses also refer to this figure). Each trial started with the presentation of two German six-letter words, each located in a rectangular frame (screen: start). Letters were always presented in lower case. A small line was placed under each of the 12 letters. Participants memorised the two words and started a trial by pressing the space bar. This erased the 12 letters, and one single letter was presented on one of the lines in one of the two frames (screen: item 1). In the example (Figure 2) this is the letter ''h'' on the left-most line of the left frame. (Note that the grey letters in Figure 2 were not actually visible.) Thus participants were supposed to replace the first letter ''l'' in the initial (German) word ''leiter'' (ladder) with the letter ''h'' yielding the new (German) word ''heiter'' (cheerful). After having formed the new word, the participants pressed the space bar, and thereby progressed to item 2 without any response–stimulus interval. After nine items, the final words were probed (screen: probing) in a random order. A question mark was presented in the centre of the screen and the participants were prompted to type the final words in the respective frames. In the example the correct words are ''beißen'' (to bite) and ''futter'' (food) (screen: correct). After both words had been typed, the start screen of the next trial was displayed. The time that elapsed from the onset of one letter to the space bar press (i.e., the RT) was measured in milliseconds. Similar to the updating tasks described above, a letter substitution was either applied to the same frame as previously (= word repetition item) or to the other frame (= word switch item). Each trial consisted of four switches and four repetitions randomly distributed across items 2–9 (item 1 can neither be a switch nor a repetition item). We also categorised each word repetition item according to whether the substituted letter was at the same position (= letter position repetition item) or at a different position than in the previous item (= letter position switch item). Both factors ''word switch'' and ''letter position switch'' were within-participant factors with two levels (repetition vs switch).

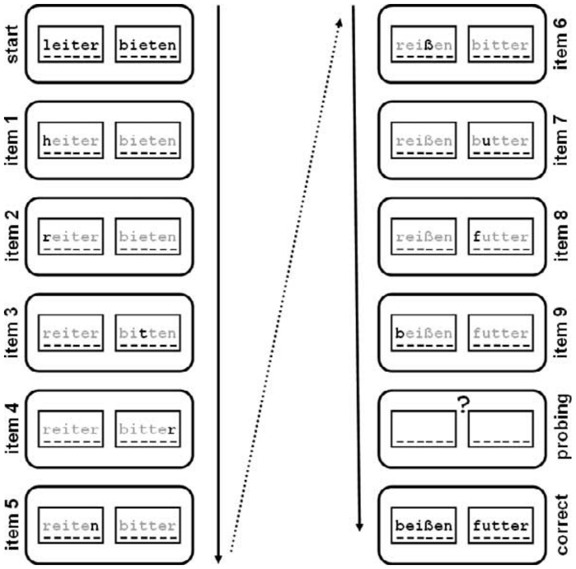

Figure 2. Illustration of a complete trial of the word updating task. ''Start'' refers to the first screen, where participants memorised the initial words, ''item 1'' to ''item 9'' are the nine subsequent updating operations, ''probing'' refers to the final screen where participants typed their final words, and ''correct'' shows the correct final words in this example. (Note that the light grey letters were not visible in the experiments proper; they are only added for illustrative reasons.)

Apparatus and materials. Stimuli were presented in black against a white background on a 17-inch computer screen via a personal computer. Font type was set to Courier size 20, and all words and letters were presented in lower case. The two frames were 7.1 cm wide and 1.9 cm high. Their location was vertically and horizontally centred with a distance of 2.0 cm between both frames. The lines were 0.6 cm wide.

Each trial included two lists of successive orthographic neighbours. These lists were built from a word list of 3518 six-letter words that was derived from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993).[1] A total of 38 words were deleted in cases where the letter "ß" needed to be replaced by "ss" (due to the recently modified German orthography). Further, all non-German words and technical terms (except those commonly known; 520 words) and words that had a total frequency smaller than 1 per 1 million words in cumulated spoken and written German language (519 words) were deleted. Finally, all words without at least one orthographic neighbour within the remaining words were excluded. From the remaining 1344 words we built lists of 5–10 orthographic neighbours, with the only restriction that within each list no word was used more than once. The 48 trials were created by selecting 96 lists randomly. The same set of trials was used for all participants. All steps in trial construction were performed by a C++ computer program.

Procedure. The participants were tested individually in an experimental room in one single session of about 30–45 minutes. Written instructions were given on the computer screen, and after three unanalysed practice trials participants had the opportunity to clarify any remaining questions, before the experimenter left the room. The subsequent 45 test trials were arranged in three blocks of 15 trials each, separated by a forced pause of 30 seconds. In sum, testing comprised three blocks of 15 trials of nine items. Thus each participant performed on a total of 405 test items.

Data treatment and analyses. A trial was considered correct only if both probes exactly matched the intended words (not case sensitive). Incorrect trials were categorised according to the number of probes being wrong (1 or 2). Only RTs from correct trials were further analysed. RTs less than 300 ms were excluded as anticipations, and RTs exceeding an individual's mean RT by more than 2.5 individual standard deviations (calculated separately for each participant and for the analysed conditions) were also excluded (3.0–3.4% of trials). An alpha level of .05 was adopted throughout this paper, and sample effect sizes are reported as η_p^2.

Results

Error analyses. Mean percentage of correct trials was 76.33 ($SD = 14.63$) ranging from 40 to 96. In most of the incorrect trials only one probe word was wrong (81.9%), and both probes were wrong in the remaining 18.1% of the incorrect trials.

RT analyses. Mean RTs were longer to word switch items, $M = 2374$ ($SD = 543$), than to word repetition items, $M = 2018$ ($SD = 443$), and repeating vs switching the to-be-substituted letter position had a large impact on word repetition items: Mean RTs for letter position switches, $M = 2067$ ($SD = 456$), were longer than to letter position repetitions, $M = 1520$ ($SD = 320$). Both effects are supported by the corresponding repeated measures analysis of variance (RM-ANOVA). First, we submitted the mean RTs to a RM-ANOVA with word switch as a within-participant factor. In accordance with the descriptive results, this yielded a significant effect, $F(1,\ 13) = 38.86$, $p < .01$, $\eta_p^2 = .75$. In a second step only the mean RTs from word repetition items were submitted to an additional RM-ANOVA with letter position switch as a within-participant factor. The observed difference between letter position switches and repetitions was significant, $F(1,\ 13) = 43.21$, $p < .01$, $\eta_p^2 = .77$. (Note that this comparison is based on highly uneven sample sizes within participants with the median n being 13 and 125 for letter position repetitions and letter position switches, respectively. The low n might question any outlier screening, but the effects remained stable even when re-running the analyses without any outlier elimination at all.)

Discussion

Experiment 1 was run as a first empirical test of the novel word updating task. For one thing, observing switch costs on the word level is consistent with earlier findings (see introduction), and thus supports a 1-item focus of attention also for this type of stimulus material and updating operation. Because orthographic neighbours are phonologically highly similar, an alternative

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[1] We are grateful to Arthur Jacobs (Humboldt University Berlin) and Ralf Graf (Catholic University Eichstätt) who allowed us to use their elaborated word list for the selection of appropriate words and the control of their orthographic neighbours.

explanation for this result might be some sort of phonological priming. However, phonological priming is not as stable as is semantic priming (e.g., Lupker, 1988). Rather, phonological priming is observed only under specific conditions like, for example, subliminal prime presentation (Humphreys, Evett, Quinlan, & Besner, 1987). Clearly this was not the case in the present experiment. In addition we found a similar switch effect on the level of letters in word repetition items: Replacing the same letter position twice allows for faster processing than replacing two letters at different positions in succession. On the basis of this finding, a 1-item focus of attention could be proposed for this level as well. However, this finding also allows for an alternative explanation of the word switch costs. It might be that the letter position switch costs increase with the distance to the new position. If this was the case and the to-be-covered distance is, on the average, larger with word switches than with word repetitions, the letter position switch costs can easily account for the word switch costs, too. Figure 3 shows the mean RTs in word repetition items as a function of the to-be-covered distance (a distance of 0 refers to a letter position repetition item): First, covering a distance of 5 (i.e., from the first to the last letter, or vice versa) is nearly as fast as a letter position repetition, ascribing to the first and the last letter of a word a somewhat special role (Rayner, White, Johnson, & Liversedge, 2006). Second, and more important, there is clearly no increase in RTs from distances of 1 to 4 (in fact an RM-ANOVA with distance (1–4) as the within-participant factor on these data was non-significant). We therefore think of the word switch cost as an independent effect, and strictly speaking, must propose a 1-item focus of attention on both the word and the letter (position) level. At this point we refrain from interpreting the letter position switch effect further, and strive to replicate and investigate it with more detail in Experiments 2 and 3.

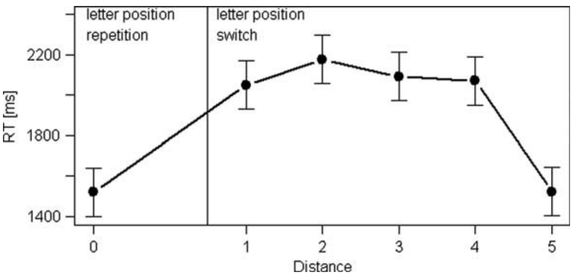

Figure 3. RTs (in milliseconds) from word repetition items of Experiment 1 as a function of the to-be-covered distance from previous letter substitution. (Error bars are 95% within-participant confidence intervals according to Loftus & Masson, 1994.)

A final remark about errors in the word updating task: With two six-letter word frames, mean error percentage was roughly 25. We consider this an acceptable difficulty. However, in a pre-test we ran the same experiment with three six-letter words. One participant did not achieve even one correct trial, another participant was correct in only two trials. In sum, participants reported that the task was far too difficult, and that they were only successful when concentrating on two out of the three words (accepting one wrong probe from the very beginning). We therefore conducted Experiment 1 with only two six-letter words, and will turn to four-letter words in the following Experiment 2. Note that the two reported effects remained stable when excluding the six participants with less than 75% correct trials.

EXPERIMENT 2

The results from Experiment 1 extend (on the word level) earlier findings of item switch costs to a new set of stimuli and updating operations. According to the concentric model of working memory (Oberauer, 2002) switch costs should increase with set size, i.e., the number of (active) working memory items currently stored within the region of direct access, due to more competition for selection by the focus of attention (Janczyk et al., 2008, Experiment 2; Oberauer, 2002, 2003). In Experiment 2 we therefore varied the word set size, and expected larger word switch costs for three words than for two words. To keep the task on a feasible difficulty level, we opted for using four-letter words in Experiment 2, thereby generalising the word switch effect to a different set of words.

The results from Experiment 1 further showed that a switch effect does not only exist on the level of words but also on the level of letter positions within words: Word repetition items were updated faster when the letter substitution occurred at the same letter position as in the previous item. Strictly speaking, a 1-item of focus of attention can be proposed for this level as well. To put this effect on a firmer ground we introduced trials with only one word (i.e., word set size 1) where each item is a word repetition item.

Finally we assessed working memory capacity using the listening span procedure (Daneman & Carpenter, 1980). Using an extreme-group comparison, in three experiments Unsworth and Engle (2008) found differences between participants with high and low operation spans (Turner & Engle, 1989) only for the accuracy but not for the speed of focus switching in a counter updating task. We here pursue a correlational approach, and expect a positive relation of listening span and accuracy measures but not the speed of focus switching in the word updating task. (We also applied a simple word span measure to consider further possibly pre-existing individual differences of basic memory spans.)

Method

Participants. A total of 26 undergraduate students (21 female) from Dortmund University of Technology participated in this experiment (mean age: 22;7 years). They were paid course credit in return for their participation. Participants were naïve regarding the hypotheses underlying this experiment, and were native speakers of German.

Design. Participants worked on a word updating task with German four-letter words (see the design section of Experiment 1 for a detailed description). Word set size (i.e., the number of concurrently memorised words) was varied from one to three block-wise. Each item was categorised as either being a word repetition or a word switch (for set sizes 2 and 3 only), and word repetition items were additionally categorised as a letter position repetition or a letter position switch. All three factors "word switch", "letter position switch" (both: repetition vs switch), and "word set size" (1 vs 2 vs 3) were within-participant factors.

Apparatus and materials. Stimuli were presented in black against a white background on a 15-inch computer screen via a personal computer. Font type was set to Courier size 20, and all words and letters were presented in lower case. The frames within which the words were presented were 4.8 cm wide and 1.2 cm high. For set size 1 trials the frame was centred. For set size 2 trials the frames' locations were vertically and horizontally centred with a distance of 3.6 cm between both boxes. For set size 3 trials the frames were located on the edges of an (invisible) triangle. Two frames were located as in set size 2 trials; the third frame was located horizontally centred with its own centre 5.5 cm above screen centre. The lines were 0.5 cm wide.

The trials were built from the same word list used to prepare Experiment 1 containing 1055 four-letter words; 4 words were deleted due to the recent orthographic reformation, and 97 words were deleted as non-German words or technical terms. Finally, all words without at least one orthographic neighbour were excluded. We did not reduce this list further, and constructed lists of 5 to 10 orthographic neighbours from the remaining 851 words. The lists for set sizes 2 and 3 were drawn at random from this list pool, whereas the lists of 10 words with the highest percentage of letter position repetitions were selected as set size 1 trials. This allowed us to better equate the frequencies of letter position repetitions and switches at least for word set size 1 trials. (Of the analysed word set size 1 trials the median *n*s for letter position repetitions and switches were 91 and 122.) The same set of trials was used for all participants.

The *word span* and the *listening span* stimuli were extensions of sets originally used in research with children (Grabowski, 2010): (1) Stimuli in the word span task were seven blocks of three word lists with an increasing number of words (3–9) per block. The participants' task was to repeat the words after they were presented once at a 1-second pace. Two practice trials of two words ensured understanding of the task, followed by a maximum of the seven test blocks. (2) Stimuli in the listening span task (Daneman & Carpenter, 1980) were five blocks of three lists with an increasing number (2–6) of short affirmative sentences like "60 Minuten sind eine Stunde" ("60 minutes are one hour") per block. The participants' task was to judge each sentence as "true" or "false" within 1.5 seconds, to memorise the last word of this sentence, and eventually to recall the final words of all sentences of the respective list. Correct order was not required and the correctness of the judgements was not evaluated. (Semantic correctness answers are solely intended to prevent participants from merely rehearsing the last words of the sentences rather than processing the meaning of the sentences.) Two practice trials of two sentences ensured understanding of the task, followed by a maximum of five test blocks. Testing in both tasks terminated when a participant failed in all three lists of one block. The achieved score was the number of words or sentences in the lists of the last administered block before the termination;

0.5 points were subtracted if a participant was only correct in one of the three items of the last-administered lists.

Procedure. The participants were tested individually in single sessions of 90–120 minutes. The sessions consisted of three parts, and at the beginning of each part participants were given written instructions. The word span test was administered first, followed by the listening span test. The final part was the word updating task. After six unanalysed practice trials (two of each set size) participants had the opportunity to clarify any remaining questions before the experimenter left the room. The subsequent 90 test trials (30 trials of each set size) were arranged in blocks of 15. Set size was varied block-wise and two order conditions were realised (1-2-3-3-2-1 and 3-2-1-1-2-3). Participants were assigned to one of the two conditions in alternation. In sum, testing comprised 810 test items (270 of each set size).

Data treatment and analyses. A trial was considered as correct only if all probes exactly matched the intended words (not case sensitive). Incorrect trials were categorised according to the number of probes being wrong (1, 2, or 3). Only RTs from correct trials were further analysed. RTs less than 300 ms were excluded as anticipations, as well as those exceeding an individual's mean RT by more than 2.5 individual standard deviations (calculated separately for each participant and for each analysed condition; 2.9–3.9%). Where necessary, Greenhouse-Geisser corrections were applied. (However, for easier communication we report uncorrected degrees of freedom.)

Results

Error analyses. For set size 1 mean percentage of correct trials was 90.64 ($SD = 8.33$) ranging from 70 to 100. For set size 2 mean percentage of correct trials was 73.97 ($SD = 15.95$) ranging from 43 to 97 (similar to the results of Experiment 1). In 73.4% of the incorrect trials only one probe was incorrect, and both probes were incorrect in 26.6%. For set size 3 mean percentage of correct trials was 39.36 ($SD = 17.00$) ranging from 17 to 80. In 51.6% of the incorrect trials only one probe was incorrect, two probes were incorrect in 34.2%, and all three probes were incorrect in 14.2%. In sum, there were fewer correct trials with larger word set size, and within each word set size in the majority of the incorrect trials only one probe was wrong. Mean percentages of correct trials were submitted to a RM-ANOVA with the within-participant factor word set size (1 vs 2 vs 3). Helmert contrasts confirmed this decrease in accuracy with larger word set sizes, first comparison: $F(1, 25) = 191.00$, $p < .01$, $\eta_p^2 = .88$, second comparison: $F(1, 25) = 223.13$, $p < .01$, $\eta_p^2 = .90$.

RT analyses. The mean RTs relevant to the following analyses are illustrated in Figure 4. As expected, participants' responses were faster to word repetitions than to word switches, and this difference (the switch costs) was larger with word set size 3 than with word set size 2 (see Figure 4, upper panel). Accordingly, a RM-ANOVA on the mean RTs with factors word switch and word set size as within-participant factors (only word set sizes 2 and 3 were included) yielded significant main effects of word switch, $F(1, 25) = 59.14$, $p < .01$, $\eta_p^2 = .70$, and word set size, $F(1, 25) = 64.96$, $p < .01$, $\eta_p^2 = .72$, and the interaction was also significant, $F(1, 25) = 4.75$, $p < .05$, $\eta_p^2 = .16$.

To investigate the letter position switch effect observed in word repetitions of Experiment 1, subsequent analyses included only word repetition items (trivially, for word set size 1 all items are word repetitions). Overall, responses to items with letter position repetitions were faster than to items

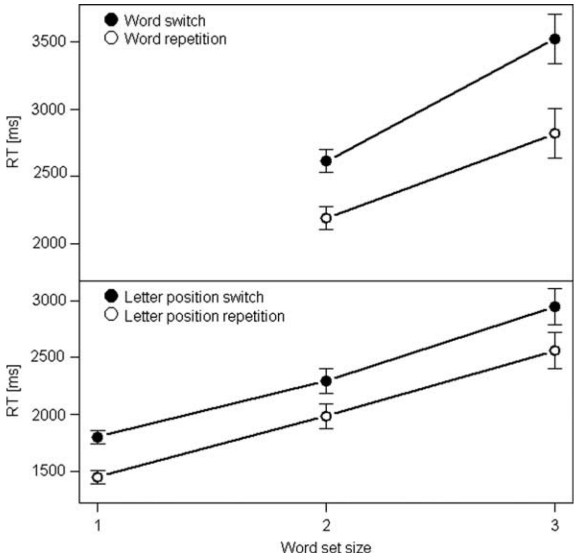

Figure 4. RTs (in milliseconds) from Experiment 2 as a function of word switch and word set size (upper panel), and letter position switch and word set size (lower panel). (Error bars are 95% within-participant confidence intervals according to Loftus & Masson, 1994.)

with letter position switches. Although the mean RTs increased with word set size, the letter position switch costs showed no systematic variation depending on word set size (see Figure 4, lower panel). Accordingly, a RM-ANOVA with factors letter position switch and word set size yielded only two significant main effects, $F(2, 50) = 69.52$, $p < .01$, $\eta_{\mathrm{p}}^{2} = .74$ for word set size, and $F(1, 25) = 33.92$, $p < .01$, $\eta_{\mathrm{p}}^{2} = .58$ for letter position switch. Additional paired t-tests confirmed significant letter position switch costs within each word set size condition, $3.59 \leq |t|(25) \leq 8.54$, all ps $< .01$.

Correlations. The complete pattern of correlations is summarised in Table 1. First, word span and listening span were positively correlated. Apart from this, and as expected, only listening span and the mean percentages of correct trials for all word set sizes separately, as well as across all word set size conditions, were positively correlated. All other correlations were nonsignificant, except for one isolated correlation between ERR-1 and SC-2 that we do not consider indicative.

Discussion

The purposes of Experiment 2 were threefold: First, we sought to generalise the basic finding of item switch costs with the word updating task to a new set of words, and to explore an additional relevant assumption of the concentric model of working memory (Oberauer, 2002). Second, we aimed at investigating the letter position switch costs observed in Experiment 1 in greater detail. A third objective was to consider the correlations between working memory capacity (listening span; Daneman & Carpenter, 1980) and the accuracy and speed of focus switching within working memory.

The results regarding item switching on the word level are straightforward: Word switch costs again became evident, and increased with increasing word set size (2 vs 3 words), exactly meeting a central expectation from the concentric model of working memory. This effect has been empirically already shown by Oberauer (2002, 2003; see also Janczyk et al., 2008, Experiment 2); here we present concurring evidence from a novel and important domain of stimuli and updating operations.

A particularly interesting and continuative finding is the similar switch effect on the letter level. With better-equated probabilities for letter position repetitions and letter position switches for word set size 1 trials we again observed letter position switch costs; and they were also evident across all three word set size conditions. Interestingly, the magnitude of these letter position switch costs was not systematically related to *word* set size, a finding that will be further addressed in the General Discussion section.

The last objective of this experiment was to analyse the interrelations between working memory capacity and focus switching: Listening span (Daneman & Carpenter, 1980) was correlated with accuracy but not with RT switch costs. While we used different tasks and correlations (rather than an extreme-group comparison), our results are convergent to what Unsworth and Engle (2008) recently reported for the operation span (Turner & Engle, 1989) and a counter updating task. Hence our results provide independent support in favour of the assumption that speed and accuracy of focus

TABLE 1

Correlations of listening and word span, word switch costs, and mean error percentages from Experiment 2

	LS	*WS*	*SC-2*	*SC-3*	*ERR-1*	*ERR-2*	*ERR-3*
WS	.64(**)						
SC-2	.35	.33					
SC-3	−.12	−.01	.17				
ERR-1	.42(*)	.02	.53(**)	−.345			
ERR-2	.44(*)	.10	.19	−.35	.59(**)		
ERR-3	.40(*)	.08	.33	.00	.50(**)	.74(**)	
ERR-TOT	.48(*)	.09	.36	−.23	.72(**)	.92(**)	.91(**)

LS = Listening span; WS = Word span; SC-2 = Switch costs, word set size 2; SC-3 = Switch costs, word set size 3; ERR-1 = Mean error percentage, word set size 1; ERR-2 = Mean error percentage, word set size 2; ERR-3 = Mean error percentage, word set size 3; ERR-TOT = Mean error percentage across word set size 1–3.

**$p < .01$ (2-tailed); *$p < .05$ (2-tailed).

switching are two dissociable characteristics of item switching in working memory.

EXPERIMENT 3

In Experiments 1 and 2 we have repeatedly observed word and letter position switch costs. On both levels, however, only switches required a re-orientation of visual spatial attention, and this confound may explain the respective switch costs as well. Such account has already been ruled out for the arithmetic updating task (Oberauer, 2003, Experiment 1b). Our Experiment 3 was run to further rule out this objection on the letter position level, where only letter position switches required an attentional visual re-orientation. Thus in Experiment 3 the spatial location of a word was varied for each updating operation. As a consequence, both letter position switches and repetitions required visual attentional shifts. When letter position switch costs still occur, these can no longer be attributed to visual attentional processes, thus rejecting this alternative explanation of letter switch costs.

Method

Participants. A total of 10 undergraduate students (9 female) from Dortmund University of Technology participated in this experiment (mean age: 22;6 years). They were paid course credit in return for their participation. Participants were naïve regarding the hypotheses underlying this experiment, and were native speakers of German. None of them had participated in one of the previous experiments.

Design. Participants worked on a word updating task (see the design section of Experiment 1 for a detailed description) with German four-letter words. Word set size for this experiment was 1. Thus each item was a word repetition and ‘‘letter position switch’’ (repetition vs switch) was the sole within-participant factor.

Apparatus, materials, and procedure. The apparatus and stimuli were the same as in Experiment 2, except that only word set size 1 trials were used. The first item of each trial was presented centrally. Then, for each updating operation, the word (plus the surrounding frame) changed its location unpredictably within an (invisible and centred) rectangle stretching across 400×200 pixels. The participants were tested individually in a single session of 30 minutes and were given written instructions. After two unanalysed practice trials participants had the opportunity to clarify any remaining questions before the experimenter left the room. The subsequent 30 test trials were divided into two blocks of 15 trials each. The order of these blocks was counterbalanced across participants.

Data treatment and analyses. A trial was considered as correct only if the final probe exactly matched the intended word (not case sensitive), and only RTs from correct trials were further analysed. RTs less than 300 ms were excluded as anticipations, as well as those exceeding an individual's mean RT by more than 2.5 individual standard deviations (calculated separately for each participant and for each analysed condition; 3.0%–3.2% of the trials).

Results and discussion

Mean percentage of correct trials was 89 ($SD = 0.6$). Mean RTs were 1547 ms ($SD = 403$ ms) and 1921 ms ($SD = 500$ ms) for letter position repetitions and switches, respectively, and this difference was significant, $F(1, 9) = 22.60$, $p < .01$, $\eta_p^2 = .72$. Thus, despite introducing the requirement of visual attentional shifts for every item, we still found substantial letter position switch costs of 374 ms that cannot be attributed to a concurrent change of letter position and the target place of visual attention. Based on a different experimental manipulation, a similar conclusion has been drawn for the arithmetic updating task earlier (Oberauer, 2003, Experiment 1b).

GENERAL DISCUSSION

How many items of working memory can cognitive processes access simultaneously? Despite the varying estimates in the literature, we believe that it is only one item. One argument for this belief is the observation of item switch costs from several kinds of working memory updating tasks: When an already selected item remains the target of the next cognitive operation, this operation is accomplished several hundred milliseconds faster than when the next target is a different item. In this latter case the new target item needs first to be retrieved into a highly accessible state, and apparently only one item can be in this state at any given time. This is often interpreted as evidence for a 1-item focus of attention (e.g., Garavan, 1998; Oberauer, 2002). The present work is settled in the framework of the concentric model of working memory (Oberauer, 2002), which distinguishes three different layers of items according to their accessibility: the activated long-term memory, the region of direct access, and the focus of attention selecting the one item to which the next cognitive operation can be applied. Critically, the focus of attention can only directly retrieve items from within the region of direct access. Thus, with increasing numbers of items within this region, selection becomes more difficult and more time-consuming. In contrast, items stored outside this region are assumed not to interfere with selection through the focus of attention.

With the word updating task we introduced a novel task to research on item switching. To the best of our knowledge this is the first time linguistic stimuli (namely words) plus a language-related updating operation have been used in an updating task. This is surprising since working memory (in particular Baddeley's model) has extensively been applied to psycholinguistic research (e.g., Gathercole & Baddeley, 1990, 1993; Kellogg, 1999). This circumstance clearly suggests incorporating the linguistic domain into experimental paradigms on which alternative working memory models are based. If, for a start, we consider each memorised and manipulated word in an experimental trial of the word updating task as an instance of a single working memory item, the results are straightforward: In Experiments 1 and 2 word switch costs were observed, and in Experiment 2 they increased with word set size. Thus the concentric model (Oberauer, 2002) receives independent empirical support from our experiments.

In addition, words are built of smaller units, namely letters, which constitute another self-contained symbol system. This allowed the present study to explore the role of this finer-grained level. In any (word repetition) item in the word updating task, the letter substitution either occurred at the same position as in the previous item or at a different position (letter position repetitions and switches, respectively). Across all three experiments, letter position switch costs were evident, and they were not merely based on the re-orientation of visual spatial attention for letter position switches as opposed to repetitions (Experiment 3). Moreover, letter position switch costs do not determine word switch costs through larger distances to be covered in word switch items (Experiment 1). In contrast to the word switch costs, the size of letter position switch costs was not systematically related to word set size. Although the number of letters per word (i.e., letter set size) has not been varied within one experiment, an analysis of the combined data from Experiment 1 (letter set size: 6) and the comparable word set size 2 trials from Experiment 2 (letter set size: 4) indeed suggests increasing letter position switch costs (within-participant factor) with increasing letter set size (between-participants factor), $F(1,\ 38) = 4.94$, $p < .05$, $\eta_p^2 = .12$ for the interaction. It is further interesting to note that overall RTs, at least in the comparable word set size 2 conditions, were faster with six-letter words (Experiment 1) than with four-letter words (Experiment 2). We suggest that, similar to the TRACE model for spoken word recognition (McClelland & Elman, 1986), more bottom-up activation from the letter to the word level can be expected for six-letter words, thus predicting faster word recognition and faster overall performance. If this is true, it is notable that working memory related results were observable and robust, despite the influence of other, complex but explainable, phenomena.

In sum we have two levels, words and letters, and both levels appear to behave in quite the same way: What implications do these results have? Remember that the concentric model assumes that only items within, but not outside, the region of direct access affect the functioning of the focus of attention. In this respect our results suggest a theoretically highly interesting possibility, which is illustrated in Figure 5. The results concerning word switches and word set size can easily be accounted for by the concentric model: All words are stored inside the region of direct access with the one word, in which a letter is substituted, being in the focus of attention (Figure 5a). (We have not introduced passive items—Oberauer, 2002—thus we cannot say anything about the influence of words stored outside the region of direct access.) To account for the results concerning the letter position switch costs, we draw on a similar argument (Figure 5b): All letters of the currently updated word are stored inside the region of direct access, with the substituted letter (position) being in the focus. In this case the other words would be stored outside the region of direct access, thus not affecting the size of letter position switch costs. However, such reasoning ignores the effect of word set size on word switch costs. To account for the effects on both levels we need to resort on a post-hoc explanation and suggest a recursive model as illustrated in Figure 5c: All words are simultaneously stored within the (global) region of direct access. The (global) focus of attention selects the word to which the next updating operation will be applied. Within the (global) focus of attention another instance of a more local focus of attention then selects a specific letter (position), and the global focus of attention serves as a more local region of direct access. To avoid misunderstandings we do not intend to propose a fourth entity to be incorporated into the concentric model of working memory (Oberauer, 2002). Although this might offer a tempting solution in our particular case, it does not appear to be parsimonious: One might think of even more levels with repeated recursive effects on each of them. Rather, we prefer to propose that the mechanisms suggested by the concentric model apply on several levels. In particular, the focus of attention may first select a word and then narrow down, zooming into a specific letter position, thereby turning the former focus of attention into a new region of direct access in a recursive manner. Such a construction would not question the current version of the concentric model, but rather should be conceived as an interesting elaboration when multiple levels of items are analysed. Of course, this interpretation also raises several continuative questions. If, for example, the focus of attention zooms into one word that is broken down into its constituent letters: What happens to a second word that was also held in the area of direct access? Is it kept as a whole or also broken down? Answering this question touches other topics as well. If the level of representation (and thus the granularity) can change at any time, does this affect the measurement of working memory capacity? At present, however, we could only speculate, and find it premature to deliver a modified, and partially overarching, theory.

In addition to the results summarised above, Experiment 2 offered a chance to investigate the interrelations of working memory span and focus switching speed and accuracy. Recently, Unsworth and Engle (2008) reported that participants with high and low operation spans (Turner & Engle, 1989) differ in the accuracy but not in the speed of focus switching in a counter updating task. Conceivably, the listening span (Daneman & Carpenter, 1980) is more akin to the word updating task than the operation span, and whereas Unsworth and Engle (2008) used comparisons between extreme groups, we calculated bivariate correlations. Still we found supportive results: The higher the listening span, the greater was the accuracy in the word updating task. On the other hand, word switch costs showed no association with listening span. Two limitations of these analyses should be noted. First, the sample size ($n = 26$) may be considered too small to

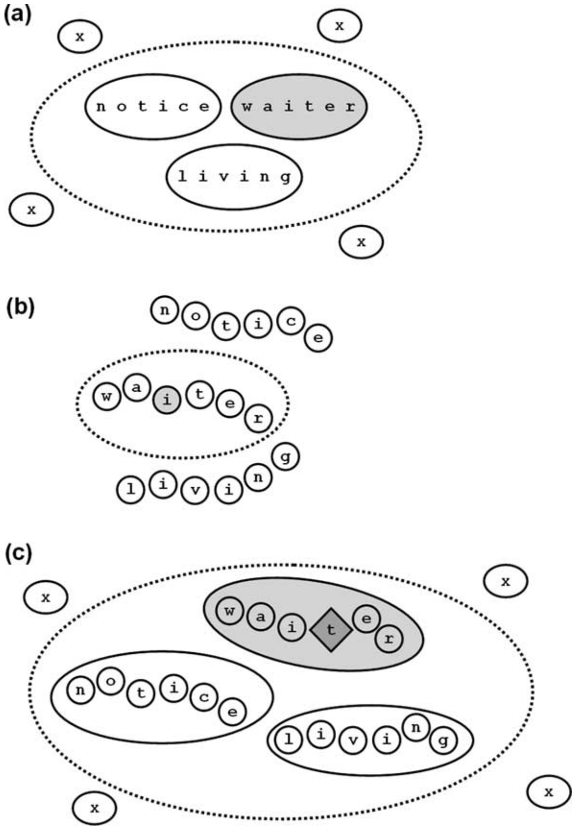

Figure 5. Illustrations of three alternative models to account for the word switch costs and the letter position switch costs. (a) The original concentric model applied to the word level: Working memory items (solid ovals) are whole words stored within the region of direct access (dotted oval), from where the focus of attention selects one word (light grey shaded oval). Potential items outside the region of direct access are drawn as circled Xs. (b) The original concentric model applied to the letter level: Working memory items (solid ovals) are single letters. All letters of the currently updated word are stored within the region of direct access (dotted oval), from where the focus of attention selects one specific letter position (light grey shaded oval). Letters of other words are stored outside the region of direct access. (c) The recursive model combining letter and word levels: This model is similar to (a), however, the global focus of attention (light grey shaded oval) serves as a local region of direct access, from where a local focus of attention selects a specific letter position (dark grey shaded diamond). (See text for further explanations.)

produce interpretable results. Second, switch costs were measured on the item level, whereas accuracy was measured only overall. With the current paradigm this latter point cannot be overcome, and also applies to the study by Unsworth and Engle (2008). Still, despite these limitations and using a different updating task plus a different complex span measure, our results corroborate those reported by Unsworth and Engle (2008). Accordingly, they provide evidence for the assumption that the speed and the accuracy of focus switching are two dissociable characteristics of item switching.

In sum, with the present work we introduced a novel task to the research on item switching, and (on the word level) we were able to replicate common findings from working memory updating tasks thereby providing new evidence for the 1-item focus of attention (e.g., Garavan, 1998) and the concentric model of working memory (Oberauer, 2002). Whether our recursive model (Figure 5c) is a valid account of our overall data is of course a question for future research. Thus far it is unknown whether similar structures can be uncovered with proper materials other than words, but we are convinced that the possibility of such a recursive functioning of working memory structures is theoretically interesting and deserves further empirical attention.

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